



Article

Growth, Productivity, and Nutrient Return of a Mixed Plantation of Fast-Growing *Eucalyptus* Hybrid and *Acacia auriculiformis* Trees in Thailand

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Abstract: Mixed-species plantations involving *Eucalyptus* and *Acacia* trees are an effective alternative for managing sustainable plantations. In this study, we evaluated the growth, productivity, nutrient return, and soil properties of a mixed *Eucalyptus* hybrid (*Eucalyptus camaldulensis* Dehnh. × *E. urophylla* S.T. Blake; E) and *Acacia auriculiformis* A. Cunn. ex Benth. plantation (A) and *Eucalyptus* hybrid and *A. auriculiformis* plantations. The mixed *Eucalyptus* hybrid and *A. auriculiformis* plantation included three ratios at E33:A67, E50:A50, and E67:A33, while the *Eucalyptus* (E100) and *A. auriculiformis* (A100) plantations were established on degraded lands in the Had Wanakorn Forestry Research and Student Training Station, Prachuap Khiri Khan province, Thailand. Three replications within a plot size of 20 × 20 m² were designed to plant *Eucalyptus* hybrid and *A. auriculiformis* seedlings at a spacing of 2 × 3 m². The diameters at breast height (DBH) and height (H) of the *Eucalyptus* hybrid and *A. auriculiformis* were measured and monitored after planting for five years. The aboveground biomass of the five-year-old mixed and monoculture plantations was then estimated. Litterfall production and nutrient return from the mixed and monoculture plantations were measured for three years. In addition, soil samples at depths of 0–5, 5–10, and 10–20 cm were collected to analyze the soil's chemical properties. Differences in growth, aboveground biomass, litterfall production, nutrient return, and soil properties were analyzed and tested using Tukey's HSD. The results indicated that both the DBH and H of the *Eucalyptus* hybrid in the mixed and monoculture plantations were not significantly different ($p > 0.05$). Similarly, the DBH and H of *A. auriculiformis* in each treatment were also not significantly different ($p > 0.05$). However, the DBH and H of the *Eucalyptus* hybrid were higher than those of *A. auriculiformis*. The aboveground biomass for the mixed plantation ratios E50:A50, E100, E67:A33, and E33:A67 was not significantly different, while the stem biomass was the highest in E100. Litterfall production was influenced by the proportion of the *Eucalyptus* hybrid relative to *A. auriculiformis*, but the monoculture A100 plantation had the highest litter production. The nitrogen return estimated for the mixed plantation was between A100 and E100. Similarly, the total nitrogen in the topsoil (0–5 cm) of the mixed plantation was higher than that in the monoculture E100 plantation. These results indicate that mixing *A. auriculiformis* with *Eucalyptus* can improve soil nutrients and nutrient cycling and increase nutrient returns, suggesting that mixed plantations are an effective option for sustainable plantation management and can mitigate the negative environmental impacts of *Eucalyptus* monocultures.

Keywords: growth; aboveground biomass; litterfall; nutrient return; *Eucalyptus* hybrid; *Acacia auriculiformis*; mixed plantation



Academic Editor: Mark S. Ashton

Received: 25 November 2024

Revised: 12 January 2025

Accepted: 14 January 2025

Published: 19 January 2025

Citation: Wongprom, J.; Jumwong, N.; Sangvisitpirom, P.; Diloksumpun, S.; Thaopimai, L.-o. Growth, Productivity, and Nutrient Return of a Mixed Plantation of Fast-Growing *Eucalyptus* Hybrid and *Acacia auriculiformis* Trees in Thailand. *Forests* **2025**, *16*, 182. <https://doi.org/10.3390/f16010182>

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1. Introduction

Eucalyptus is a multi-purpose tree and plays an important role in the economics of the private sector and local communities. Due to its high growth rate, this tree has been widely planted across Thailand, especially in the northern and eastern regions [1]. *Eucalyptus camaldulensis* Dehnh. has also been reported to be drought-tolerant [2]. In Thailand, the area covered by *Eucalyptus* plantations is estimated to be approximately 846,708 ha [3]. However, several concerns related to its impact on the environment have arisen [4,5]. At the same time, fast-growing trees such as *Acacia* species can be planted in plantations owned by individual farmers and the private sector as an alternative. These nitrogen-fixing trees have been reported to improve soil properties and increase organic matter and soil nutrients, especially nitrogen [6,7]. Additionally, a high litter production of 5.94 to 10.38 Mg ha⁻¹ has been reported from an *Acacia* plantation [8,9].

Fast-growing tree species are mostly planted in monoculture plantations. The rotation of woody species is between three and seven years. They are harvested for woodchips, plywood, and pulp for use in the paper industry. The wood production of plantations can vary depending on genetics, as was the case for the wood volume of *Acacia mangium* Willd. at approximately 73–106 m³ ha⁻¹ and that of an *Acacia* hybrid at 138 m³ ha⁻¹ [10]. Thus, commercial plantations have benefited from planting high-quality genetic clones to enhance their growth and productivity [10,11].

Mixed plantations of *Eucalyptus* and nitrogen-fixing trees have been planted in many areas. The growth and productivity of these plantations depend on the species being used [12] and the proportion of each planted species [13–16]. Mixed plantations of *Eucalyptus globulus* Labill. and *Acacia mearnsii* De Wild. can lead to an increase in the diameter at the breast height and the height of *E. globulus*. The productivity of mixed plantations can be comparable to that of *Eucalyptus* monoculture plantations [17]. In addition, the absorbed photosynthetically active radiation (APAR) and light use efficiency of mixed plantations (*Eucalyptus* and *Acacia*) have been reported to be greater than those of monoculture plantations [18].

The mixing of nitrogen-fixing trees and *Eucalyptus* has been reported to enhance the growth of *Eucalyptus* relative to monocultures [14,19]. Mixed plantations of *E. globulus* and *A. mearnsii* can increase soil nutrients, especially nitrogen, which is crucial for promoting the productivity of intercropped trees [20]. Fertilizers are important for increasing growth and productivity [21]. Soil nutrients in long-term agriculture and degraded lands are commonly very low. Adding fertilizer in plantations is needed to maintain adequate nutrient levels in the soil. In addition, mixed plantations of *Eucalyptus* and nitrogen-fixing trees can accelerate litter decomposition and improve litter quality [22]. Additionally, mixed plantations of *Eucalyptus* and *Acacia* can promote soil microbial diversity and activity and improve carbon and nitrogen cycling [23]. The nutrient status of the topsoil, especially N, tends to increase shortly after the establishment of a mixed plantation, in part due to higher nutrient return via litterfall [14]. From a long-term sustainability perspective, nutrient cycling in a mixed plantation can improve soil properties and maintain nutrient balance [24].

