

Evaluation of Carbon Stock, Nitrogen, and Phosphorus Contents in Forest Soil and Litter at Bintulu's *Acacia mangium* Chronosequence Age Stand Plantation, Sarawak, Malaysia

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ABSTRACT

Acacia mangium is the major species used in the forest plantation industry due to its fast-growing feature. However, there is still a lack of research on the nutrient concentration, specifically nitrogen (N) and phosphorus (P), as well as carbon content in Malaysia's forest plantations. Hence, this study aimed to assess the total N and P concentrations in the soil and forest litter. Carbon content in different ages (Year 2, Year 4, and Year 9) of *A. mangium* plantation (together with a natural forest as a comparison) was also determined. This study was conducted in a Licensed Planted Forest, Bintulu, Sarawak, Malaysia. The natural forest was a control variable in this study. The Kjeldahl method was used to determine the total N. In contrast, dry ashing and double acid (Mehlich-1) methods were used to determine the total P in forest litter and available P in forest soil. The allometric biomass equations were used to estimate the carbon content. Total N in forest litter and forest soil was similar in all treatments. Total P in the Year 4 stand was significantly higher than in the Year 2 stand, yet, no differences were observed when compared with the control. Whereas soil

available P showed no significant difference among all treatments. *Acacia mangium* stands recorded significantly lower total carbon content compared to the control. Old plantation stands contained much more total carbon stock than the younger stands. Also, deadwood is important in determining total carbon stock when it can account for almost 59% of above-ground biomass (AGB) carbon stock. This study revealed that forest

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plantations could function well in providing an adequate supply of available nutrients as well as have a potential role in carbon sink.

Keywords: *Acacia mangium*, biomass, carbon pool, soil N, soil P

INTRODUCTION

Trees need nutrients to survive and grow healthily. Nitrogen (N) is one of the essential elements required by trees. In the plant metabolism process, N plays a prominent role. According to Leghari et al. (2016), protein, in which N is an important component, is involved in all critical processes in plants. Moreover, N also is a significant constituent of chlorophyll, enabling photosynthesis that can be found in many large parts of the plant cell. Nitrogen is vital for various physiological processes as it encourages tree growth and development as well as promotes the uptake and utilization of other nutrients such as potassium (K) and phosphorus (P). Phosphorus is considered one of the macronutrients. As every crop needs P for its growth, this nutrient has always been unavailable and unreachable in the soil. Consequently, this deficiency leads to the interruption in the photosynthesis process (H. Li et al., 2016), and plants' morphology, physiology, and metabolism may all be affected too (Hammond et al., 2004).

According to Intergovernmental Panel on Climate Change (IPCC) guidelines for national greenhouse gas inventories, there are five carbon pools of a terrestrial ecosystem, namely the above-ground

biomass, below-ground biomass, the dead mass of litter, woody debris, and soil organic matter (Eggleston et al., 2006). Carbon sequestration in terrestrial ecosystems plays an important role in regulating gas exchange between plants, soils, and the atmosphere as it contributes to greenhouse gas emissions. Carbon exists in the atmosphere primarily in the form of carbon dioxide and approximately about 0.04%. The carbon stored in the plants is released back into the atmosphere during the respiration, decomposition of dead plant biomass and soil organic matter, or through combustion in nature (Vashum & Jayakumar, 2012).

Currently, forests cover 31% of the world's land, about 4.06 billion ha in total (Food and Agriculture Organization of the United Nations [FAO], 2020a). Of the total, 45% of them are in tropical regions. FAO (2020a) also found that due to land conversion, approximately 420 million ha of forests have been destroyed since 1990. Even so, different regions have different rates of forest depletion. Therefore, for tropical forests, statistics indicated that vegetation cover loss was estimated at 12 million hectares yearly between 2010 and 2018, up from 8.5 million hectares per year between 2002 and 2009 (Butler, 2019). As a result, forest plantations are established worldwide to cover the forest loss and act as substitutes for the natural forest. However, Liao et al. (2012) found that soil fertility in plantations is unlikely to return to that of natural forests, suggesting that replacing natural forests with plantations is a trend that should be avoided if environmental stability is maintained.

Koutika and Richardson (2019) revealed that *A. mangium*, a fast-growing tree native to parts of Indonesia, Papua New Guinea, and Australia, has been planted and imported into wet tropical lowland areas of Asia, South America, and Africa in recent times. The ability of *A. mangium* to deposit N-rich bases (low carbon to nitrogen [C/N] ratio) able to increase microbial activities, thus improving labile nutrients quantities in the soil (Bini et al., 2014), altering soil faunal, microbial, and bacterial populations, and promote crop or tree growth and forest productivity are key reasons for its extensive planting in commercial monoculture plantations or mixed plantings with other tree species or crops in areas with poor soil condition (Koutika & Richardson, 2019). In Malaysia, *A. mangium* has been planted widely since the 1960s to produce pulp and paper (Sukganah et al., 2005). Sabah was the first state in Malaysia to introduce this species in 1966 as a fire breaker species. Due to its rapidly growing and high survival rate, *A. mangium* was found to be suitable to be used in plantation establishments. Since then, the utilization of this species in forest plantations has expanded.

