EFFECTS OF *ACACIA MANGIUM* ON MORPHOLOGICAL AND PHYSICOCHEMICAL PROPERTIES OF SOIL

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TANAKA S, KANO S, LAT J, MOHD EFFENDI W, TAN NP, ARIFIN A, SAKURAI K & KENDAWANG JJ. 2015. Effects of *Acacia mangium* on morphological and physicochemical properties of soil. This study was conducted in an industrial *Acacia mangium* plantation in Sarawak, Malaysia, to investigate the effects of planting and harvesting *A. mangium* on soil morphological and physicochemical properties. In *A. mangium* sites, the disruptive effect of planting practices extended to morphological properties in subsoil layers. The A horizon redeveloped during early stages after planting which could be ascribed to plentiful supply of organic matter through rapid decomposition of vegetation residues produced upon land preparation. However, soil C- and N-related properties appeared to decrease with stand age, while the levels of exchangeable bases and available P remained low even after 10 years. In post-harvest sites, distinct soil horizons were not observed due to severe disturbance. The levels of total C, N and exchangeable bases at depth of 0–5 cm for sites assessed 3 years after harvesting were higher than those of sites assessed 1 year after harvesting. This might be ascribed to relatively gradual release of organic matter and nutrients from harvest residues into soil due to low level of decomposition as well as low nutrient uptake of poor vegetation regrowth.

Keywords: Exchangeable bases, planting, harvesting, Malaysia, soil organic matter, Typic Dystrudepts

INTRODUCTION

Acacia species planted on degraded forest and grassland for the purpose of reforestation or rehabilitation have been known to restore soil conditions (Yamashita et al. 2008, Inagaki & Titin 2009, Yang et al. 2009). Many of such studies were conducted in subtropical monsoon, semi-arid or arid climates. In contrast, several studies conducted under tropical humid climate have reported a decrease or no change in soil C, N and other nutrients over time after planting with *Acacia* (Norisada et al. 2005, Nykvist & Sim 2009, Vijayanathan et al. 2011).

In Sarawak, Malaysia, a large area of land (i.e. 480,000 ha) was designated as Planted Forest Zone (PFZ), within which 125,000 ha were planted with *Acacia mangium* in 2011. The PFZ was established mostly on non-degraded secondary forests caused by shifting cultivation or logging activities. Due to its industrial purpose, a short-term rotation system was adopted in the PFZ. The climate is characterised by high annual precipitation of 3800 mm. Although detailed soil information is required to attain sustainable management of industrial forest plantations using fast-growing tree species in short-rotation systems (Mackensen et al. 2003), soil condition after planting has yet to be investigated in the PFZ. The purpose of this study was to assess effects of planting and harvesting *A. mangium* on morphological and physicochemical properties of soil in the PFZ.

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MATERIALS AND METHODS

Planted Forest Zone

The PFZ extends over the Bintulu and Sibu Divisions spanning 480,000 ha, consisting of 210,000 ha of forest plantation to provide pulp, 110,000 ha for local agriculture and 160,000 ha for forest conservation and other miscellaneous purposes (Figure 1; State Government of Sarawak 2009a, b). After commencement of planting in 1997, the area planted with *A. mangium* reached 125,000 ha in 2011. The planted area was divided into 118 planting blocks (ranging from 200–4900 ha) as management units. The blocks are coded as T1C or T2C as shown in Figure 1 and Table 1. Planting spacing was 3 m × 3 m. Fire was not used in management practices, including land preparation. Chemical fertilisers were applied only at the time of planting. Weeding was conducted twice within half a year after planting. In spite of the planned 7-year rotation system, harvest practices were delayed and, subsequently, started in 2007. Heavy machinery such as caterpillars were used for harvesting and loading. The conservation forest patches were designated by the plantation company to conserve wildlife and constituted borders between blocks.

