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Stand productivity, carbon content, and soil nutrients in different stand ages of *Acacia mangium* in Sarawak, Malaysia

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Abstract: Land degradation and declining soil fertility challenge the productivity of forest plantations. Changes in soil properties could act as indicators for monitoring forest plantation management and productivity. This study highlights changes in soil properties and stand productivity over time (1, 3, and 5 years) in an *Acacia mangium* plantation in Bintulu, Sarawak, Malaysia. Soil pH, total N concentration, and available P were found to decline significantly with stand age. Significant differences were observed between soil organic C for different stand ages, with the youngest stand showing the highest C. The study showed that the current *A. mangium* plantation was able to store 74.9, 89.9, and 138.9 t C ha^{-1} in the 1-, 3-, and 5-year-old stands, respectively, and soil was the main contributor for the total C pools. All soil chemical attributes showed declining trends with stand age. These declines indicated that the present management practices are not sustainable and that management inputs are necessary.

Key words: *Acacia mangium*, carbon content, soil properties, stand age, tree growth

1. Introduction

The greenhouse effect has become a major challenge in recent years and requires instantaneous action to deal with its negative effects (Smith et al., 2007). The establishment of industrial forest plantation to restore degraded land, which results from unsupervised logging and land clearing for nonsustainable agriculture practices, and the increase of terrestrial C sequestration are some ways to alleviate the greenhouse effect (Smith et al., 2007).

Land must be cleared during site preparation in order to establish forest plantations. Mechanical clearing followed by stacking and burning of forest residuals are the preferred management practices in Malaysia, as these activities are simple, fast, and effective for clearing a large area of land in a short period of time. These practices lead to various levels of soil disturbance (Cavelier et al., 1999; Certini, 2005). These include the reduction of surface organic matter, worsening of soil physical properties such as decrease in porosity and increase in bulk density, loss of nutrients through stand removal, volatilization and ash, soil loss through erosion, and destruction of soil microbial and other invertebrates that are beneficial to the forest ecosystem.

In 1997, the State Government of Sarawak, Malaysia, set a target to plant 1×10^6 ha of forest by 2020. Until now, only 289,900 ha, or 29% of the target, has been achieved, with 12,000 ha planted in 2011 (http://www.thestar.com.my/story/?file=%2f2012%2f7%2f20%2fsarawak%2f11695002&sec=sarawak). In order to achieve the initial target for the period 2012–2020, planting activity must be intensified to 78,900 ha $year^{-1}$. The main species used in the plantation program is *Acacia mangium* Willd. Even though numerous studies have examined the growth and biomass production of different tree species in Peninsular Malaysia and Sabah, including *A. mangium*, information on these attributes is still very scarce in Sarawak. Furthermore, reports on the performance of tree species planted at an industrial scale are very limited in Sarawak.

Acacia mangium is a fast-growing nitrogen fixer. It is an attractive species for plantation establishment because it grows satisfactorily even in unproductive sites. Average increment in diameter at breast height (*d*) could reach 3–4 cm $year^{-1}$ on good sites (Awang and Taylor, 1993). The wood is suitable for many uses such as pulp and paper, particle board, woodchips, sawn timber, veneer, and plywood, as well as firewood (Lemmens et al., 1995).

Sarawak is the largest state in Malaysia and is located on the island of Borneo. Most plantations in Sarawak were established in the central lowland region, which comprises elevated wave-cut platforms developed over sedimentary rocks. The Red-Yellow Podzolic soils are low in fertility and water-holding capacity. These limitations

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reduce the growth potential of trees. However, no report has been found to examine soil nutrient dynamics after the establishment of the forest plantation on such soil.

Soil is the most essential element in sustaining the productivity of forest plantations (Bouma, 1994). Assessment of soil quality and its alteration over time is a primary indicator for sustainable forest plantation management (Arshad and Martin, 2002; Doran, 2002). There are several studies quantifying the extent and rate of soil fertility changes in forest plantations of different ages (Hardiyanto and Wicaksono, 2008; Siregar et al., 2008). Nevertheless, no study of this kind has previously been carried out in Malaysia.