Generally, *Eucalyptus* monocultures are often of concern given their high water and nutrient demand for growth and nutrient removal after harvesting [24]. In contrast, mixed plantations of *Eucalyptus* and nitrogen-fixing species are less popular due to potential competition for resources, resulting in lower growth rates and productivity [25]. In addition, a mixed plantation is usually characterized by intra- and inter-specific competition. The competition between species is different depending on their interaction [26,27], and appropriate species matching can promote growth and reduce inter-specific competition in a mixed plantation. A better understanding of mixed plantations can be beneficial in managing fast-growing tree plantations. Therefore, this study aimed to investigate the

growth, productivity, nutrient return, and soil nutrients of mixed (*Eucalyptus* hybrid and *Acacia auriculiformis*) and monoculture plantations. These results can provide an alternative approach for the sustainable management of such plantations.

2. Materials and Methods

2.1. Site Description and Plant Materials

The experimental plot was located at the Had Wanakorn Forestry Research and Student Training Station (11°37'11" N; 99°41'08" E), Thapsakae district, Prachuap Khiri Khan province, Thailand (Figure 1), which is a 15-year-old abandoned coconut plantation. The experimental plot was located approximately 2 km from the coast and had a sandy soil texture. The mean microclimatic conditions during the period of investigation (2018–2023), as measured by the maximum temperature, minimum temperature, rainfall, and humidity, were 35.8 °C, 21.9 °C, 1108 mm, and 76.8%, respectively. The rainy season usually spanned from May to November, and the dry season from December to April, as per the Prachuap Khiri Khan Meteorological Station, Thailand.

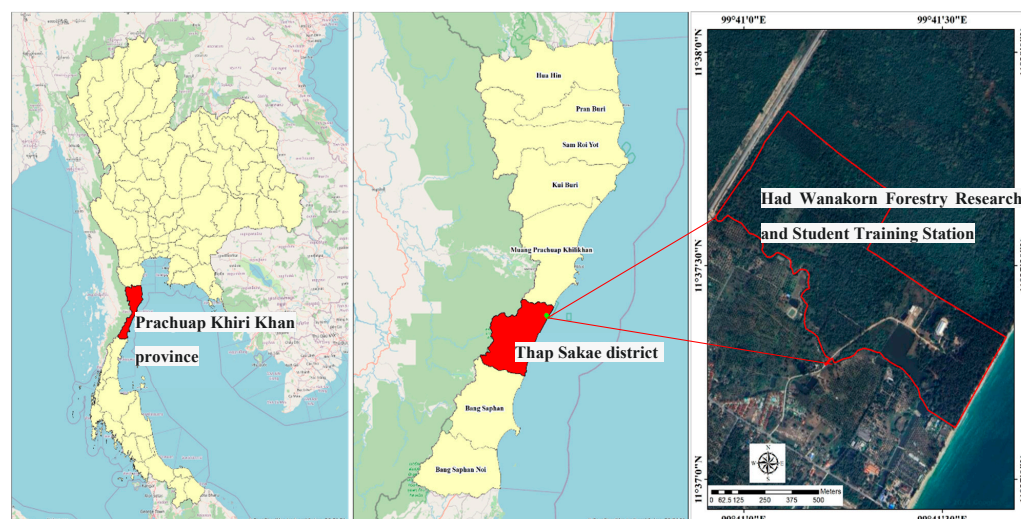


Figure 1. Location of study site at Had Wanakorn Forestry Research and Student Training Station, Thap Sakae district, Prachuap Khiri Khan province, Thailand.

2.2. Experimental Design

Experimental plots of $20 \times 20 \text{ m}^2$ were established in an area of approximately 0.8 hectares, which was cleared out before planting the trees. The planted *Eucalyptus* hybrid (E) was a clone of *E. camaldulensis* Dehnh. \times *E. urophylla* S.T. Blake, while the *A. auriculiformis* A. Cunn. ex Benth. (A) was a clone of *Acacia* hybrids (intra-specific hybrids of *A. auliciformis*). Seedlings of the *Eucalyptus* hybrid and *A. auriculiformis* were produced from clonal cutting and planted in October 2018.

The *Eucalyptus* hybrid and *A. auriculiformis* were planted in monoculture and mixed-species plots that contained 100% *Eucalyptus* (E100), 100% *A. auriculiformis* (A100), 67% E + 33% A (E67:A33), 50% E + 50% A (E50:A50), and 33% E + 67% A (E33:A67), with each plot containing 66 individuals (100%).

A randomized complete block design (RCBD) with three replications was implemented in plots of the *Eucalyptus* hybrid and *A. auriculiformis* planted at a spacing of $2 \times 3 \text{ m}^2$. Fertilizer application was not carried out in any treatment.

The layout of mixed-species and monoculture plantations of E33:A67, E50:A50, E67:A33, E100, and A100 is shown in Figure 2. Weeds were removed twice a year during the

first two years. In addition, pruning was practiced on 50% of the stems for the 1-year-old *A. auriculiformis* and was repeated on the 2-year-old trees at a height of 2 m aboveground.

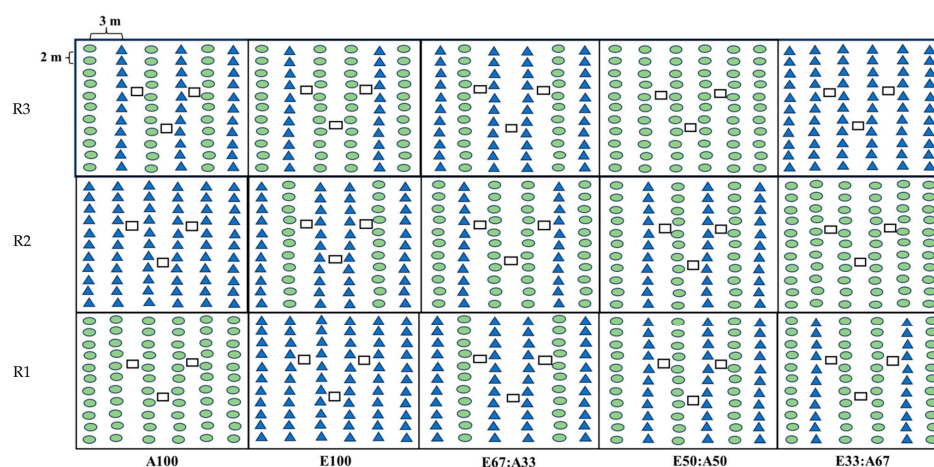


Figure 2. The layout of the *Eucalyptus* hybrid (\blacktriangle) and *Acacia auriculiformis* (\bullet) in the mixed-species and monoculture plantations, with the location of litter traps (\square), at the ratios A100, E100, E67:A33, E50:A50, and E33:A67 at the Had Wanakorn Forestry Research and Student Training Station, Thap Sakae district, Prachuap Khiri Khan province, Thailand.