Annual precipitation at the Bintulu airport ranged from 2809 to 4692 mm from 1997 till 2006. Average temperature was 26–27 °C. The terrain is composed mainly of undulating or rolling hills with elevation lower than 60 m above sea level. The bedrock is composed mainly of fine- to medium-grained sandstone alternating with shale and sand shale of the Nyalau Formation during the Miocene. Although the original vegetation was lowland dipterocarp forest, vegetation before conversion to plantation was primarily non-degraded secondary forest, which was affected by shifting cultivation practices or logging activities.

Study sites, soil surveys and sampling

Field surveys were conducted at nine *A. mangium* planted sites with stand ages ranging from 2 to 10 years after planting in the first rotation (designated as AM and numbered as AM1–AM9) (Table 1, Figure 1). Six post-harvest sites (three sites each at 1 year and 3 years after harvest) were also surveyed (designated as AH and numbered as AH1–AH6). The AH sites were harvested for *A. mangium* during the first rotation but was not replanted. Surveys were also conducted at the conservation forest (CF) patches adjacent to each AM and AH, except for

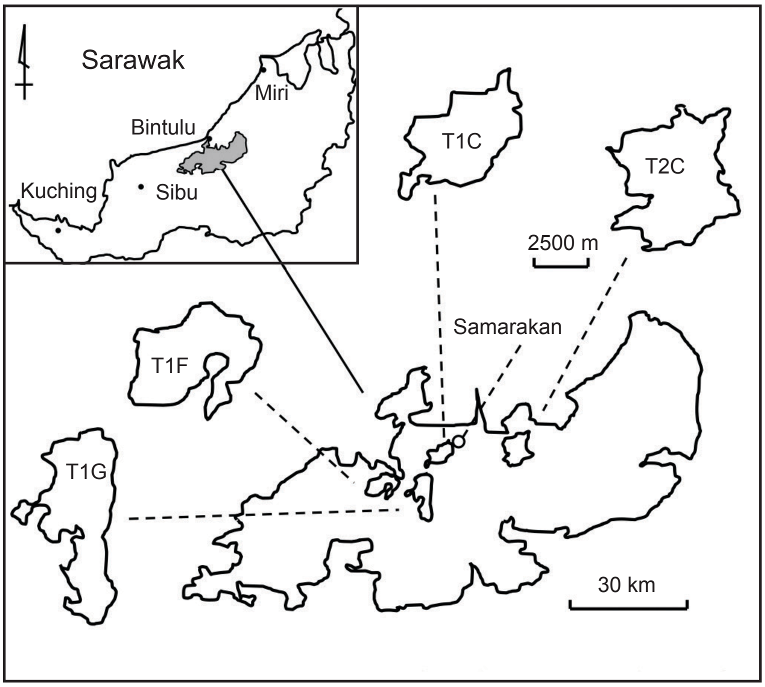

Figure 1 Planted Forest Zone and locations of studied planting blocks (T1C, T2C, T1F and T1G) and the plantation office (Samarakan)

Table 1 Study sites

Acacia mangium site							Adjacent forest site		
Site name	Block code	Years after planting/ harvesting	Slope direction	Slope gradient (°)	Height (m)	Dbh (cm)	Site name	Slope direction	Slope gradient (°)
AM1	T2C	2	N 40° W	18	9.7 ± 0.7	9.1 ± 1.2	CF1	N 70° E	20
AM2	T2C	2	N 10°W	18	10.4 ± 2.0	11.7 ± 0.9	CF2	S 70° E	22
AM3	T2C	3	N 50° W	15	11.7 ± 1.1	10.9 ± 1.4	CF3	N 70° E	26
AM4	T1G	6	S 10° E	24	17.9 ± 1.6	17.3 ± 2.2	CF4	W	23
AM5	T1G	8	N 70° E	7	19.9 ± 2.6	18.5 ± 3.0	CF5	N 70° W	15
AM6	T1G	8	S 10° E	21	16.3 ± 2.4	14.5 ± 2.7	CF6	S 70° W	13
AM7	T1C	9	S 70° E	20	17.7 ± 2.2	20.1 ± 4.9	CF7	N 70° W	12
AM8	T1C	10	N 10° E	13	21.2 ± 3.9	19.3 ± 4.0	CF8	N 50° E	7
AM9	T1C	10	N 30° W	13	19.2 ± 0.8	29.4 ± 5.8	CF9	S 70° E	25
AH1	T1F	11/1	S 50° E	7			CF11	S 80° E	10
AH2	T1F	11/1	S 45° E	5			CF12	S 50° E	12
AH3	T1F	11/1	S 60° E	7			CF13	S 10° W	10
AH4	T1F	10/3	S 35° E	10					
AH5	T1F	10/3	S 50° E	12					
AH6	T1F	10/3	S 40° E	7					