Fast-growing tree species such as *A. mangium* play a role in C sequestration, especially when they are established on a large-scale plantation. Information about the capacity of *A. mangium* plantations to sequester C at different ages is important. Thus, this study aims to determine the amount of C in *A. mangium* stands as well as the soil chemical properties of different-aged stands (1, 3, and 5 years) in Bintulu, Sarawak, Malaysia. This study addresses the following questions: 1) Can forest plantation establishment rapidly increase soil organic carbon (SOC) on degraded Red-Yellow Podzolic soil? 2) Can soil properties, especially chemical components, be recovered to their original levels through forest plantations? 3) Can soil fertility support plantation growth and SOC accumulation?

2. Materials and methods

2.1. Site and stands description

The study was conducted at a forest plantation situated at 3°20′364″N, 113°27′03.5″E, approximately 54 km from the town of Bintulu in Sarawak, Malaysia. The site receives a total annual rainfall of 2749 mm and the average temperature ranges from 23 to 32 °C. The type of soil is a well-drained Bekenu series characterized by fine, loamy, siliceous, isohyperthermic, and red-yellow to yellow Tipik Tualemkuts. The main factor restricting the use of this soil is its low fertility status (Paramanathan, 2000).

The initial soil conditions were considered to be similar for all stands, as the terrain was undulating with a slope of less than 6° (Figure 1) and was covered by the same type of vegetation. The plantation was originally a secondary forest (Matius, personal communication) and was planted with *A. mangium* at the commencement of this research. All stands were established using the same site preparation methods. The area was cleared mechanically and the residuals were burnt. During planting, each 3-month-old seedling was provided with 20 g of slow-release fertilizer (Agroblen 10-26-10+3MgO), which was applied into the planting hole. The planting spacing adopted was 3 × 3 m.

2.2. Plot establishment and soil sampling

Four 20 × 20 m plots were randomly established for each stand age (1, 3, and 5 years) with 36 trees planted in each plot. Each plot was established on a relatively flat area and was separated by at least 7 rows of trees or 20 m of distance. As pointed out by Yanai et al. (2003), initial soil conditions before planting are important; thus, a nearby secondary forest with the same type of soil series was used for comparison. Similarly, 4 plots of 50 × 20 m were established on flat areas. Tree *d* was measured for each individual stem. Soil samples were collected from the 4 corners and the center of each square plot. Soil samples were taken at 2 different depths (0–15 cm and 15–30 cm) using a soil auger.

2.3. Stand carbon content

The aboveground biomass (*W*, in kg) of each tree was estimated using the allometric equation developed by Heriansyah (2005) for *A. mangium* with *d* as the independent variable as in Eq. (1).

$$W = 0.0477d^{2.6998} \tag{1}$$

The C content of each tree was estimated based on the biomass value with 0.474 as the conversion factor (Martin and Thomas, 2011).

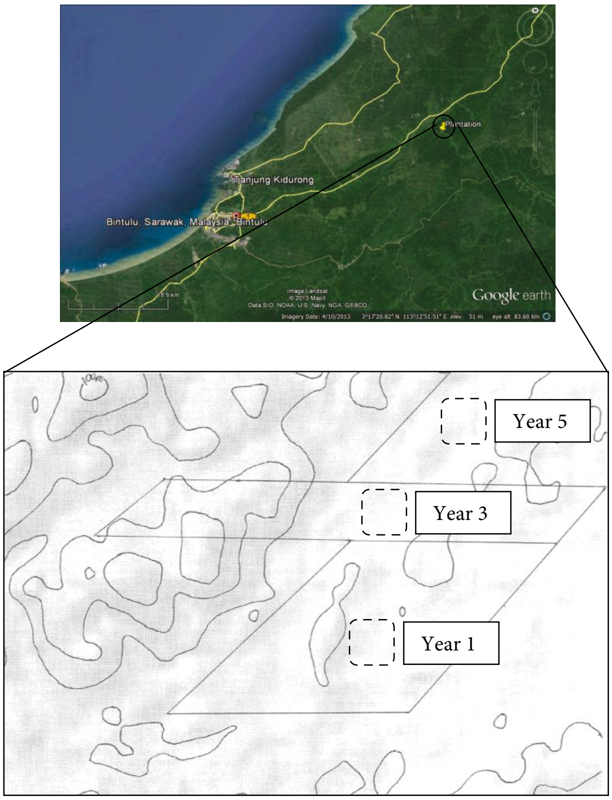

Figure 1. Location of research plots within the plantation area (topographically shown). Four 20 × 20 m plots were established within each stand age (inside the circle) on relatively flat area.