However, there is still a lack of research on the nutrient concentration, specifically N and P, as well as carbon content in Malaysia's forest plantation, particularly in Sarawak, Malaysia, although 43 Licensed Planted Forest (LPF) have been established. Currently, only a handful of a study conducted in Sarawak for soil properties and growth of *A. mangium* (Jusoh et al., 2017; K. L. Lee et al., 2015; Lim, 1986;

Lim & Mohd. Basri, 1985; Nazeri et al., 2021, 2022; Tanaka et al., 2015). Only Tanaka et al. (2015) compared different age stands with adjacent existing natural vegetation stands. Nazeri et al. (2021) found that the diameter at breast height (dbh) and height of *A. mangium* stand increased over time. They found stand dbh increased from 15.5 cm at 3.7 years stand to 28.2 cm at 12.7 years stand. Meanwhile, tree height increased from 17.6 m to 27.6 m during the same period. Hence, the study aimed to assess the total N and P concentration in the soil and forest litter and carbon content in different ages of *A. mangium* plantation. The hypothesis is that the nutrient concentrations and carbon content assessed in the forest plantation are lower than the natural forests.

MATERIALS AND METHODS

Study Site

The study area was in an LPF in the Bintulu district, Sarawak, Malaysia. The total area of the LPF is 10,804 ha. This study area receives high annual rainfall with an average of 16.6 rainy days per month and 183 rainy days per year. Meanwhile, the type of soil found here is sandy loam, with a moderate amount of clay and silt (Chua, 2018). The sandstone mixed with shale and sand shale is the main component of bedrock found in the study areas, resulting in the Nyalau Formation (haplic Acrisols) formed during the Miocene. However, fertilisers were only supplied during the planting, and weeding was carried out twice only during the first year of establishment.

Plot Establishment and Sampling

Sampling was conducted in four different stands, consisting of a natural forest area and three other age *A. mangium* stands (Year 2,

Year 4, and Year 9). In each stand, four plots with a size of 20×20 m were established randomly. Figure 1 shows the conditions of each stand.



(a) Natural stand



(b) 2-year-old stand



(c) 4-year-old stand



(d) 9-year-old stand

Figure 1. Conditions of each study stand. (a) Natural; (b) 2-year-old; (c) 4-year-old; (d) 9-year-old

Forest Litter. Collecting forest litter was done using a 50 × 50 cm quadrat, placed randomly with the subplots of 10 × 10 m of each plot. Four samplings were carried out in each plot. Collected forest litter was put into a plastic bag according to their quadrat and brought to the laboratory for preparation and analysis.

Litter biomass and carbon estimation were conducted directly in the laboratory. First, the total dry weight of litter was converted into carbon by multiplying by 0.40 (Eggleston et al., 2006).

Forest Soil. Soil samples were collected from the same quadrat sampling as the forest litter samples. Coring with a height of 5 cm was used to collect soil samples. The first soil sample was taken from 0 to 15 cm soil depth, and the second sample was taken from 20 to 35 cm soil depth. This sampling was repeated in every quadrat in each plot. The soil samples were air dried before getting crushed manually and being sieved to remove large particles with a sieve tube of 2 mm in size.

Soil organic matter (SOM) was estimated by using a loss of weight on ignition (LOI) method (Schulte & Hopkins, 1996). The soil organic carbon (SOC) was calculated as 58% of SOM (Nelson & Sommers, 1996). The SOM, SOC, and soil carbon content (SCC) were calculated as:

$$\text{SOM (\%)} = \left(\frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \right) 100 \quad (1)$$

$$\text{SOC (\%)} = \text{SOM (\%)} \times 0.58 \quad (2)$$

$$\text{SCC (t/ha)} = \text{Bulk density} \times \text{SOC} \times \text{Soil volume} \quad (3)$$

Tree Biomass. Forest inventory was performed to obtain biomass estimation using the allometric model. Tree dbh in natural forest (control), four-year-old *A. mangium* stand (Year 4), and nine-year-old *A. mangium* stand (Year 9) was measured at 1.3 m above the ground of the tree in each plot with a diameter limit of 10 cm and above. While in a two-year-old *A. mangium* stand (Year 2), collar diameter was measured.

The allometric model by Kenzo et al. (2009) was used to calculate above-ground biomass (AGB) for natural forest stands. The allometric model used in this study for *A. mangium* stands of Year 4 and Year 9 has been developed by Adam and Jusoh (2018), while for *A. mangium* stands of Year 2 has been proposed by Thanh and Thu (2015). This present study uses an allometric model Niiyama et al. (2010) developed to estimate below-ground biomass (BGB) for the control site. Levan et al. (2020) developed the allometric model to estimate the BGB of *A. mangium* stands. The conversion factor of 0.47 was used to calculate carbon in AGB and BGB (FAO, 2020b).

Deadwood. All deadwood, standing or laying on the ground with a diameter limit of 10 cm above (FAO, 2020b), were identified and measured. Deadwood biomass included standing deadwood, fallen deadwood, and stumps. Measurement of dbh was used to estimate the biomass of standing deadwood. Meanwhile, fallen deadwood was divided into the tree and the main stem. The diameter size of both fallen deadwood

classes, as well as stumps, was determined to estimate the biomass.

Deadwood standing biomass was determined using the same AGB equations used for live stands. Whist fallen whole tree biomass was estimated using allometric models proposed by Kenzo et al. (2015) and Levan et al. (2020) for the control and different age of *A. mangium* stands, respectively. The stump biomass was estimated using equations suggested by Niiyama et al. (2010) for the control, while the estimation of stump biomass in *A. mangium* stands was using equations suggested by Levan et al. (2020). The total deadwood biomass was calculated by standing deadwood, fallen deadwood (whole

tree and main stem), and stumps. Carbon content in deadwood is also calculated as 47% of the biomass followed FAO (2020b).