Values are averages ± standard deviations for height and diameter at breast height (dbh) of 10 *Acacia mangium* trees

AH4–AH6. CF patches were numbered CF1–CF9 and CF11–CF13 and corresponded to AM1–AM9 and AH1–AH3 respectively. CF sites were regarded as control sites for their respective AM and AH sites. Locations of the study sites were limited within a distance of about 15 km from Samarakan (the location of the plantation office: N 2° 56', E 113° 07') due to accessibility.

The vegetation in CF comprised well-developed secondary forest and included *Artocarpus elasticus*, *Macaranga* spp., *Semecarpus rufovelutinus*, etc. Some of the trees exceeded 30 m in height and 30 cm in diameter. In AM, the canopy of AM1–AM3 was open while that of AM4–AM9 was closed. The average height and diameter at breast height (dbh) of 10 selected *A. mangium* trees located around the soil pit are shown in Table 1. The undergrowth in AM was dominated by *Melastoma malabathricum*, *Soleria pupurescens*, *Dicranopteris linearis*, *Cyclopeltis mirabilis* and *Hornstedtia* sp. and was much denser than that in CF. In AH sites, in spite of similar species composition to those of the undergrowth in AM sites, the vegetation growth was poorer than those in the latter and there were small bare spots without any vegetation cover.

For soil survey and sampling, we selected the middle parts of the slopes with similar landforms for each AM and CF as well as AH and CF pairs. We did not describe the soil profiles for AH1–AH6, and therefore, CF11–CF13 because distinct horizons were not observed in AH soil. Soil samples were collected from the 0–5, 5–10 and 30–40 cm layers, in triplicates and mixed well to make one composite sample for each depth. The samples were air dried and passed through 2-mm mesh sieve for physicochemical analysis. Fresh samples were collected for determination of mineral N and the microbial biomass of C and N (MBC and MBN respectively). Fresh samples from the 5–10 and 30–40 cm layers of AH soil were analysed for mineral N only. They were kept cool at 4 °C in refrigerator and passed through 4-mm mesh sieve prior to analyses.

Soil analysis

Soil pH (H_2O) was determined in water and pH (KCl) in 1 M KCl in a soil to solution ratio of 1:5 using glass electrode method. Total C and N contents were analysed using NC analyser. The contents of exchangeable bases (Ca, Mg, K and Na) and the cation exchange capacity (CEC) were measured after three times extraction using 1 M ammonium acetate (pH 7) and 10% NaCl respectively in a soil to solution ratio of 1:5. The amount of NH_4 replaced by Na was determined for the CEC using steam distillation and titration methods, whereas contents of exchangeable bases were determined by atomic absorption spectrophotometry for Ca, Mg and K and by flame photometry for Na. Available P was quantified by the Bray II method in a soil to extractant ratio of 1:20. Particle size distribution was determined using pipette method without treatment to remove Fe oxides. NH_4-N and NO_3-N were extracted with 2 M KCl in the ratio of 1:5 and the amounts were determined by steam distillation and titration method with 0.005 M H_2SO_4. The levels of MBC and MBN were determined by chloroform fumigation extraction method (Brookes et al. 1985, Vance et al. 1987). Detailed procedures employed for MBC and MBN are given in Tanaka et al. (1998).