2.3. Tree Growth and Aboveground Biomass

The survival and growth of the *Eucalyptus* hybrid and *A. auriculiformis* in all treatments were monitored for the entire duration of plantation rotation (5 years). The crown diameter, diameter at breast height (DBH), and height (H) of all trees among the treatments were measured. The aboveground biomass of the 5-year-old *Eucalyptus* hybrid and *A. auriculiformis* was estimated using the methodology developed by Wongchai et al. (2020) [28]. The equations for *Eucalyptus* and *Acacia* species are given in Table 1.

Table 1. Aboveground biomass equations of *Eucalyptus* and *Acacia* species in the mixed and monoculture plantations.

Species	Components	Equations
<i>Eucalyptus</i>	Stem	$0.027 (\text{DBH})^{1.625} \text{H}^{1.212}$
	Branch	$0.004 (\text{DBH} + 1)^{2.642}$
	Bark	$0.009 (\text{DBH})^{1.800} \text{H}^{0.670}$
	Leaf	$-1.121 + 0.272 (\text{DBH})$
<i>Acacia</i>	Stem	$0.044 [(\text{DBH})^2 \text{H}]^{0.894}$
	Branch	$0.022 (\text{DBH})^2 \text{H}^{0.727}$
	Bark	$0.006 [(\text{DBH})^2 \text{H}]^{0.894}$
	Leaf	$-0.701 + 0.361 (\text{DBH})$

Remark: DBH is the diameter at the breast height, and H is the height of trees.

2.4. Litterfall Production

Three litter traps (constructed using a nylon mesh suspended inside a PVC frame) of $1 \times 1 \text{ m}^2$ were set up within the treatments (Figure 2) to estimate litter production. Weeds under the traps were removed, and litter for all treatments was collected monthly for three years, collecting the litterfall from the age of 2.5 years. Any damaged traps were repaired immediately. Once collected, the litter was separated by species into various components, i.e., leaves, branches, barks, reproductive parts (flowers, seeds, and their

supporting structures), and miscellaneous items. These components were then sorted and oven-dried at 70 °C for 48 h or until they reached a constant weight, after which each of the samples was weighed individually.

The litter components were analyzed for their nutrient concentration. To reduce the cost of analyses, monthly litter samples were homogenized, and 50 g subsamples were pooled to make composites for the dry and rainy seasons. All of the samples were analyzed at the Forest Soil Laboratory, Faculty of Forestry, Kasetsart University. The N concentration was based on dry combustion using a CNHS analyzer (Perkin Elmer model 2400 Series II CHNS/O Elemental Analyzer), and the concentrations of P, K, Ca, and Mg were determined by wet washing the litter with $\text{NH}_4\text{OH}-\text{HClO}_4$ acid ($\text{HNO}_3:\text{HClO}_4$; 5:2). The concentration of P was analyzed using the vanadomolybdate yellow color method with a spectrometer at a wavelength of 440 nm, while the concentrations of K, Ca, and Mg were analyzed using atomic absorption spectrometry.

2.5. Soil Nutrients

Samples at three soil depths (0–5, 5–10, and 10–20 cm) around five points in the monoculture plantations (A100 and E100) were collected. However, eight soil samples were collected in the mixed-species plantation (four samples were collected between *Acacia* rows and four samples between *Eucalyptus* rows). The soil samples from each soil depth were mixed to make one sample. The samples were then air-dried and sieved through a 2 mm sieve, and any root fragments were removed. The organic matter (OM) was determined as per the recommendations of Walkley and Black (1934) [29]. Total nitrogen (N) was measured using the Dumas method and a CHNS analyzer. Available phosphorus (P) was determined using the method proposed by Bray and Kurtz (1945) [30]. The levels of exchangeable potassium (K) were determined using atomic absorption spectrophotometry.

3. Data Analysis

Growth in terms of DBH and H, aboveground biomass, litterfall production, nutrient return, and soil nutrients, including total N, available P, exchangeable K, Ca, and Mg, was analyzed using a one-way analysis of variance (ANOVA), and the means were compared using Tukey's HSD test at a 95% significance level.

4. Results

4.1. Growth Performance

The survival of the five-year-old *Eucalyptus* hybrid and *A. auriculiformis* in the monoculture and mixed plantations was not significantly different ($p > 0.05$). The survival percentages of the *Eucalyptus* hybrids in E100, E67:A33, E50:A50, and E33:A67 were 96.92, 97.04, 95.96, and 95.45, respectively, while those for *Acacia* were 96.41, 96.30, 94.95, and 93.94, respectively.

The DBH and H of the *Eucalyptus* hybrid in the mixed and monoculture plantations were not found to be significantly different (both $p > 0.05$). The DBH and H of the *Eucalyptus* hybrid and *A. auriculiformis* increased with the age of the plantations. The DBH and H of the five-year-old *Eucalyptus* hybrid in E100, E67:A33, E50:A50, and E33:A67 ranged from 11.19 to 12.08 cm and 16.75 to 17.41 m, respectively (Figure 3). Additionally, the DBH and H of *A. auriculiformis* among treatments were also found to be not significantly different (both $p > 0.05$). The DBH and H of the five-year-old *A. auriculiformis* in A100, E33:A67, E50:A50, and E67:A33 ranged from 9.61 to 9.89 cm and 11.87 to 12.00 m, respectively.