Soil Chemical Analysis

The micro-Kjeldahl procedure was used to analyze N concentration in forest soil and forest litter samples (Horneck & Miller, 1998). At the same time, two different methods were used to determine P concentration: the double acid method (Mehlich, 1953) and the single dry ashing method (Lambert, 1976) for forest soil and forest litter analysis, respectively. The followings are the formula used to calculate the total P (mg kg⁻¹) and available P (mg kg⁻¹):

$$\text{Total P (mg/kg)} = \text{UV VIS reading} \times \left(\frac{\text{Mark up volume of sample after single dry ashing}}{\text{Weight of soil sample}} \right) \times \left(\frac{\text{Mark up volume of sample after developing blue colour}}{\text{The volume of sample used to develop blue colour}} \right) \quad (4)$$

$$\text{Available P (mg/kg)} = \text{UV VIS reading} \times \left(\frac{\text{Volume of double acid used}}{\text{Weight of soil sample}} \right) \times \left(\frac{\text{Mark up volume of sample after developing blue colour}}{\text{The volume of sample used to develop blue colour}} \right) \quad (5)$$

Statistical Analysis

Data analysis has been done by using one-way analysis of variance (ANOVA) to see whether there is statistical confirmation that the related treatment means vary substantially. The significance level was determined using a probability standard of $p < 0.05$. When the ANOVA revealed statistically significant results, the means were compared using Tukey's studentized

range test. Other than ANOVA, a *t*-test was performed to compare two groups' means, namely the upper and lower soil layers. Pearson's correlation coefficient test was also conducted to observe the relationship between the total N and P concentration with AGB, BGB, and litter biomass. Statistical Analysis System (SAS) (version 9.4) (SAS Institute, USA) was used for the statistical analysis.

RESULTS

Total Nitrogen

The control recorded the highest mean total N in its forest litter with a value of 0.39%, followed by Year 9, Year 4, and Year 2 (Table 1). However, no significant difference was observed among all four treatments (Table 1).

There was no significant difference among treatments for total soil N of both soil layers, as illustrated in Table 1. Year 2 recorded the highest values of total soil N in both soil layers. No significant difference was detected between the two layers (Table 1).

Phosphorus

Year 4 recorded the highest mean total P in its forest litter with the value of 131.74 mg kg⁻¹, followed by Year 9, the control, and Year 2 (Table 1). A significant difference was detected between Year 4 and Year 2 (Table 1), whilst no difference was observed between the control and other *A. mangium* stands (Table 1).

In both soil layers, the control recorded the highest mean for available P concentration (Table 1). However, the difference between treatments is not significant (Table 1). The upper soil layer recorded more than 50% higher available P than the lower soil layer (Table 1).

Carbon Stock

Results indicated a significant difference in AGB carbon stock in the control compared with three other treatments in *A. mangium*

stands (Table 1). Besides, within the *A. mangium* stands, AGB carbon stock in Year 2 and Year 4 were statistically similar but significantly lower than in Year 9 (Table 1).

The control recorded significantly higher BGB carbon stock than *A. mangium* stands of Year 2, Year 4, and Year 9 (Table 1). Results also indicated a significant difference in BGB carbon content between *A. mangium* stands in Year 2 and Year 9 (Table 1).

There was a significant difference in deadwood carbon stock between the control and *A. mangium* stands of Year 2, Year 4, and Year 9 (Table 1). Within the *A. mangium* stands, deadwood carbon stock in Year 2 and Year 9 were statistically similar but significantly lower than in Year 4 (Table 1).

The mean comparison indicated that litter carbon in *A. mangium* Year 2 and Year 4 was similar but significantly lower than the control (Table 1). Meanwhile, litter carbon of Year 9 was significantly higher than another three stands (Table 1).

Results indicated a significant difference in soil carbon at both depths (Table 1). The control had significantly higher SCC than another three acacia stands at both soil depths (Table 1). However, at a depth of 0–15 cm, SCC in *A. mangium* Year 4 is significantly higher than in Year 2 and Year 9 (Table 1). While at a depth of 20–35 cm, the mean comparison indicated that the SCC in *A. mangium* Year 4 and Year 9 were similar but significantly higher from Year 2 (Table 1).

The total carbon stock in the control was statistically higher than the three ages

Table 1
Site chemical properties of logged over and Acacia mangium stands at different ages