Statistical analyses

All data for the soil were expressed on oven-dry basis. All statistical analyses were performed using Excel Statistics version 2010 for Windows. Prior to comparison of soil parameter for each layer in AH, AM and CF sites, Bartlett's test ($p < 0.05$) for homogeneity of variance was performed. When the variances were shown to be homogenous, one-way analysis of variance, and subsequently, Scheffe's multiple comparison ($p < 0.05$) were computed. When variances were not homogeneous, the Kruskal–Wallis test and, subsequently, the Scheffe's multiple comparison ($p < 0.05$) were performed. To verify the correlation of a soil parameter for each layer of AM + AH (all together) and their corresponding CF, or between AM and CF, and the correlation between stand age and a soil parameter for each AM layer, Pearson's correlation analysis ($p < 0.05$) was applied. For the comparison of a soil parameter for each layer between the soil from AH1–AH3 and that from AH4–AH6, Student's t-test was used when variances were homogenous based on the Bartlett's test ($p < 0.05$), while Welch's t-test was used when variances were not homogenous.

RESULTS

Morphology of soil profiles

The O horizon in AM1–AM3 was shallower than that in the corresponding CF1–CF3, while the horizon of AM4–AM9 was thicker than that for CF4–CF9 respectively (Table 2). The O horizon of AM consisted of mainly *Acacia* leaf litter. In this horizon, partially decomposed tree barks were found in AM1–AM3, while a dense root mat of *A. mangium* and undergrowth with thickness of 2–5 cm was distributed throughout AM4–AM9. The thickness of the A horizon, plus the AB horizon if any, at each AM was similar to their corresponding CF. The B horizon for AM1, AM5 and AM6 was shallower than that in the corresponding CF1, CF5 and CF6 respectively, while this horizon was not observed for AM2, AM3, AM7, AM8 and AM9. In the latter cases, the A horizon was immediately overlain with the AC or C horizon. No difference was found in soil structure between each AM and CF pair. Although there were no differences in rooting depth between each AM and CF pair, more medium- to coarse-sized roots were recorded in the latter. In AH sites where distinct pedological horizons were not found, relatively dry plant residues, mainly of *A. mangium*, produced by harvest practices covered the ground surface. The soil was severely disturbed with caterpillar tracks and skid trails.

Soil properties

Studied soil could be characterised primarily as Typic Dystrudepts, while some were Typic Hapludults (Soil Survey Staff 2010). No significant correlations could be found for most soil properties of AM and AH with those of their corresponding CF sites (results not shown).

Soil texture

Figure 2 shows particle size distribution at CF2, AM2, CF13 and AH3 as the representative for AM, AH and the corresponding CF. At each CF (as shown for CF2 and CF13), clay contents slightly increased and sand contents decreased with depth (Figure 2). On the other hand, an abrupt increase in silt contents was observed in the 5–10 cm layer for AM2 and an abrupt decrease in the contents was noted in AH3 (Figure 2). AM1 and AM8 showed similar trends to AM2. Such changes were also found in AH5 and AH6, although we did not have the corresponding CF samples. These changes are reflected in the average values of particle size distribution of AM and AH sites (Table 3). In AM sites, clay, silt and sand contents did not significantly correlate with stand age (results not shown). Similarly, in AH sites, clay, silt, and sand contents did not significantly differ between the soil from AH1–AH3 and the soil from AH4–AH6 (results not shown).

Acidity, CEC, exchangeable bases and available P

Table 3 gives average values of acidity, CEC, exchangeable bases and available P for AM, AH and CF sites. All soil was strongly acidic with low levels of exchangeable bases (Table 3). The Ca level in the 0–5 cm layer of AH sites was significantly higher than those of AM and CF sites. The level of available P was very low, < 5 mg P kg^{-1}, although the difference in the 5–10 cm layer was significant between AM, AH and CF sites.

Soil properties in AM sites did not correlate significantly with stand age. For AH sites, the averages of exchangeable K in AH4–AH6 were 0.09 $cmol_c\ kg^{-1}$ for the 0–5 cm layer and 0.07 $cmol_c\ kg^{-1}$ for the 5–10 cm layer, while those of AH1–AH3 were 0.06 $cmol_c\ kg^{-1}$ for the 0–5 cm layer and 0.01 $cmol_c\ kg^{-1}$ for the 5–10 cm layer (results not shown). They were significantly higher in AH4–AH6 than in AH1–AH3 ($p < 0.05$). A similar tendency, although not significant, was obtained for the levels of exchangeable Ca and Mg in the 0–5 cm layer.