2.4. Soil analysis

Soil samples were dried and homogenized after being sieved using a 2-mm sieve. They were then stored in air-tight plastic vials.

Soil bulk density (BD) at both depths was determined using the coring method (Brady and Weil, 2002), while the hydrometer method (Tan, 2005) was used for the soil particle size analysis. The pH was determined in a 1:2.5 suspension of soil and distilled water and/or 1 M KCl using a glass electrode (Peech, 1965). The loss on ignition method was used to determine total organic matter (OM). SOC was estimated by multiplying the OM value by 0.58 (Chefetz et al., 1996). Soil carbon content (SCC) was estimated using the following equation:

$$SCC\ (Mg\ ha^{-1}) = BD \times SOC \times soil\ volume \qquad (2)$$

Total soil N was determined using the Kjeldahl method where samples were subjected to acid digestion, distillation, and titration, as described by Foster (1995). Soil available P was extracted using NaHCO and determined colorimetrically using the molybdenum-blue method (Jones, 2001).

2.5. Data analysis

Effects of stand age on soil chemical properties and stand C stock were assessed using analysis of variance (ANOVA) with the new Duncan multiple range test (DMRT) to compare means between treatments. The t-test was used to compare means between soil depths. Percentage values were log-transformed before being subjected to ANOVA. Statistical analysis was performed using SAS for Windows Version 9.1.

3. Results

3.1. Stand growth, biomass and carbon content

The oldest stand had *d* values that were 2.1 and 1.2 times bigger and was 4.3 and 1.5 times higher in the basal area as compared to the 1- and 3-year-old stands, respectively (Table 1). Biomass increased with stand age from 19.76 t ha^{-1} in the 1-year-old stand to 139.99 t ha^{-1} in the 5-year-old stand (Table 1). Meanwhile, 1-, 3-, and 5-year-old stands had 9.37, 39.26, and 66.36 t ha^{-1} of C, respectively (Table 1).

3.2. Soil properties under *Acacia mangium* plantations

Soil texture according to plantation age is shown in Table 2. The soil underlying the 3-year-old stand showed the

Table 1. Growth of *Acacia mangium* at different plantation ages.

Year	Diameter (cm)	Basal area ($m^2\ ha^{-1}$)	Biomass ($t\ ha^{-1}$)	Stand C ($t\ ha^{-1}$)
1	8.84 ± 1.22	6.94 ± 0.52	19.76 ± 6.86	9.37 ± 3.25
3	15.10 ± 1.62	20.11 ± 1.27	82.83 ± 26.28	39.26 ± 12.46
5	18.39 ± 1.47	29.70 ± 1.42	139.99 ± 36.41	66.36 ± 17.26

Values are means ± standard deviation.

Table 2. Soil physical properties of *Acacia mangium* at different plantation ages.

Properties	Soil depth (cm)	Plantation age (years)			
		0*	1	3	5
Bulk density ($g\ cm^{-3}$)	0–15	1.12 ± 0.15^{a1}	1.06 ± 0.11^{a1}	1.08 ± 0.18^{a1}	1.12 ± 0.17^{a2}
	15–30	1.28 ± 0.13^{ab1}	1.13 ± 0.18^{b1}	$1.19 \pm 0.24^{ab}1$	1.33 ± 0.17^{a1}
Sand (%)	0–15	68.0	53.40	65.95	51.60
	15–30	63.6	56.10	66.55	59.05
Clay (%)	0–15	14.7	19.20	18.30	23.70
	15–30	16.5	19.50	18.50	21.70
Silt (%)	0–15	17.3	27.40	15.75	24.70
	15–30	19.9	24.40	14.95	19.25

*: Corresponds to the secondary forest. Values are means ± standard deviation. Means within rows with different letters indicate significant difference between plantation ages by DMRT at P < 0.05, while means within columns with different numbers indicate significant difference between soil depths by independent t-test at P < 0.05.

highest sand percentage, whereas the highest percentage of silt was recorded in the youngest stand. Meanwhile, the oldest stand had the highest clay content (Table 2). No significant difference between stands for soil bulk density at 0–15 cm depth (Table 2) was observed. Regarding the 15–30 cm subsoil layer, significant increase in bulk density was observed between the youngest and oldest stand (Table 2). Bulk density increased with depth of soil (Table 2). Only the 5-year-old stand had significant difference between depths.