Properties	Control	Year 2	Year 4	Year 9
Soil pH (water) (0–15 cm)	4.44 ± 0.29 ^{a2}	4.36 ± 0.27 ^{a2}	4.21 ± 0.09 ^{a2}	4.66 ± 0.15 ^{a2}
Soil pH (water) (20–35 cm)	4.66 ± 0.17 ^{a1}	5.02 ± 0.14 ^{a1}	4.86 ± 0.06 ^{a1}	4.99 ± 0.26 ^{a1}
Total N in forest litter (%)	0.39 ± 0.23 ^a	0.25 ± 0.05 ^a	0.32 ± 0.08 ^a	0.35 ± 0.13 ^a
Total N in soil (%) (0–15 cm)	0.06 ± 0.00 ^{a1}	0.08 ± 0.01 ^{a1}	0.06 ± 0.01 ^{a1}	0.06 ± 0.01 ^{a1}
Total N in soil (%) (20–35 cm)	0.08 ± 0.02 ^{a1}	0.08 ± 0.03 ^{a1}	0.07 ± 0.02 ^{a1}	0.06 ± 0.02 ^{a1}
Total P in forest litter (mg kg ⁻¹)	53.47 ± 34.98 ^{ab}	34.21 ± 10.52 ^b	131.74 ± 63.14 ^a	117.62 ± 41.39 ^{ab}
Available P in soil (0–15 cm) (mg kg ⁻¹)	1.23 ± 0.19 ^{a1}	0.82 ± 0.41 ^{a1}	0.60 ± 0.26 ^{a1}	0.79 ± 0.47 ^{a1}
Available P in soil (20–35 cm) (mg kg ⁻¹)	0.53 ± 0.46 ^{a2}	0.25 ± 0.13 ^{a2}	0.24 ± 0.12 ^{a2}	0.29 ± 0.37 ^{a2}
Above-ground C (t ha ⁻¹)	104.71 ± 15.46 ^a	2.11 ± 0.44 ^c	7.67 ± 1.48 ^c	29.78 ± 2.66 ^b
Below-ground C (t ha ⁻¹)	37.97 ± 6.69 ^a	0.52 ± 0.11 ^c	2.23 ± 0.42 ^{bc}	8.33 ± 0.73 ^b
SCC (0–15 cm) (t ha ⁻¹)	61.09 ± 1.80 ^{a1}	39.49 ± 3.71 ^{d1}	55.25 ± 2.56 ^{b1}	50.76 ± 2.80 ^{c1}
SCC (20–35 cm) (t ha ⁻¹)	50.99 ± 1.31 ^{a2}	35.78 ± 3.91 ^{e2}	45.51 ± 1.48 ^{b2}	45.03 ± 1.11 ^{b2}
Litter C (t ha ⁻¹)	5.05 ± 0.62 ^b	3.35 ± 0.90 ^e	2.95 ± 0.46 ^c	11.74 ± 2.99 ^a
Deadwood C (t ha ⁻¹)	273.31 ± 49.51 ^a	59.45 ± 16.62 ^c	185.05 ± 27.66 ^b	37.89 ± 1.33 ^c
Total C (t ha ⁻¹)	533.12 ± 103.50 ^a	140.70 ± 36.25 ^d	298.67 ± 81.59 ^b	183.51 ± 35.24 ^c

Note. Means with same lowercase letters indicated no significant difference between Tukey's HSD test treatments at $p < 0.05$. Meanwhile, means with the same numbers indicated no significant difference between soil layers (0–15 cm and 20–35 cm soil depths) by independent *t*-test at $p < 0.05$

of *A. mangium* stands (Table 1). Meanwhile, within the *A. mangium* stands, the total carbon content in Year 4 was significantly higher than in Year 2 and Year 9 (Table 1).

Relationships Between Phosphorus and Biomass

Available soil P at 0–15 cm depth was found to have a positive and significant correlation with AGB ($r = 0.5520$, $p < 0.05$) and BGB ($r = 0.5559$, $p < 0.05$). Meanwhile, a negative correlation was observed between total P in forest litter and available soil at 20–35 cm depth ($r = -0.5178$, $p < 0.05$).

DISCUSSION

Total Nitrogen in Forest Litter

Acacia mangium is a leguminous species overflowing with N due to its symbiotic N fixation capability (Arai et al., 2008). Therefore, it is expected that high N concentration can be found in the litterfall of acacia stands. However, our study revealed that the total N of forest litter in acacia stands is equivalent to the control (Table 1).

Tamm (1995) explained that natural forest ecosystems often have well-balanced nutrient cycles with negligible nutrient loss. Nevertheless, aspects such as forest successional stage, water regime, mineralogy and rate of soil weathering, external inputs of nutrients and hazardous chemicals, nitrogen fixation, denitrification, nitrification, and natural or anthropogenic disturbances all have an impact on the balanced cycle. The similar total N of natural forest (the control) with acacia stands in our study is

contributed by this condition. The control has established a rooting network that has enabled the nutrient cycle, particularly the N cycle, to be conducted at a peak level. Thus, an adequate amount of N could be supplied to the mixed species that stands in control, resulting in a similar concentration of total N in forest litter in all treatments.

Our finding was consistent with previous studies (Maro et al., 1991; Ngaba et al., 2019). The highest total N concentration was observed in the natural forest (the control), with no remarkable difference between the treatments. It is owing to the mixed tree species found in the plot. Compared to monocultures, mixed rainforest roots access several N pools and reduce N absorption from a single source, for instance, ammonium ion (NH_4^+). It is due to the great plant diversity, which can lead to species complementarity in N resource usage based on individual preferences and capacities to absorb N (Wang & Macko, 2011). In addition, Britto and Kronzucker (2013) pointed out that plants use a variety of ways to get N from the soil. There are species that, for example, take up N as nitrate (NO_3^-), NH_4^+ , or amino acids, obtain N sources at different soil depths, or are linked with N fixing organisms and mycorrhizal fungi for N supply (Brundrett & Tedersoo, 2018), resulting to an adequate supply of N to the mixed tree species.