C- and N-related properties

Table 4 shows average values of C- and N-related properties for AM, AH and CF sites. The C/N ratio and the MBN in the 0–5 cm layer were significantly different between AM, AH and CF sites (Table 4). The dominant form of mineral N was NH_4-N in AM and CF sites while NO_3-N, in AH sites. In AM sites, in particular, NH_4-N conspicuously accumulated in the 0–5 cm layer.

In AM sites, there was no significant correlation between soil C- as well as N-related

Table 2 Soil profile description for selected *Acacia mangium* and adjacent forest sites

Acacia mangium site							Adjacent forest site						
Horizon	Depth (cm)	Colour	Texture	Structure[@]	Root[+]	Boundary[#]	Horizon	Depth (cm)	Colour	Texture	Structure[@]	Root[+]	Boundary[#]
AM1 (T2C, 2 years, N 02° 55', E 113° 16', N 40° W, 18°)							CF1 (N 02° 55', E 113° 16', N 70° E, 20°)						
O	2–0	including tree bark					O	5–0					
A	0–2	10YR3/4	LS	2fcr	4vf-f	cs	A	0–8	10YR4/6	SL	2fcr	2vf-m	gs
AB	2–12	10YR4/6	LS	2fsbk	3vf-f	cs	AB	8–18	10YR5/8	SL	2msbk	1vf-c	cs
B	12–28	10YR5/8	LS	2msbk	3vf-f, 2m-c	gs	B1	18–32	10YR6/8	SL	2m-csbk	1vf-c	gs
C	28–50+	10YR6/8	LS	no	1vf-f		B2	32–60+	10YR6/8	SCL	2msbk	none	
AM4 (T1G, 6 years, N 02° 53', E 113° 05', S 10° E, 24°)							CF4 (N 02° 53', E 113° 05', W, 23°)						
O	10–0						O	1–0					
A	0–6/12	10YR4/6	SL	2mcr	3vf-f, 2m	gw	A	0–5	10YR3/4	SL	2msbk	3vf-f, 2m, 1c	gs
AB	6/12–12/15	10YR5/6	SL	2f-msbk	2vf-m	gw	AB	5–18	10YR6/6	SL	2msbk	2vf-m	gs
B	12/15–27	10YR6/8 & 10YR7/6	SL	2msbk	1vf-f	gs	B	18–37	10YR7/8	SCL	2msbk	1vf-f	gs
BC	27–38	10YR6/8 & 10YR7/6	SL	2msbk	1vf-f	ds	C	37–60+	10YR7/8	SC	no	1vf-f	
C	38–70+	10YR6/8 & 10YR7/8		no	1vf-f								
AM7 (T1C, 9 years, N 02° 55', E 113° 05', S 70° E, 20°)							CF7 (N 02° 54', E 113° 05', N 70° W, 12°)						
O	15–0						O	1–0					
A	0–3/5	10YR6/6	SL	1msbk	3vf-f	gw	A	0–5	10YR5/4	LiC	2msbk	2vf-m	gs
C1	3/5–40/45	10YR6/4	SL	no	2vf-f	gw	AB	5–14	10YR6/6	LiC	2csbk	1vf-c	gs
C2	40/45–70+	10YR4/4	SL	no	2vf-f		Bt	14–30	10YR7/8	HC	no	none	gs
							BC	30–55+	10YR6/8	HC	no	none	

[@] Grade: 1 = weak, 2 = moderate; size: f = fine, m = medium; type: sbk = subangular blocky, cr = crumb; [+] abundance: 1 = very few, 2 = few, 3 = common, 4 = many; size: vf = very fine, f = fine, m = medium, c = coarse; [#] distinctness: c = clear, g = gradual, d = diffuse; topography: s = smooth, w = wavy