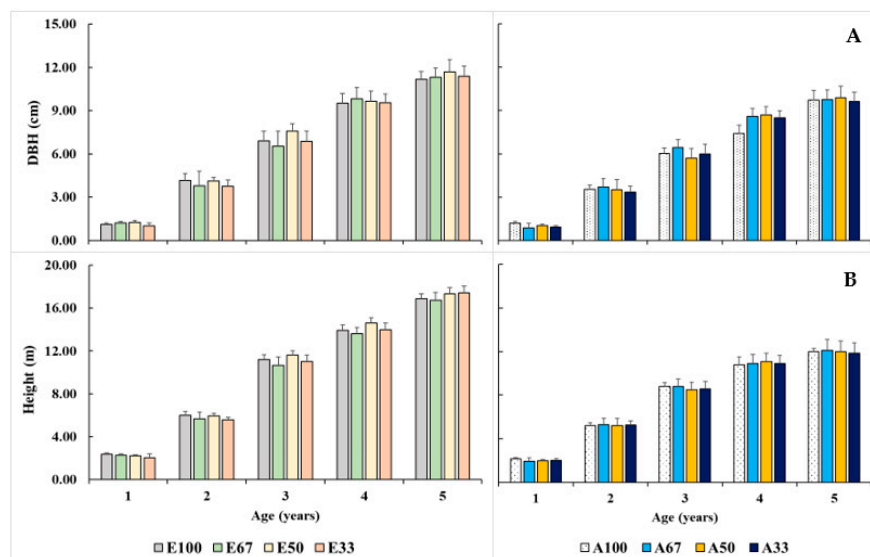


Figure 3. DBH (A) and H (B) of the 1–5-year-old *Eucalyptus* hybrid (E) and *A. auriculiformis* (A) in the mixed and monoculture plantations.

The *Eucalyptus* hybrid was taller than the *A. auriculiformis* in all treatments. On the contrary, the crown diameter of the *Eucalyptus* hybrid was smaller than that of *A. auriculiformis* (Table 2). This corresponded with the canopy stratification observed between the *Eucalyptus* hybrid and *A. auriculiformis* in the mixed plantation.

Table 2. Crown diameters of the 5-year-old *Eucalyptus* hybrid (E) and *A. auriculiformis* (A) in the mixed and monoculture plantations.

Treatment	Tree Species	
	<i>A. auriculiformis</i> (A)	<i>Eucalyptus</i> Hybrid (E)
E100	-	2.02
E67:A33	3.18	2.07
E50:A50	3.20	2.06
E33:A67	3.45	2.10
A100	3.51	-
<i>p</i> -Value	0.28 ^{ns}	0.96 ^{ns}

Remark: ns indicates a non-significant difference ($p > 0.05$).

4.2. Aboveground Biomass

Statistically significant differences were observed in the stem biomass among the various treatments ($p < 0.05$), with E100 having the highest stem biomass (77.44 Mg ha^{-1}), while that of A100 was the lowest (41.79 Mg ha^{-1}) (Figure 4). The stem biomass of E67:A33, E50:A50, and E33:A67 was in between the above-mentioned levels (65.27 , 67.23 , and 56.44 Mg ha^{-1} , respectively). The stem biomass of *Eucalyptus* was higher than that of *A. auriculiformis* because it grew well. Given its large and dense canopy, the amount of branch and leaf biomass produced by *A. auriculiformis* was higher than that of the *Eucalyptus* hybrid. The bark biomass of the *Eucalyptus* hybrid and *A. auriculiformis* in the E100, A100, E67:A33, E50:A50, and E33:A67 plantations was 8.33 , 5.71 , 7.02 , 8.04 , and 6.85 Mg ha^{-1} , respectively. The aboveground biomass of the E100, A100, E67:A33, E50:A50, and E33:A67 plantations was found to be significantly different ($p < 0.05$) (74.31 , 94.40 , 86.17 , 94.67 , and 83.83 Mg ha^{-1} , respectively), but that of E100, E67:A33, E50:A50, and E33:A67 was similar. In this case, the *Eucalyptus* hybrid was a major contributor to the biomass pool in E50:A50 and E67:A33, while *A. auriculiformis* was a major contributor to the biomass pool accumulated in

A67:E33. Additionally, the aboveground biomass of the E67:A33 and E33:A67 plantations was proportional to the number of planted *Eucalyptus* hybrid and *A. auriculiformis* trees.

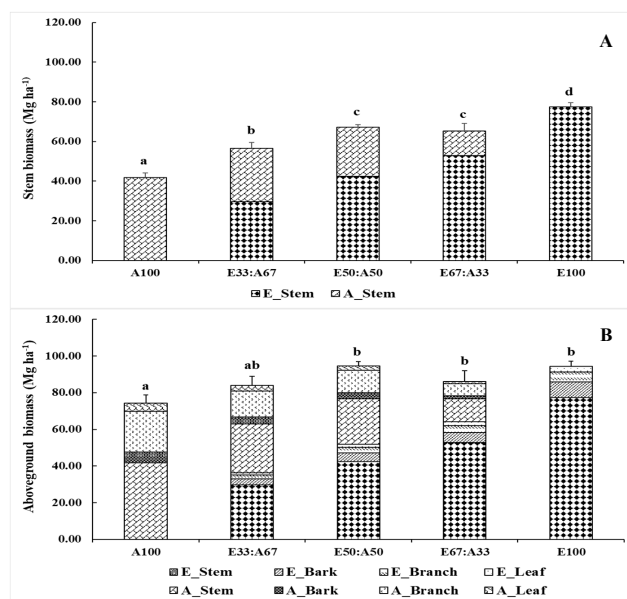


Figure 4. Stem biomass (A) and aboveground biomass (B) of the 5-year-old *Eucalyptus* hybrid and *A. auriculiformis* in the mixed and monoculture plantations. The letters (a, b, c, and d) above the bars indicate statistical differences at $p < 0.05$, as determined by Tukey’s HSD.

4.3. Litterfall

The amount of litterfall in all plantations increased during the months of December and January, which corresponded with the early dry season (Figure 5). Leaves were the major litter component falling onto the forest floor, followed by branches, reproductive parts, barks, and miscellaneous components, respectively (Figure 6). Bark litter was exclusively found in the hybrid *Eucalyptus* plantation, while the reproductive parts were exclusive to the *A. auriculiformis* plantation. The litter production varied according to the age and proportion of the planted *Eucalyptus* hybrid and *A. auriculiformis* trees. The litter production of the 3.5-year-old *Eucalyptus* hybrid and *A. auriculiformis* in the mixed and monoculture plantations was similar, but no significant difference was observed in the 4.5- and 5.5-year-old plantations. The amount of litter produced by the 3.5- and 4.5-year-old *Eucalyptus* hybrid plantation was relatively high, but it reduced when the plantation reached an age of 5.5 years, as the canopy was lighter after natural pruning.