Total N is directly proportional to the ages of the stands (Table 1) as the older the tree, the greater the surface area of its roots, increasing the nutrient acquisition by the tree (Näsholm et al., 2008), which elucidates the

concentration of total N in each treatment. Other than that, the amount of N supplied by the soil affects the concentration of total N in the plants (Morgan & Connolly, 2013). As all the plots studied showed a similar total N concentration in their forest litters, the amount of N supplied by the soil might be similar. According to Baldwin (1975), the total amount of diffusible nutrients, the pace at which the nutrient may move, and the distance it needs to travel to a root surface are the main parameters influencing nutrient delivery to a specific plant. The rooting volume is swiftly decreased, and the amount absorbed is completely determined by the quantity in the rooting volume. Thus, this study area is assumed to have the equivalent amount of nutrient delivery to the plants from the soil, describing the similar total N in all treatments (Table 1).

Total Nitrogen in Forest Soil

Total N in forest soil is expected to be similar between *A. mangium* plantation and natural forests, as found by Yamashita et al. (2008). It corresponds with our present study, which recorded the similar soil N in both layers in all treatments (Table 1).

Year 2 has the highest total N in forest soil of both soil layers (Table 1) due to the accumulation of wood residues during previous tree felling. Siregar et al. (1999) mentioned that all slash left remains, debris that has piled and some of which has decayed, and understorey that stays in place will all play an essential part in the site's nutritional budget. In addition to wood residues, the size of the roots also has

resulted in high N concentration in Year 2. Smaller volume, size, and structure may result in lower nutrient adsorption from the soil; thus, higher concentrations of nutrients can be expected in younger stands. It is well-known that the bigger the tree size, the bigger the roots. Therefore, root size and structure significantly affect plant nutrient absorption efficiency (Fitter et al., 1991). Generally, Germon et al. (2018) disclosed that a high capacity of N absorption could be gained from the greater root length and root area of a tree. Simulations on this aspect have revealed that root structure influences the volume of soil from which nutrients may be extracted (Fitter, 1987; Fitter et al., 1991) as the higher the volume of soil accessed, the more nutrients can be absorbed by the roots. Thus, explaining stand age does influence the concentration of N in the soil. The youngest stand (Year 2) recorded higher total soil N may be related to lower N uptake, while older stands with more established root networks have higher N uptake, leaving less N concentration in the soil.

Even so, there was no significant difference observed between the treatments. It is due to the contribution of the forest litter itself. *Acacia mangium* is known for its capability to fix N. Thus, the concentration of N in the *A. mangium* tree would be high. The N will be released into the soil when the plant parts, such as stem twigs, primarily leave fall to the ground and undergo decomposition.

The total N concentration in forest soil recorded in the current study corroborated

with a study conducted in South Sumatra, Indonesia, by Yamashita et al. (2008) as well as a study held in Sabah, Malaysia, by Inagaki and Titin (2009).

Xue and An (2018) revealed in their study that a higher total N could be found in the surface soil layer compared to the deeper soil layer. However, our analysis indicated a different result, where both soil layers have a similar total N in the soil (Table 1). This situation may be related to the leaching process in the below-ground zone. Because of the frequent and severe rainstorms (Halmi & Simarani, 2021), higher temperatures, and high carbonic acid concentration in soil (Johnson et al., 1975), leaching losses are typically believed to be greater in the humid tropics than in temperate countries. Therefore, it is expected that soil leaching is rather high in our study site, causing the accumulation of N in the deeper soil layer as the concentration of total N is equivalent in both soil depths.

Total Phosphorus in Forest Litter

Acacia mangium in Year 4 showed the highest mean of litter P might be due to root morphology, such as root length and root diameter. Variations in root morphology would result in various amounts of P uptake by plants. Plants can increase their ability in soil exploration if their roots are long (Batista et al., 2016) and when greater surface areas for nutrient absorption are covered, leading to higher nutrient acquisition. In contrast, a shorter length of roots would limit the accessibility of the roots to the available nutrients in the

soil. It explains why Year 4 has a higher total P concentration in litter than Year 2, as these stands consisted of juvenile *A. mangium* trees with shorter and smaller roots compared with older *A. mangium* in Year 4, which would have longer and bigger roots. Laclau et al. (2013) found higher root density in older *Eucalyptus grandis* plantations.

Furthermore, Y. Li et al. (2018) mentioned that large trees have an abundance of nutrient reserve, but young trees have a limited deposit. Hence, large trees absorb higher P concentrations than small trees. Besides, K. L. Lee et al. (2015) noted that the sturdy development of *A. mangium* would consume a massive amount of nutrients. The four-year-old *A. mangium* stand has these traits, which are large and vigorous development, resulting in a higher P requirement than Year 2.

Forest plantation is expected to have a lower total P accumulated in the litter than natural forest, as found by Yang (2005). However, Mani and Cao (2019) also reported that the natural forest they studied had a higher total P which ranged from 600 to 700 mg kg⁻¹. Similarly, the control recorded a higher total P in the forest litter in the current study.

However, our study recorded that the total P in both acacia stands and the control forest litter were similar (Table 1). It was probably owing to the physiological properties of the species planted itself. Fast-growing species like *A. mangium* can use nutrients more efficiently than slow-growing species (Cossalter & Pye-Smith, 2003;

Inagaki & Tange, 2014). A response made by a plant to alter its development and metabolic process as well as interact with soil microbes that could provide soluble P, called P starvation response (Isidra-Arellano et al., 2021), combined with the nutrient use efficiency, led to the equivalent total P between the acacia stands and the control.