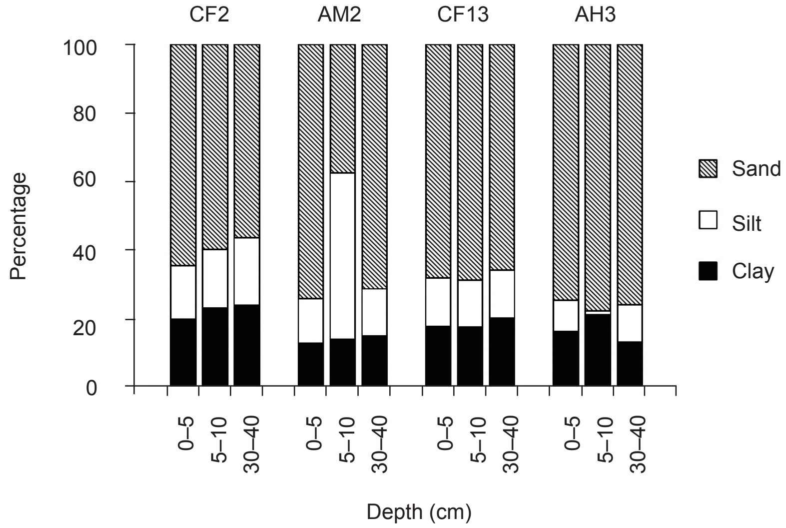

Figure 2 Comparison of particle size distribution between sites CF2 and AM2, CF13 and AH3; CF = conservation forest, AM = *Acacia mangium*

properties and stand age (Figure 3, Table 5). However, in the 0–5 cm layer, negative correlations were obtained when data from AM1 soil, for which clay content was extremely low (i.e. 7.7%), was excluded or when data was expressed as percentage clay to reduce the influence of different clay contents on the levels of these properties. The levels of total C and N in the 0–5 cm and 5–10 cm layers of AH4–AH6 did not differ significantly but tended to be higher than those of AH1–AH3. For example, total C and N at 0–5 cm in AH4–AH6 were 43.9 g kg^{-1} and 2.27 g kg^{-1} respectively, on average, while those in AH1–AH3 were 23.1 and 1.20 g kg^{-1} respectively (results not shown). However, no differences were found in MBC, MBN and mineral N between AH1–AH3 and AH4–AH6 (results not shown).

DISCUSSION

Soil disturbance by planting and harvesting practices

Despite being located adjacent to each other, no significant correlations could be found for most of the soil properties of AM and AH with those of their corresponding CF sites, suggesting that the soil was largely affected by planting and harvesting practices. Soil morphological properties in AM sites (Table 2) were affected by planting practices such as heavy machinery used for removal of vegetation. The lack (or shallowness) of the B horizon recorded in the eight soil profiles was one particular feature. The abrupt changes in soil particle distribution were also observed in the three AM sites (Figure 2), which might be due to selective translocation of mineral particles with different size classes. These results indicated that the influence of disturbance had extended down to the subsoil. However, the A horizon was observed in AM sites including AM1–AM3. Partially-decomposed tree bark fractions in the O horizon were found in AM1–AM3 but not in AM4–AM9, while root residues of the previous vegetation were rarely observed for all the AMs. Therefore, the relatively fast redevelopment of the A horizon could be due to plentiful supply of organic matter through rapid decomposition of vegetation residues produced upon land preparation for planting as well as the supply of organic matter from dead undergrowth. These results were in accordance with those of Vijayanathan et al. (2011), who reported temporal increases in the levels of soil organic matter and nutrients immediately after harvest in an *A. mangium* plantation in Peninsular Malaysia.

On the other hand, in AH sites, the presence of small bare spots could be due to disturbance at harvesting such as soil compaction, exposure of subsoil, washing away of seeds by heavy rain and overlay of harvesting residues on the ground surface. Abrupt changes in soil particle