Soil pH (either in water or KCl) increased significantly for both soil depths in the year after planting (Table 3). Significant reduction in pH was observed in older stands as compared to the 1-year-old stand (Table 3). Significant differences for SOC were detected between stand ages (Table 3), with the youngest stand showing the highest SOC as compared to the 3- and 5-year-old stands. However, no significant difference was observed between the youngest stand and the control or secondary forest (Table 3). The 3-year-old stand had the lowest SOC for both soil depths (Table 3).

Soil total N followed a similar trend as SOC. The secondary forest and the 1-year-old stand had significantly higher N than the 3- and 5-year-old-stands (Table 3). The lowest N was recorded in the 3-year-old stand (Table 3). Available P trend was similar to that of pH, where significant increase was observed in the 1-year-old stand, followed by a significant decline thereafter (Table 3).

The secondary forest had significantly higher SCC than the 3- and 5-year-old stands (Figure 2) but was not significantly different than the 1-year-old stand (Figure 2).

3.3. Soil properties and growth

Table 4 shows the relationship between the stand parameters and soil properties. Carbon content was negatively correlated with *d* (surface: $P < 0.05$) and sand content (surface: $P < 0.05$; subsoil: $P < 0.05$) but was positively correlated with silt content (surface: $P < 0.05$; subsoil: $P < 0.05$). Total N was positively correlated with C content (surface: $P < 0.001$), silt content (surface: $P < 0.001$), and available P (subsoil: $P < 0.05$), but was negatively

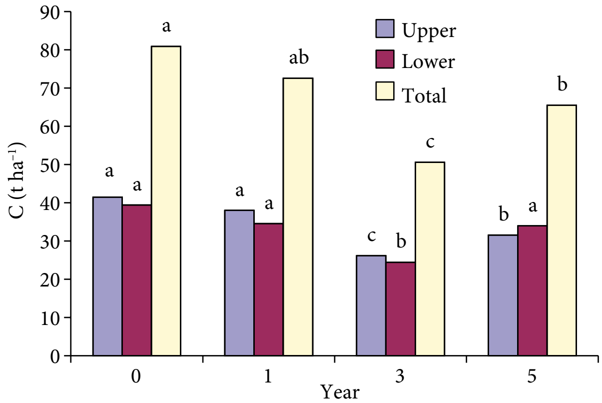

Figure 2. Soil carbon content in stands of different ages. Letters reflect significant differences.

Table 3. Soil chemical properties of *Acacia mangium* at different plantation ages.

Properties	Soil depth (cm)	Plantation age (year)			
		0*	1	3	5
pH (water)	0–15	4.53 ± 0.05^{c2}	5.00 ± 0.04^{a2}	4.92 ± 0.15^{a1}	4.76 ± 0.09^{b1}
	15–30	4.75 ± 0.14^{b1}	5.06 ± 0.08^{a1}	4.85 ± 0.14^{b1}	4.78 ± 0.16^{b1}
pH (KCl)	0–15	3.67 ± 0.09^{c1}	3.93 ± 0.07^{a1}	3.86 ± 0.18^{b1}	3.80 ± 0.30^{b1}
	15–30	3.83 ± 0.13^{b1}	3.93 ± 0.07^{a1}	3.89 ± 0.30^{ab1}	3.82 ± 0.39^{b1}
SOC (%)	0–15	2.44 ± 0.43^{a1}	2.32 ± 0.17^{a1}	1.61 ± 0.43^{c1}	1.88 ± 0.21^{b1}
	15–30	2.04 ± 0.57^{a1}	1.97 ± 0.15^{ab2}	1.35 ± 0.41^{c1}	1.74 ± 0.14^{b2}
Total N (%)	0–15	0.17 ± 0.04^{ab1}	0.19 ± 0.03^{a1}	0.12 ± 0.03^{c1}	0.16 ± 0.03^{b1}
	15–30	0.11 ± 0.04^{b1}	0.16 ± 0.03^{a2}	0.12 ± 0.03^{b1}	0.12 ± 0.03^{b2}
Available P (mg kg^{-1})	0–15	3.52 ± 0.32^{b1}	5.21 ± 2.88^{a1}	2.09 ± 0.57^{c1}	1.63 ± 0.35^{c1}
	15–30	2.78 ± 0.30^{b1}	3.79 ± 2.48^{a1}	1.39 ± 0.40^{c2}	1.57 ± 0.73^{c1}
SCC (t ha^{-1})	0–15	41.49 ± 9.25^{a1}	38.02 ± 4.99^{a1}	26.17 ± 8.28^{c1}	31.55 ± 5.14^{b1}
	15–30	39.43 ± 12.33^{a1}	34.55 ± 6.25^{a1}	24.47 ± 9.67^{b1}	33.98 ± 3.98^{a1}