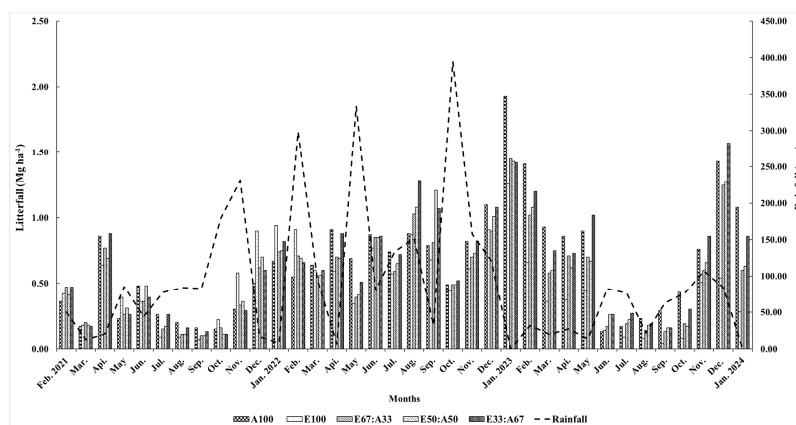


Figure 5. Monthly litterfall of the *Eucalyptus* hybrid and *A. auriculiformis* in the mixed and monoculture plantations from February 2021 to January 2024.

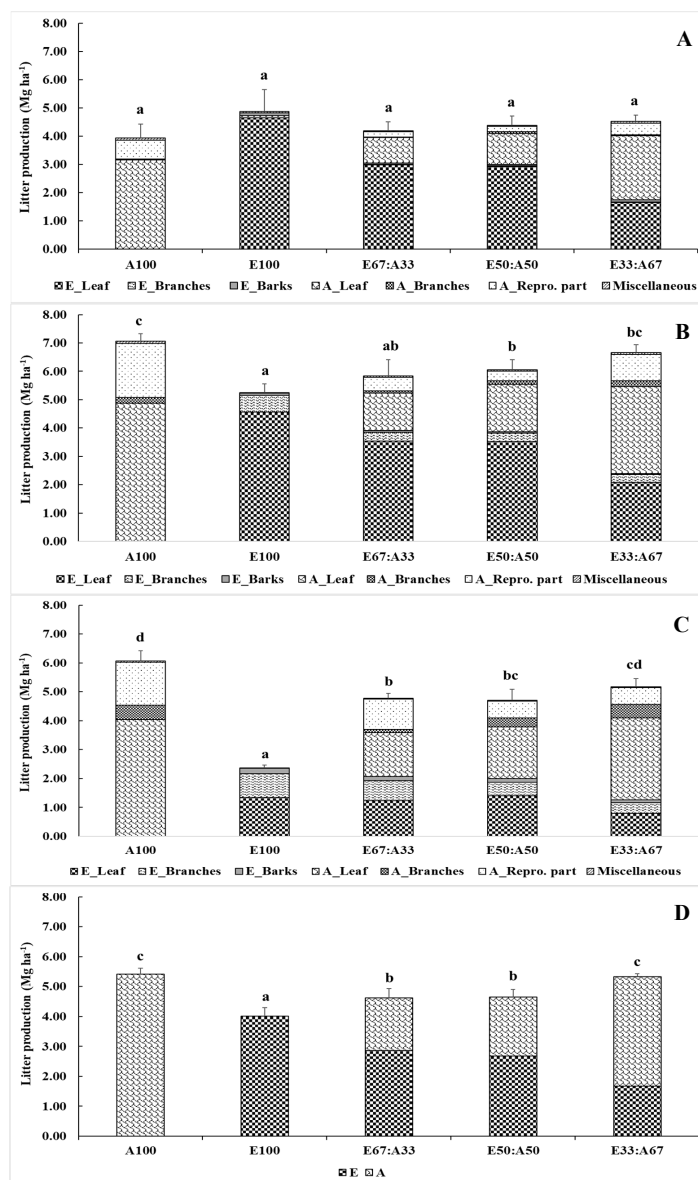


Figure 6. Litterfall separated by components, including leaves, branches, barks, reproductive parts, and miscellaneous parts, of the *Eucalyptus* hybrid and *A. auriculiformis* at ages of 3.5 (A), 4.5 (B), and 5.5 years (C). The mean litterfall (D) estimated for the mixed and monoculture plantations. The letters (a, b, c, and d) above the bars indicate statistical differences at $p < 0.05$, as determined by Tukey’s HSD.

The mean litterfall of A100 was the highest, followed by E33:A67, E50:E50, E67:A33, and E100 (5.42, 5.32, 4.65, 4.61, and 4.01 Mg ha⁻¹, respectively). The litterfall of the mixed plantation was estimated to be at average levels, with the majority of litter produced by *A. auriculiformis*.

4.4. Nutrient Return

The mean nutrient return in the mixed plantation varied according to the proportion of the *Eucalyptus* hybrid and *A. auriculiformis*. The nitrogen return was the highest in A100 and the lowest in E100 (Table 3). The nitrogen return of the mixed plantation increased according to the proportion of *A. auriculiformis*. On the contrary, calcium return was relatively high in the E100, E33:A67, E50:A50, and E67:A33 plantations. The nutrient return

in A100 was in the order $N > Ca > K > Mg > P$, while that of the E100, E67:A33, E50:A50, and E33:A67 plantations was in the order $Ca > N > K > Mg > P$, respectively.

Table 3. Mean nutrient return of the *Eucalyptus* hybrid and *A. auriculiformis* growing in the mixed and monoculture plantations.

Nutrient	A100 (kg ha ⁻¹ yr ⁻¹)	E100 (kg ha ⁻¹ yr ⁻¹)	E67:A33 (kg ha ⁻¹ yr ⁻¹)	E50:A50 (kg ha ⁻¹ yr ⁻¹)	E33:A67 (kg ha ⁻¹ yr ⁻¹)	F-Value
N	88.63 ^d	22.36 ^a	42.92 ^b	47.84 ^b	57.50 ^c	93.10 ^{**}
P	0.54 ^b	0.40 ^a	0.48 ^{ab}	0.47 ^{ab}	0.55 ^b	12.65 [*]
K	19.38	20.86	16.69	14.32	20.43	3.17 ^{ns}
Ca	61.33 ^b	46.19 ^a	58.93 ^b	68.79 ^{bc}	79.00 ^c	27.12 ^{**}
Mg	8.40 ^b	8.97 ^b	8.73 ^b	9.50 ^b	7.16 ^a	9.39 [*]

Remark: * significant difference; ** highly significant difference; ns, non-significant difference; letters (a, b, c, d) in the same row indicate significant differences at $p < 0.05$, as determined by Tukey's HSD.