Table 3 Average values of soil chemical properties

Parameter	*A. mangium* (AM) site (n = 9)	Post-harvest (AH) site (n = 6)	Conservation forest (CF) site (n = 12)
0–5 cm			
pH (H_2O)	4.56 (0.27)	4.42 (0.30)	4.41 (0.24)
pH (KCl)	3.56 (0.16)	3.57 (0.19)	3.48 (0.18)
Clay (%)	20 (10)	16 (4)	18 (7)
Silt (%)	16 (6)	18 (22)	15 (11)
Sand (%)	65 (16)	66 (21)	67 (17)
CEC (cmol$_c$ kg^{-1})	9.7 (2.6)	10.4 (2.4)	10.2 (2.6)
Exchangeable Ca (cmol$_c$ kg^{-1})	0.35 (0.48) ab	0.88 (1.00) b	0.18 (0.20) a
Exchangeable Mg (cmol$_c$ kg^{-1})	0.35 (0.23)	0.27 (0.17)	0.24 (0.13)
Exchangeable K (cmol$_c$ kg^{-1})	0.09 (0.05)	0.08 (0.02)	0.11 (0.04)
Exchangeable Na (cmol$_c$ kg^{-1})	0.02 (0.00)	0.02 (0.01)	0.02 (0.00)
Available P (mg P kg^{-1})	3.3 (1.7)	3.5 (0.8)	4.3 (1.8)
5–10 cm			
pH (H_2O)	4.55 (0.20)	4.53 (0.21)	4.55 (0.19)
pH (KCl)	3.62 (0.12)	3.74 (0.14)	3.67 (0.17)
Clay (%)	23 (9)	15 (4)	20 (8)
Silt (%)	22 (18)	11 (5)	15 (9)
Sand (%)	55 (24)	74 (3)	66 (16)
CEC (cmol$_c$ kg^{-1})	9.3 (1.5)	7.3 (2.3)	8.3 (1.9)
Exchangeable Ca (cmol$_c$ kg^{-1})	0.09 (0.12)	0.35 (0.49)	0.09 (0.10)
Exchangeable Mg (cmol$_c$ kg^{-1})	0.21 (0.13)	0.12 (0.12)	0.16 (0.14)
Exchangeable K (cmol$_c$ kg^{-1})	0.04 (0.03)	0.04 (0.03)	0.06 (0.04)
Exchangeable Na (cmol$_c$ kg^{-1})	0.02 (0.00)	0.01 (0.00)	0.02 (0.00)
Available P (mg P kg^{-1})	1.6 (1.0) a	2.8 (1.1) ab	2.9 (0.8) b
30–40 cm			
pH (H_2O)	4.71 (0.22)	4.73 (0.23)	4.75 (0.16)
pH (KCl)	3.73 (0.14)	3.87 (0.11)	3.76 (0.19)
Clay (%)	20 (13)	15 (3)	23 (11)
Silt (%)	17 (10)	19 (20)	14 (8)
Sand (%)	63 (22)	66 (23)	63 (18)
CEC (cmol$_c$ kg^{-1})	7.1 (2.5)	5.7 (1.3)	7.0 (2.5)
Exchangeable Ca (cmol$_c$ kg^{-1})	0.04 (0.05)	0.06 (0.05)	0.04 (0.05)
Exchangeable Mg (cmol$_c$ kg^{-1})	0.10 (0.10)	0.06 (0.08)	0.09 (0.07)
Exchangeable K (cmol$_c$ kg^{-1})	0.04 (0.04)	0.02 (0.01)	0.03 (0.02)
Exchangeable Na (cmol$_c$ kg^{-1})	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)
Available P (mg P kg^{-1})	1.5 (0.5)	1.2 (0.9)	1.6 (0.5)

Values are averages, standard deviations in parentheses; values in the same row followed by different letters are significantly different at $p < 0.05$ (Scheffe's multiple comparison test)

distribution were also observed. Unlike AM, the A horizons did not redevelop, although the levels of soil organic matter and nutrients were higher in the 0–5 cm layer (Tables 3 and 4). Such insufficient recovery of the A horizons might be explained by smaller input of plant residues derived from harvesting compared with input from the secondary forests upon