*: Corresponds to the secondary forest. Values are means ± standard deviation. Means within rows with different letters indicate significant difference between plantation ages by DMRT at $P < 0.05$, while means within columns with different numbers indicate significant difference between soil depths by independent t-test at $P < 0.05$.

Table 4. Pearson correlation coefficients between growth and soil properties.

Parameters	Stand diameter	C content	Total N	Available P	Sand content	Silt content
Soil depth of 0–15 cm (surface)						
C content	−0.5860*	-	0.8617**	0.4531	−0.6095*	0.7067*
Total N	−0.5214	0.8617**	-	0.4768	−0.7095**	0.8220**
Available P	−0.7102**	0.4531	0.4768	-	−0.0536	0.1998
Stand age	0.9802**	−0.4796	-0.3890	−0.6440*	−0.0918	−0.1697
Soil depth of 15 – 30 cm (subsoil)						
C content	−0.4013	-	0.5049	0.3678	-0.7014*	0.7291*
Total N	−0.7559**	0.5049	-	0.7195*	-0.2631	0.4141
Available P	−0.6314*	0.3678	0.7195*	-	0.0934	0.0449
Stand age	0.9807**	−0.2833	−0.6849*	−0.5529	0.1644	−0.4342

**, *: Significant at 1% and 5% probability levels, respectively.

correlated with sand content (surface: $P < 0.001$) and d (subsoil: $P < 0.001$). Available P was negatively correlated with d (surface: $P < 0.001$; subsoil: $P < 0.05$). Meanwhile, stand age was negatively correlated with total N (subsoil: $P < 0.05$) and available P (surface: $P < 0.05$).

4. Discussion

4.1. Soil properties

Soil texture appears to be a critical factor in determining the outcome of soil C and N during plantation establishment. The variable charges found in clays are dominant in many tropical Oxisols and Ultisols, which adsorb organic matter and form organomineral complexes (Oades et al., 1989). In the present study, a negative relationship was found between sand content and both N and C (Table 4). Meanwhile, silt content was positively correlated with both N and C (Table 4). These findings were different from the results reported by Tiessen et al. (1994) and Moraes et al. (1995), where a strong positive relationship between clay content and concentrations of C, N, or P was found, irrespective of land use. High sand content and low clay and silt content could be a reason for low C and N accumulation in the 3-year-old stand (Table 2). Botschek et al. (1996) noted that low clay content and lack of aggregation (i.e. absence of soil organic matter protection and stabilization) in coarse-textured soil are major factors limiting soil C storage capacity, despite higher C input from litterfall in the stand. Although litter production and accumulation were not determined in the present study, the contribution of litterfall in all stands was expected to be high. In Sumatra, Indonesia, litter accumulated under *A. mangium* stands was reported at 16.8 t ha^{-1} (Hardiyanto et al., 2000) and litterfall in 5-year-old *A. mangium* stands was 12.5 t ha^{-1} (Hardiyanto and Wicaksono, 2008).

Soil productivity depends not only on the storage of plant nutrients but also on physical properties such as bulk density. Greacen and Sands (1980) reported 20%–30% increase in soil bulk density due to logging activities. The present result is in accordance with their observation of an increment of 29.3%–30.0% in soil bulk density at the surface layer of the soil as compared to a nearby secondary forest (Table 2). The use of machinery during site clearing and preparation clearly increased soil bulk density in the plantation. In this study, a similar increase in surface soil bulk density was found in different stands (Table 2), implying that plantation establishment failed to improve the physical condition of the soil. This may be related to the development of the root systems and the presence of microorganisms. A longer time period is required for observing any substantial changes in soil bulk density, as reported by Markewitz et al. (2002) and Coleman et al. (2004).