4.5. Soil Nutrients

Soil nutrients, including total nitrogen, available phosphorus, and potassium, in the topsoil (0–5 cm) of the mixed and monoculture plantations were significantly different, except for calcium and magnesium. The A100 plantation had the highest total estimated nitrogen at 0.90 g kg⁻¹, with E50:A50 and E33:A67 having similar levels (0.82 and 0.83 g kg⁻¹, respectively) (Table 4). In the mixed plantation, the total nitrogen, available phosphorus, organic matter, and potassium levels in the topsoil were between the values measured for A100 and E100. In the subsoil (5–10 and 10–20 cm), the levels of total nitrogen, available phosphorus, organic matter, potassium, and magnesium among treatments were not different ($p > 0.05$). In addition, the soil nutrients decreased with soil depth.

Table 4. Soil nutrients of the 5-year-old *Eucalyptus* hybrid and *A. auriculiformis* in the mixed and monoculture plantations.

Soil Depth (cm)	Treatment	OM (g kg ⁻¹)	Total N (g kg ⁻¹)	Avai. P (g kg ⁻¹)	K (g kg ⁻¹)	Ca (g kg ⁻¹)	Mg (g kg ⁻¹)
0–5	A100	16.60 ^c	0.90 ^c	4.60 ^b	61.80 ^b	164.33	60.17
	E100	10.67 ^a	0.59 ^a	3.51 ^a	28.50 ^a	189.33	52.17
	E67:A33	12.90 ^{ab}	0.71 ^{ab}	3.58 ^{ab}	35.50 ^a	210.67	76.10
	E50:A50	16.10 ^{bc}	0.82 ^{bc}	4.40 ^{ab}	55.23 ^b	236.00	66.97
	E33:A67	15.33 ^{bc}	0.83 ^{bc}	4.22 ^{ab}	45.83 ^{ab}	169.07	72.67
	F-value	12.53 ^{**}	19.99 ^{**}	4.96 [*]	12.54 [*]	0.96 ^{ns}	3.38 ^{ns}
5–10	A100	7.89	0.46	3.14	34.13	27.47	41.57
	E100	8.72	0.39	3.34	20.17	41.17	40.27
	E67:A33	8.96	0.43	2.75	27.03	31.27	46.30
	E50:A50	9.70	0.46	3.85	30.97	44.57	56.53
	E33:A67	7.60	0.44	3.56	31.77	36.67	57.23
	F-value	0.31 ^{ns}	0.89 ^{ns}	1.64 ^{ns}	3.07 ^{ns}	1.60 ^{ns}	4.01 ^{ns}
10–20	A100	5.24	0.38	2.65	18.27	25.87	30.10
	E100	6.46	0.30	2.75	13.70	20.70	36.67
	E67:A33	4.76	0.33	2.84	18.80	26.33	33.93
	E50:A50	7.58	0.37	2.56	19.13	36.00	49.10
	E34:A67	4.76	0.35	2.63	15.33	35.93	45.53
	F-value	1.01 ^{ns}	0.74 ^{ns}	0.23 ^{ns}	1.97 ^{ns}	1.52 ^{ns}	2.39 ^{ns}

Remark: * significant difference; ** highly significant difference; ns, non-significant difference; different letters (a, b, and c) in the same column indicate significant differences at $p < 0.05$, as determined by Tukey's HSD.

5. Discussion

5.1. Growth Performance

The *Eucalyptus* hybrid and *A. auriculiformis* have been reported to have a high survival rate as they can adapt well to poor soil conditions [31,32]. In addition, *A. auriculiformis* is an intra-specific hybrid between two distinct provenances, which is capable of tolerating drought conditions [33]. On the contrary, the *Eucalyptus* hybrid, which is a hybrid of *E. camaldulensis* and *E. urophylla*, can grow well on degraded lands with low rainfall [31,34].

Mixed *Eucalyptus* hybrid and *A. auriculiformis* in the E33:A67, E50:A50, and E67:A33 plantations had no effect on the growth of *Acacia* or *Eucalyptus* compared to the monoculture plantations. The measured DBH and height of the *Eucalyptus* hybrid and *A. auriculiformis* in the mixed plantation exhibited good growth. Previously, the DBH and H of a four-year-old *Eucalyptus* hybrid in E100 (9.50 cm and 13.94 m, respectively) were reported to be similar to the *Eucalyptus* hybrid (K62) (8.80 cm and 12.99 m, respectively) in the eastern part of Thailand [35]. However, the DBH and H of the five-year-old *Eucalyptus* hybrid in this study were higher than those of *E. camaldulensis* planted in northern Thailand (10.06 cm and 15.34 m, respectively) [28].

In the *A. auriculiformis* plantation, the DBH and H among treatments were also similar, with *A. auriculiformis* experiencing good growth compared to other sites. Additionally, genetic improvement of the *Eucalyptus* hybrid and *A. auriculiformis* has been reported to enhance the growth rate and productivity [11,36–38]. The DBH and H of four-year-old *A. auriculiformis* were similar to the *Acacia* hybrid in BaVi (9.20 cm and 10.70 m, respectively) [39] and *A. auriculiformis* in Vietnam (8.75 cm and 7.84 m, respectively) [11]. In addition, the estimated growth was also similar to an *Acacia* hybrid (5.7 years old) plantation in northern Thailand (9.54 cm and 11.83 m, respectively). However, the growth of the five-year-old *A. auriculiformis* in this study was lower than that of *A. auriculiformis* of the same age planted in Vietnam (12.0 cm and 18.8 m, respectively). Higher levels of nitrogen are important for growth [40] but are a critical limiting factor [41]. The differences observed in DBH and H may be due to higher soil nitrogen in the *A. auriculiformis* plantation, which was in its third rotation [40].

Besides nitrogen supply, environmental factors such as rainfall, light, and soil properties are equally important for growth. The growth of *Eucalyptus* facilitated through a mixed plantation of *Eucalyptus* and nitrogen-fixing trees has been reported in numerous planting sites [16,42,43]. In contrast, this study found that the growth of the *Eucalyptus* hybrid was not affected by the introduction of *A. auriculiformis* in a mixed plantation setting. This result may be attributed to relatively high rainfall after planting, as evidenced by the site's total rainfall of 1443.6 and 1812.0 mm in 2018 and 2022, respectively. Additionally, the 30-year annual average of rainfall in Prachuap Khiri Khan province has been reported to be between 965.7 and 1112.60 mm [44].