Other than that, the symbiosis relationship between the acacia trees and soil microbes has enabled the similar uptake of P by the trees in the natural forest. Plants are known to evolve, especially when the nutrients are limited (Morgan & Connolly, 2013). Karandashov and Bucher (2005) described that this type of symbiosis promotes plant P absorption from the soil by expanding the absorptive surface area of the root. The associated mycorrhizal hyphae bridge the internal root environment and the region beyond the depletion zone, allowing the plant to obtain substantially more P via its symbiotic partner than it could alone (Chiu & Paszkowski, 2019). Hence, this explains why the total P uptake by the *A. mangium* trees is not lower but similar to the natural forest, as the soil microbes assist this species in improving its nutrient absorption rate.

Available Phosphorus in Forest Soil

Although there was no significant difference between treatments for both soil layers, the control recorded the highest soil available P in both layers, similar to previous studies by Chauhan et al. (2008). The higher P is probably due to the heterogeneity in the soil organic matter. As the control consists of

mixed-species trees, the forest litter would also consist of multi-species organic matter that would contribute to higher P availability in the soil. Koutika et al. (2020) found that the mixed-species forest stands accumulated more P in organic forms, limiting P losses through leaching and helping to the medium-term sustainability of P requirements. Moreover, Cissé et al. (2021) revealed that mixed species of tree litters would facilitate a higher decomposition rate than pure litters. With the high proportion of tree biomass in the study site, there will be more forest litter that would supply nutrients needed by the plants. Therefore, this would increase nutrient cycling in the soil, which elucidates the higher P concentration in the control soil.

Meanwhile, Binkley (1992) mentioned that because root nodules' biological N fixation process mainly depends on P, legumes consume more P than non-leguminous plants. However, according to Mitran et al. (2018), to optimize the functionalities of legumes in the N fixation process via reciprocal symbiotic connection with certain bacteria in the soil, legumes require additional P, which is essential for energy transformation in nodules. Furthermore, P is important for root formation, nutrient absorption, and legume crop growth, which makes the P availability in the soil lower in the acacia plantation but not significantly different from the control.

Approximately 90% of flora species could establish a mutual connection with the arbuscular mycorrhizal fungi (AMF) (Smith & Read, 2008; Zhu et al., 2010). These fungi supply a variety of pivotal ecological

functions, including enhancing plant nutrition, stress responses and endurance, soil properties, and fertility (Chen et al., 2018). The plants and the AMF benefit each other as the AMF will be supplied with carbon by the host plants while, in return, the AMF facilitates their hosts in nutrient absorption, including P (Ferrol et al., 2004). Thus, this elucidates the similarity of available soil P in all treatments as *Acacia* species and multi-species in control rely on the AMF to increase their P availability in the soil.

The topsoil is generally more fertile than the lower layers (Table 1) and contains the most plant roots. Therefore, tree litter that falls onto the ground would supply nutrients to the soil, primarily into the upper layer. Litterfall quality would affect the soil nutrient availability (Ge et al., 2013). Soil organisms will decompose those plant residues under certain environmental conditions related to the temperature, moisture, and soil properties (Bot & Benites, 2005), which would contribute to the nutrients in the soil. Plus, the upper soil layer has the highest concentration of roots, with more than 90% of the roots being found in the surface soil due to nutrient absorption (Pierret & Moran, 2011). Consequently, higher P concentration can be observed in the upper layer (Table 1) as many roots can be spotted here during the P absorbance through diffusion.

This study proved that the tree biomass contributed significantly to the available P in the soil. The high amount of biomass will create more organic matter (Bot & Benites,

2005) that will eventually decay and be converted into available nutrient forms for plant uptake by related microorganisms.

Chatzistathis and Therios (2013) concluded that soil nutrient availability is one of the factors that could increase tree biomass. Therefore, the higher the soil's available P, the more biomass can be produced. Halomoan et al. (2015) reported the same findings where the tree biomass increased directly proportional to the amount of P available. Phosphorus is vital for the biological N fixation and the tree growth of leguminous plants. Hence, its deficiency would influence not only the N fixation process but also the development of a tree (Le Roux et al., 2008; Power, 2010). According to Lynch et al. (1991) as well as Radin and Eidenbock (1984), leaf expansion is very susceptible to P deficit, and it has been proposed that impairment in leaf expansion is a reaction to low P availability in P-deficient plants. Therefore, an adequate amount of P will result in an increase in leaf area, which will improve light interception and biomass output. The relationship between available P and the tree biomass works both ways as they benefit each other in the nutrient cycle.

In the current study, total P in the litter negatively correlated with the soil available P (especially at 20–35 cm depth), indicating that the high concentration of total P in the litter would lead to a lower concentration of available P in soil. It might be related to, among others, plant uptake, which in turn results in higher P concentration in the litter (Prasad & Chakraborty, 2019).

Tree Biomass Carbon

The control had significantly higher tree biomass carbon (AGB and BGB) compared to all *A. mangium* stands (Table 1). The results also showed the increase of tree biomass carbon in *A. mangium* stands from youngest to oldest. This pattern can be explained by tree biomass and carbon content related to stem size.

According to Niyama et al. (2010), the tree size has good linearity to estimate BGB carbon. This consequence was also reported by Kueh et al. (2012, 2013), who stated that the larger the diameter size of the tree, the more biomass and carbon storage capacity was held. Moreover, the result of this study explains that the tree biomass carbon of *A. mangium* increased significantly with increasing stand age. This finding is consistent with those reported in other previous studies (Herdiyanti & Sulistyawati, 2009; Levan et al., 2020; Palma, 2014).