Soil pH declines gradually with stand age (Table 3). In the present study, higher soil pH in the 1-year-old stand as compared to the secondary forest may be due to site preparation activities where biomass residuals were burnt. The burning activity added mineralized base cations (in the form of ash) into the soil and raised soil pH (Khanna et al., 1994; Arocena and Opio, 2003). Reduction in soil pH in the older stands of this study was probably related to vegetative coverage, which caused extensive secretion of organic acids associated with accelerated organic matter decomposition. Decrease in soil pH has often been found to be the result of plantation establishment (Rhoades and

Binkley, 1996). Similar findings have been reported for other nitrogen-fixing trees (DeBell et al., 1983; Sharma et al., 2009). The buildup of acidic soil organic matter and the displacement of base cations resulted from the production of H^+ during nitrification (DeBell et al., 1983; Binkley and Sollins, 1990). Subsequently, the leaching of such cations from the soil profile due to high rainfall may be the reason for acidity rise with stand age. Such results are contrary to those reported by Siregar et al. (2008) and Hardiyanto and Wicaksono (2008). Siregar et al. (2008) found that soil pH of *A. mangium* plantations increased 5 years after planting, while Hardiyanto and Wicaksono (2008) reported no change in soil pH for the same period of time.

When a natural forest is converted into a plantation area, a significant decline in SOC is likely to occur as a result of change in both input and output of C. Decrease in the amount of SOC is attributed to a decrease in the amount of plant residues returning to the soil and to an increase in the amount of CO_2 released from the soil organic matter to the atmosphere due to decomposition (Schlesinger, 1986; Jug et al., 1999). In the present study, higher SOC in the youngest stand as compared to the older stands (Table 3) was probably due to the availability of plant residues after site clearing and preparation. Higher SOC in the 5-year-old stand as compared to the 3-year-old was probably due to higher litterfall (litter production was not determined in this study). Hardiyanto and Wicaksono (2008) reported an increase of 25% in litterfall production in the 5-year-old *A. mangium* stand as compared to the 3-year-old stand. In this study, lower fine root turnover could be another contributing factor (Ruess et al., 2003; Yuan and Chen, 2010) to the lesser SOC content in the 3-year-old stand, as the stand is still developing. An initial reduction of SOC during the first 3 years of planting and a subsequent increase in 5-year-old *A. mangium* plantations was reported by Hardiyanto and Wicaksono (2008) and Siregar et al. (2008).

Soil total N followed a similar trend as SOC (Table 3). A significant reduction of SOC in the 3- and 5-year-old stands was detected when compared to the youngest stand. Similar observations were reported by Hardiyanto and Wicaksono (2008) in South Sumatra and Siregar et al. (2008) in Riau Province, Sumatra. In Hawaii, Binkley and Resh (1999) observed a reduction of 190 kg ha^{-1} soil N despite 700 kg N ha^{-1} of fertilizer applied in a 32-month eucalyptus plantation. Higher total N in the youngest stand may also be due to the slash-and-burn activity during site preparation. Nitrogen content tends to increase immediately after burning (as reviewed by Certini, 2005). Lower N content in older stands may be due to a number of factors including rapid nutrient uptake by fast-growing *A. mangium*, lower rate of decomposition despite increase in litter production (Bargali, 1990), and leaching of available nutrients, as young developing root systems are unable to capture them (Smith et al., 1994; Certini, 2005).

Phosphorus is one of the nutrients that limit tree growth, especially in tropical areas (Zás and Serrada, 2003). Available P in the 1-year-old stand was significantly higher than in the secondary forest and the 3- and 5 year-old stands at both depths (Table 3). This was probably a result of the slash-and-burn activity, which stimulated microbial mediated organic P mineralization, increasing P availability (Sanchez, 1976). Furthermore, the application of fertilizer also added to the higher concentration of P found in the youngest stand. Available P in the soil was reduced as the stand aged (Table 4), probably as the result of the huge nutrient consumption ensuing from the vigorous growth of *A. mangium*. Hardiyanto and Wicaksono (2008) found that the highest demand for nutrients such as N, P, K, Mg, and Ca in an *A. mangium* stand occurred between the age of 1 and 2 years. In addition, available P may also decline through erosion and runoff (Bargali et al., 1993), particularly in tropical climates with heavy rainfall.