The *Eucalyptus* tree has a high water use efficiency, which promotes its growth and productivity [45,46]. In addition, the sandy soil texture provides good drainage, further supporting the growth of *Eucalyptus* hybrids. Nutrients may not be a key factor influencing the growth of *Eucalyptus* hybrids in this area. Other resources, such as available water and light and soil conditions, can play a significant role in promoting growth [25,47]. Thus, rainfall likely had a substantial impact on the growth of the *Eucalyptus* hybrid in this study.

Mixing a *Eucalyptus* hybrid and *A. auriculiformis* can also change the vertical structure of plantations. The mean height of the five-year-old *Eucalyptus* hybrid was 17.35 m, while that of *A. auriculiformis* was 12.36 m. The *Eucalyptus* hybrid dominated *A. auriculiformis*, leading to a stratified canopy. This clearly occurred in the mixed plantation and has been reported previously [48,49]. The canopy stratification of mixed plantations can positively affect the light use efficiency [17,18], with mixed plantations demonstrating a

higher efficiency compared to *Eucalyptus* monocultures. In addition, the *E. camaldulensis* hybrid undergoes natural pruning easily, which facilitates higher light penetration for *A. auriculiformis*. As a consequence, mixed plantations have been reported to have relatively higher photosynthesis compared to *Eucalyptus* monocultures [50].

5.2. Aboveground Biomass

In the present study, the stem biomass of E100 was the highest, while that of A100 was the lowest, and the stem biomasses of E67:A33, E50:A50, and E33:A67 were in between. The mixing of the *Eucalyptus* hybrid with *A. auriculiformis* trees did not increase the wood production relative to the *Eucalyptus* hybrid monoculture, mainly because the stem diameter of the *Eucalyptus* hybrid in the mixed plantation did not increase significantly. In addition, it has been observed that the growth of *A. auriculiformis* in mixed plantations is lower than that of the *Eucalyptus* hybrid, leading to low stem production in a mixed plantation setting [48]. The stem biomass of the mixed plantation in this study largely depended on the proportion and growth of the *Eucalyptus* hybrid. The stem biomass of the *Eucalyptus* hybrid was approximately 46% higher than that of the *A. auriculiformis* monoculture.

The aboveground biomass of E100, E50:A50, E67:A33, and E33:A67 was found to be similar, indicating that the nitrogen supply from *A. auriculiformis* litterfall in the mixed plantation did not influence the production of biomass. The *Eucalyptus* hybrid exhibited favorable growth and majorly contributed to the biomass produced in the mixed plantation, except for E33:A67. Litter from leaf and branch components was contributed by *A. auriculiformis*. *A. auriculiformis* had a relatively larger canopy than that of the *Eucalyptus* hybrid, leading to higher litter biomass. This result effectively increased the aboveground biomass of the mixed plantation. Previously, a less dense canopy was reported for a five-year-old *Eucalyptus* hybrid, leading to lower leaf and branch biomass compared to *E. deglupta* and *E. urophylla* [51].

Statistically similar amounts of aboveground biomass in the mixed plantation and the *Eucalyptus* hybrid monoculture indicated that *A. auriculiformis* could be intercropped with the *Eucalyptus* hybrid to increase the aboveground biomass and carbon allocation [43,48]. Santos et al. (2017) [24] indicated that mixed stands can reduce the rate of nutrient removal from a short rotation plantation. The residual of *Acacia* in mixed plantations can increase the nitrogen stock, thereby improving the nitrogen status of the plantation [52]. The density of *A. auriculiformis* in the *Eucalyptus* plantation was important for the overall productivity of the plantation, with higher numbers of *A. auriculiformis* trees leading to lower production in the mixed plantation. In contrast, the high stem production in E100 resulted in maximum economic returns, meaning that the mixed plantation would have a lower income. Although the economic return of wood in a mixed plantation could be lower than that of a *Eucalyptus* plantation, mixed plantations can reduce the cost of fertilizer during plantation management. As reported previously, the nitrogen fixation in mixed plantations of *E. grandis* and *A. mangium* (E50:A50) was 20% higher than that of E100, leading to high N mineralization in soil [42]. The N content in the biomass of the mixed plantation was higher than that of the *Eucalyptus* plantation, which can improve the soil N status of the plantation [52]. In addition, the large crown of *Acacia* in the mixed plantation can negatively impact the growth and number of weeds, leading to a lower cost for weeding.

The aboveground biomass produced by the mixed plantation ratios E50:A50 and E67:A33 was between that of E100 and A100 and was not significantly different from E100. This suggests that such mixing ratios should be promoted for sustainable plantation management. A mixed plantation can enhance the diversity and composition of under-

story vegetation and increase the levels of soil nutrients and the diversity of the bacterial community [42,53], as well as enhance nutrient cycling [25,52,54].

5.3. Litterfall and Nutrient Return

The overall litterfall peaked in December–January during the early dry season. Fast-growing trees such as the *Eucalyptus* hybrid in this study are very sensitive to water stress [9]. However, the high litterfall amounts measured in 2022 were probably a result of heavy rains and windy storms [55].

A major objective of mixed plantations involving *Eucalyptus* and nitrogen-fixing trees is to improve the aboveground nutrient status and nutrient cycling [22,47,52]. The litterfall produced by the mixed plantation in this area was intermediate. *A. auriculiformis* can promote litterfall production in mixed plantations with a large canopy, especially for ages five years and beyond. In contrast, the *Eucalyptus* hybrid had a lower litterfall production because of a small and light canopy. As such, mixed plantations can positively influence litter production [24,52].

Nutrient return has a significant relationship with litterfall production and nutrient concentration in the litter [12,22]. The nitrogen content can be particularly high in *Acacia*, a nitrogen-fixing tree. A100 had the highest nitrogen return because of higher litterfall production and nitrogen concentration. In the present study, the nitrogen return in the mixed plantation varied according to the proportion of *A. auriculiformis* and the *Eucalyptus* hybrid (E33:A67 > E50:A50 > E67:A33), canopy structure, and age. Overall, the nutrient return in the 3.5- and 4.5-year-old *Eucalyptus* hybrid monocultures was relatively high, which was probably influenced by a large canopy and crown competition, leading to high litterfall on the forest floor. Calcium was the major nutrient that returned to the *Eucalyptus* hybrid plantation because of its high concentration in *Eucalyptus* [24]. Meanwhile, the litter produced by *A. auriculiformis* gradually increased for plantations aged 3.5 years and then stabilized when the canopy closed at plantation ages of 4.5 and 5.5 years.