The total tree biomass carbon of *A. mangium* stands in this study was 2.62 t/ha, 9.90 t/ha, and 38.11 t/ha in the 2-, 4- and 9-year-old stands, respectively. This value is much lower than values reported by Leva et al. (2020) for *A. mangium* plantation in South-eastern Vietnam, where the total tree biomass carbon was 34.53 t/ha, 62.21 t/ha, and 101.52 t/ha for the 4-, 7-, and 11-year-old plantations. It could be due to various factors influencing the difference in total tree biomass carbon, such as the environmental condition of the area and the various forest management practices used. Apart from that, this may be due to different biomass equations, which influence the estimated

value of carbon content in a forest area. According to Temesgen et al. (2015), studying variations in allometric forms based on species, climatic, and edaphic factors is important to understand these variations in coordinated biomass equations because it is also sensitive to a larger number of measurable tree components.

Deadwood Carbon

This study indicated that the control contained higher deadwood carbon than all *A. mangium* stands (Table 1). It could be due to the control being logged over the forest, which produces more deadwood due to the reduced effect of the live trees from previous logging activity (Pfeifer et al., 2015). In addition, logging removed large trees and caused residual damage to other live trees. According to Matangaran et al. (2019), stand damage after logging activities dramatically affects the composition of tree species in logged-over forest areas, and higher post-logging death rates have been documented, as illustrated by the accumulation of deadwood from stand damage after logging. Moreover, the control is a natural forest comprising various tree species compared to *A. mangium* stands with monocultural tree species. Hence, various tree species can contribute to the high amount of deadwood with different decomposition rates (Pfeifer et al., 2015).

Besides, within *A. mangium* stands, Year 4 recorded higher contribution of deadwood obviously in fallen deadwood compared to other two different stands. Another proposition is site condition factors,

such as the higher terrain steepness and old skid trails from previous logging activities. Higher terrain steepness causes unstable soil conditions for standing living trees, increasing the risk of landslides. It is the same with trees planted in the old logging trails area. It is due to the soil compaction affecting the development of the root system and causing an unstable condition of the tree stand. Contribution deadwood is higher in *A. mangium* Year 4, also caused by windthrow within the stand in the current study. S. S. Lee (2018) discovered that windthrow incidence caused more than 20% mortality, on average, of 5-and-a-half year-olds of *A. mangium*, stands in Sarawak. *Acacia mangium* is recognized for having a shallow root system that spreads and is, therefore, quite vulnerable to windthrow and easily blown down. However, the trees could also fall by the wind more easily, as the root system is not stable because of the damage caused by root-rot disease (S. S. Lee, 2018). The observation was also similar to that reported by Pfeifer et al. (2015), who stated that the higher contribution of deadwood was linked with environmental factors.

Furthermore, there is no standing deadwood recorded in *A. mangium* stand Year 2. It indicates that 2 years-old *A. mangium* stand is the youngest and has a vigorous growth rate. According to Hardiyanto and Wicaksono (2008), the peak nutrient demand and growth of *A. mangium* occurred during the first three years. *Acacia mangium* stand at Year 9 shows lower deadwood carbon content statistically, and no stump deadwood was recorded. It

could be attributed to the decomposition of deadwood, which frequently occurs during this period, especially for stumps. Deadwood decomposition in degraded tropical forests is estimated to take six to nine years on average (Chambers et al., 2001; Pfeifer et al., 2015; Rice et al., 2004).

Litter and Soil Carbon Content

Litter plays an important role in the plantation and natural forest carbon cycle. According to the current study, the control contributed more litter carbon than *A. mangium* stands in Years 2 and 4 and not Year 9 (Table 1). As expected, the litter carbon in control is higher than *A. mangium* stands due to the contribution of tree biomass and various tree species that provide higher litter production. Other researchers also reported that diverse compositions have higher litter yields in both amount and quality when compared to monocultures, which could enhance tree productivity and carbon sock (Giweta, 2020). The results also show that the lower amount of litter carbon in *A. mangium* in Years 2 and 4 is due to land use change, which exposes litter to a high decomposition rate (K. L. Lee et al., 2015). Moreover, Giweta (2020) stated that the hugely disturbing area produces lower litter production compared to less disturbed areas.

However, higher litter carbon in *A. mangium* stands Year 9 is due to the contribution of false staghorn fern (*Dicranopteris linearis*). These ferocious ferns form dense thickets, contributing to a higher percentage of forest litter on the top surface. In addition, the fern sustains

and suppresses its dominance by covering the area with an extensive root system and slow-decomposing leaves (Shono et al., 2006). The low decomposition rate of *D. linearis* is due to the phenolic compounds found in their leaves (Othman et al., 2020) and the fern species' high lignin compounds (Amatangelo & Vitousek, 2009).

Land use change of forests also contributed to the decline in SCC due to the change in carbon sequestration (K. L. Lee et al., 2015). It is demonstrated by the results, which show that the control has significantly higher SCC than all *A. mangium* stands at both soil depths. It is due to the decomposition of plant debris, such as litter, twigs, brunch, and roots. Therefore, the decline of SCC in the disturbed forest (converted into plantation) is due to the reduction in the amount of plant debris returning into the soil and an increase in the quantity of carbon dioxide released into the atmosphere from the decomposing process of soil organic matter.