4.2. Changes of carbon content in stand and soil

Input and decomposition of litter are factors that influence SOC content in forests that are affected by nature and human intervention. However, human intervention is by far a greater contributing factor than natural processes (Sitaula et al., 2004; Tonitto et al., 2007). Various results have been obtained for soil C sequestration during forest establishment. After reviewing 46 studies conducted in both temperate and tropical forests, Post and Kwon (2000) noted that soil C increased at an average rate of 0.34 t ha^{-1} $year^{-1}$. Similarly, a review by Paul et al. (2002) indicated that an average of 0.14 t ha^{-1} $year^{-1}$ soil C was sequestrated. They reported that the buildup of soil C was higher under deciduous or N-fixing species in tropical or subtropical regions.

In the present study, the accumulation of soil C ranges from –15.1 to 14.7 t ha^{-1} $year^{-1}$ from year 1 to year 3 and year 3 to year 5, respectively (Figure 2). These values were much higher than previously reported values. In this study, the drastic reduction of the soil C pool in the 3-year-old stand as compared to the 1-year-old stand may be due to the higher decomposition rate of the existing residual and litter, as well as the low fine root turnover and litterfall in the 3-year-old stand. A large increase in soil sequestration rate in the 5-year-old stand was in all probability the result of litterfall buildup due to canopy closure, which in turn enhanced the decomposition rate of litter on the forest floor. In addition, the 5-year-old stand may have also experienced faster fine root turnover. In a *Eucalyptus tereticorni* hybrid plantation in Central Himalaya, Bargali et al. (1993) observed that soil C accumulation decreased at a much slower rate (about 5 t C ha^{-1} $year^{-1}$), although the initial soil C pool was similar to that of the present study. Meanwhile, in Bogor, Indonesia, Herdiyanti and Sulistyawati (2009) reported that soil C stock in a 3-year-old *A. mangium* plantation initially increased but was subsequently reduced after 5 and 7 years, respectively.

The annual rate of aboveground biomass C accumulation in this study ranges from 9.37 to 13.27 t ha^{-1} $year^{-1}$ (Table 1). These values were much higher than the 0.22 to 5.72 t ha^{-1} $year^{-1}$ reported by Herdiyanti and Sulistyawati (2009) in 1- to 7-year-old *A. mangium* plantations in Bogor, Indonesia. Meanwhile, in Sumatra, Indonesia, Hardiyanto and Wicaksono (2008) and Siregar et al. (2008) recorded C accumulation in biomass ranging from 8.5 to 18.9 t ha^{-1} $year^{-1}$ and 5.8 to 19.2 t ha^{-1} $year^{-1}$ for stands of 1 to 5 years of age, respectively. The different rate of accumulated C stock may be attributed to the influence of climatic conditions, site qualities, and stand density.

The total amount of C pools (soil and aboveground biomass) for 1-, 3-, and 5-year-old stands in this study were 74.9, 89.9 and 138.9 t ha^{-1}, respectively. The main contributor to the C stock in plantations was soil, which accounted for 52.2% to 87.5% of the total C stocks.

4.3. Managing soil productivity

Almost all soil quality attributes showed a declining trend with stand age. A continuous decline in soil quality indicated that the present land management may not be sustainable. Soil C (surface), N (subsoil), and P (both layers) were negatively correlated, with *d* suggesting that the uptake of these nutrients was much higher than their rate of return through decomposition and root turnover. Negative correlations were also observed between stand age and soil N (subsoil) as well as P (surface). Therefore, an improved management practice is imperative to sustain soil quality and maintain long-term productivity of plantation forests.

Fertilizers must be applied continuously when the stand reaches the age of 3 and 5 years in order to stimulate continuous growth. The amount of fertilizer applied will depend on the results of fertilizer trials. Thinning activity will also be required to reduce the number of trees competing for the same nutrients.

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