The higher decomposition of nitrogen in the mixed plantation was clearly influenced by the presence of *A. auriculiformis* compared to the monoculture plantations. This indicates that *A. auriculiformis* plays an important role in improving nutrient levels and promoting nutrient cycling in mixed plantations. Mixed plantations can enhance the aboveground nutrient levels, with soil nutrients being largely extracted by fast-growing trees [24]. In this study, the nitrogen return in the mixed plantation ratios E33:A67, E50:A50, and E67:A33 (57.50, 47.84, and 42.92 kg ha⁻¹ yr⁻¹, respectively) was higher than that of E100 (22.36 Mg ha⁻¹ yr⁻¹). This is a significant observation, as mixed plantations can reduce the cost of fertilizers in fast-growing tree plantations.

5.4. Soil Nutrients

Soil nutrients, including total nitrogen, available phosphorus, potassium, and organic matter, increased with the proportion of *A. auriculiformis*, particularly in the topsoil. Nitrogen levels remarkably increased in A100, E50:A50, and E33:A67 compared to E100. Previously, Tang et al. (2013) [22] similarly indicated that mixing *Eucalyptus* and nitrogen-fixing trees positively affects the soil organic carbon, total nitrogen, and available phosphorus, potassium, and magnesium compared to *Eucalyptus* monocultures. Additionally, a mixed plantation consisting of nitrogen-fixing trees can improve litter quality [9], promote soil microbial activity, and increase microbial density and diversity. These factors can improve nutrient release and nutrient cycling in such plantations [56]. The decomposition rate of litter in the mixed plantation (*Eucalyptus* and nitrogen-fixing trees) was higher than that of the *Eucalyptus* monoculture [22], leading to a higher nutrient release into the soil.

Nitrogen-fixing trees have been reported to improve soil development and soil quality in degraded lands, especially nitrogen levels [7,57]. In this area, soil nutrients increased following the establishment of a mixed plantation, as was the case for *A. auriculiformis*. A100 had the highest total nitrogen in the soil, while the mixed plantation had intermediate levels, indicating the role of *A. auriculiformis* in increasing the total nitrogen content. The lower soil nutrients in the *Eucalyptus* monoculture suggest that intercropping with *A. auriculiformis* can be considered with *Eucalyptus*. This is because the nutrient uptake by *Eucalyptus* plantations is relatively higher [58], while the nutrient return via litter is lower [52].

The low soil nutrient levels in the mixed and *A. auriculiformis* monoculture plantations measured in this study may be attributed to it being the first rotation of the plantations. Soil development can be slow, particularly in sandy soils with a low nutrient absorption capacity. According to Formaglio et al. (2023) [59], mixed *Eucalyptus* and *Acacia* plantations increase the nitrogen availability in the topsoil compared to *Eucalyptus* monocultures, which helps to meet the nitrogen requirements of the trees. This can effectively reduce the need for nitrogen fertilization in *Eucalyptus* plantations. However, subsequent rotations of plantations would be beneficial for accelerating growth and increasing productivity. Soil nutrients can be accumulated through soil amendments in a mixed plantation. The coppicing potential of *Eucalyptus* hybrids from stumps is characterized by a high number of shoots and robust growth. According to da Silva et al. (2020) [21], enhancing the nutrient availability in *Eucalyptus* plantations managed under a coppicing system can significantly stimulate growth and increase productivity. However, introducing nitrogen-fixing trees into other plantations, such as *Tectona grandis* plantations and agroforestry, should be recommended for improving soil nutrients, maintaining nutrient balance, and enhancing the growth and yield of intercropping trees.

Long-term monitoring in mixed plantations is necessary to better understand soil properties and productivity. Huong et al. (2015) [40] indicated that planting *Acacia* hybrids on degraded lands can improve soil fertility, especially nitrogen levels, and increase plantation productivity in subsequent rotations. The increased availability of nitrogen can also contribute to a higher production of wood biomass under poor soil conditions [14].

6. Conclusions

In this study, we reported the growth, productivity, nutrient return, and soil properties of a mixed *Eucalyptus* hybrid (*E. camaldulensis* × *E. urophylla*; E) and *A. auriculiformis* (A) plantation and monocultures of the *Eucalyptus* hybrid and *A. auriculiformis*. The results indicated that the DBH and H of the five-year-old *Eucalyptus* hybrid were higher than those of *A. auriculiformis*. However, the DBH and H of the *Eucalyptus* hybrid in the mixed and monoculture plantations were not different, and they were similar to those of *A. auriculiformis*. The *Eucalyptus* hybrid dominated *A. auriculiformis* in both the monoculture and mixed plantations. The aboveground biomass of the mixed plantation ratios E100, E67:A33, E50:A50, and E33:A67 was similar. However, the stem biomass of E100 was the highest, while the stem biomasses of E67:A33 and E50:A50 were intermediate. The nitrogen supplied by *A. auriculiformis* in the mixed plantation did not influence the growth or productivity of the *Eucalyptus* hybrid. Environmental factors such as rainfall might majorly influence the growth and productivity of *Eucalyptus* hybrids in this area. The mean litterfall and nutrient return of the mixed plantation were higher than those of E100. The topsoil soil nutrient levels improved significantly, especially nitrogen in A100, E67:A33, and E50:A50. Mixed *Eucalyptus* hybrid and *A. auriculiformis* plantations can be a valuable alternative to *Eucalyptus* monocultures. Such plantations can benefit from the positive influence of nitrogen-fixing trees, which can reduce the need for nitrogen fertilizers in

plantations and improve nutrient cycling. Moreover, mixed plantations can mitigate the negative environmental impacts of *Eucalyptus* monocultures.

Author Contributions: Conceptualization, J.W.; Methodology, J.W., N.J. and L.-o.T.; Formal analysis, J.W. and L.-o.T.; Investigation, J.W., N.J., P.S. and L.-o.T.; Writing—original draft, J.W.; Writing—review & editing, S.D., J.W. and L.-o.T.; Supervision, S.D. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Kasetsart University Research and Development Institute (RS (KU) 1.65).

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors are grateful to the staff at the Had Wanakorn Forestry Research and Student Training Station for their assistance during the fieldwork.

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

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