Furthermore, the SCC of *A. mangium* stand Year 9 was lower at depths of 0–15 cm and similar at depths of 20–35 cm when compared to Year 4 due to the low decomposition rate of *D. linearis*, even though the highest litter carbon was recorded. While the SCC in Year 2 was lower when compared to Year 4 and litter carbon within these ages. According to K. L. Lee et al. (2015), SCC was influenced by the decomposition of litter, which is affected by the ecological factors of the area and human activity. Year 2 was in the youngest stage

of tree growth, with the cumulative canopy openness causing rapid drying out of the litter in sunlight, potentially resulting in a decline in microbial decomposition (Paudel et al., 2015).

While SCC in Year 4 was statistically higher than the other two *A. mangium* stands because of environmental and climate factors, such as soil property, temperature, and humidity, that can affect the decomposition of litter (Giweta, 2020). Year 4 probably has higher litter decomposition due to healthier canopy covers that create a favourable microclimate and are suitable for microbial decomposer populations. Among the four forest stands of this study, SCC was the highest in the surface soil layer (0–15 cm) and indicated a decreasing trend with depth. It can be explained by the fact that it had the highest quantity of SCC, which significantly increased soil organic matter as a primary source of soil carbon and is higher in topsoil (Levan et al., 2020).

Total Carbon

Total carbon content is in line with all classes of terrestrial carbon pools, where probably a decline in the amount of carbon tends to occur due to land use change. According to Ratnasingam et al. (2016), the conversion of natural forests, especially the secondary or logged-over forests, to plantation forests assists in decreasing the amount of carbon stock in the environment due to the change in carbon-storing capacity. It is also demonstrated by the results of this study, which compares the percentage of total carbon in *A. mangium* stands in Year

2 (26.39%), Year 4 (56.02%), and Year 9 (34.42%) to the control as a benchmark.

Referring to previous studies, such as Vashum and Jayakumar (2012) and Ratnasingam et al. (2016), deadwood contributes only a small amount of carbon to forest carbon stock. However, this study is inconsistent with those in which the contribution of deadwood to total carbon content is higher. This study supported previous research by Pfeifer et al. (2015), who discovered that deadwood stores significant amounts of carbon, accounting for more than 50% of AGB carbon stock in degraded tropical forests in Sabah, Malaysia. While this study also found that total deadwood carbon stored was 59% of AGB carbon. The higher contribution of deadwood in the control and *A. mangium* plantations is due to the condition of the logged-over forest that generates higher deadwood from the reduction in the AGB by the previous logging activities. Logging removed large trees and caused residual logging damage to other live trees (Pfeifer et al., 2015). Consequently, AGB carbon stocks in some of the logged-over forest stands were severely reduced. This condition is exemplified by the fact that the control had higher deadwood carbon (273.30 t/ha) than AGB carbon (104.71 t/ha) in this study (Table 1). Moreover, the existence of various tree species also contributes to the high amount of deadwood with different decomposition rates (Pfeifer et al., 2015).

While *A. mangium* stands also recorded a high amount of deadwood carbon in Year 2 (59.45 t/ha), Year 4 (185.05 t/ha),

and Year 9 (37.89 t/ha) when compared to AGB carbon in Year 2 (2.11 t/ha), Year 4 (7.67 t/ha), and Year 9 (29.78 t/ha). However, fallen deadwood recorded a higher contribution in the total deadwood carbon of *A. mangium* Year 4 that assumes influence by environmental factors, such as the higher terrain steepness and the existence of old skid trails from previous logging activities that create unstable conditions for soil and tree stands. It also may be caused by windthrow incidence and insect infestation or disease (S. S. Lee, 2018). These environmental and previous anthropogenic factors contribute to an unstable root system and tree stand, leading to mortality and the conversion of living trees to dead, broken, or downed large woody debris.

CONCLUSION

The choices of species planted are vital to ensure that the soil can provide an adequate amount of nutrients, as the requirement for nutrients varies from one species to another. *Acacia mangium* is considered one of the best species to be cultivated as it could fix the N by itself, thus lessening the scarcity issue of N in the plantation site. Therefore, the only nutrient-related concern that should be emphasized in planting this tree species is the availability of P and other macronutrients in the soil for the tree's uptake.

Further application of fertilizer would assist in providing more nutrients, especially P, to the soil while at the same time increasing the biomass of the trees. The application of fertilizer should not only be limited to the

young ages of the tree but also the older ones like Year 4 and Year 9 acacia stands. However, further research is needed to study the fertilizer requirement by the different ages of the stands and its application as well as other nutrient availability status in this study area so that better improvement and management can be made. Silvicultural practices also significantly reduce the competition for nutrients among the planted trees. Moreover, thinning practices also would produce more high-quality trees with financial benefits. Slashing would lessen the unwanted wildings while at the same time could provide easy accessibility into the planting area.

Acacia mangium plantation also has demonstrated the potential role of carbon sink. Forest areas, either natural or plantation, must be preserved to mitigate the effects of global warming caused by increased carbon emissions in the atmosphere. *Acacia mangium* stands in the current study and recorded significantly lower total terrestrial carbon content compared to the control. The conversion of natural forest to plantation forest reduced carbon content during the early stages of plantation establishment. This study also showed that old plantation stands contained much more total carbon stock than younger ones. It can be explained by the fact that the content of tree biomass carbon has a good relationship with the stem size. At the same time, the stem size increases linearly with the age of the stand. This study also revealed that deadwood is important in determining total terrestrial carbon stock (the control and Year 4).

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