Table 4 Average values of soil C- and N-related properties

Parameter	*A. mangium* (AM) site (n = 9)	Post-harvest (AH) site (n = 6)	Conservation forest (CF) site (n = 12)
0–5 cm			
Total C (g kg^{-1})	19.3 (8.9)	33.5 (18.0)	25.2 (9.7)
Total N (g kg^{-1})	1.38 (0.51)	1.74 (0.76)	1.56 (0.65)
C/N	13.7 (2.2) a	19.0 (2.6) b	16.5 (2.5) b
Microbial biomass C (mg kg^{-1})	565 (238)	737 (240)	688 (170)
Microbial biomass N (mg kg^{-1})	54 (27) a	67 (28) ab	81 (21) b
NH_4-N (mg kg^{-1})	52 (29) b	14 (11) a	32 (18) ab
NO_3-N (mg kg^{-1})	8 (7) a	17 (6) b	9 (6) a
5–10 cm			
Total C (g kg^{-1})	12.2 (5.22)	12.9 (8.06)	13.8 (5.18)
Total N (g kg^{-1})	0.917 (0.204)	0.886 (0.529)	0.955 (0.353)
C/N	12.9 (3.4)	14.3 (1.3)	14.5 (1.4)
Microbial biomass C (mg kg^{-1})	480 (192)	ND	493 (143)
Microbial biomass N (mg kg^{-1})	40 (22)	ND	48 (15)
NH_4-N (mg kg^{-1})	18 (9) b	6 (3) a	19 (10) b
NO_3-N (mg kg^{-1})	6 (3) a	12 (2) b	4 (5) a
30–40 cm			
Total C (g kg^{-1})	5.86 (3.10)	3.65 (0.98)	5.14 (1.56)
Total N (g kg^{-1})	0.529 (0.162) b	0.257 (0.033) a	0.420 (0.096) b
C/N	10.8 (3.3)	14.0 (2.1)	12.4 (2.9)
Microbial biomass C (mg kg^{-1})	266 (118)	ND	291 (128)
Microbial biomass N (mg kg^{-1})	17 (9)	ND	20 (5)
NH_4-N (mg kg^{-1})	9 (2) b	4 (2) a	8 (2) a
NO_3-N (mg kg^{-1})	4 (3)	4 (2)	3 (8)

Values are averages, standard deviations in parentheses; values in the same row followed by different letters are significantly different at $p < 0.05$ (Scheffe's multiple comparison test)

planting *A. mangium* trees in AM sites. In the case of 10-year-old *A. mangium* plantation, some 50 Mg ha^{-1} of plant residues would remain in the field after harvesting of logs (Nykvist & Sim 2009) in Sabah. On the other hand, biomass exceeding 100 Mg ha^{-1} could be expected to be left in the field upon conversion of secondary forest to forest plantation through zero-burning land preparation (Kenzo et al. 2010). Judging from the presence of many dry residues on the ground and the higher C/N ratio in the 0–5 cm soil layers, activities of fauna and microorganisms might be suppressed in AH sites by severe field conditions after harvesting such as extreme rises in the air and soil temperatures, and drying under poor vegetation cover (Norisada et al. 2005).

Changes in soil properties over time after planting and harvesting

In Malaysia, annual litterfall and N flux were reported to be 12.8–13.5 Mg ha^{-1} and 207–223 kg N ha^{-1} for 20- to 22-year-old stands in Sabah (Inagaki et al. 2010), while litterfall was 10 Mg ha^{-1} for 4-year-old stands in Pahang (Lim 1988). Ammonium-N conspicuously accumulated in the 0–5 cm layer of AM soil (Table 4), which could be due to high N input in the form of NH_4-N through *Acacia* leaf litter decomposition and limited activities of soil nitrifiers under low pH. However, the decrease in soil C- and N-related properties with stand age in AM (Figure 3 and Table 5) indicated that the supply of plant residues upon plantation establishment and plant litter during *A. mangium* planting could not sustain the levels of these soil properties. The reason for the reduction in total C (i.e. soil organic matter) might be attributable to rapid decomposition under favourable moisture and temperature conditions in a tropical humid climate. On the other hand, the levels of exchangeable bases and available P did not change and remained very low with stand age. Judging from the presence of the thick root mat, a significant portion of the nutrients released from the litter might be recycled by *A. mangium* and undergrowth but did not contribute to the build-up of nutrient stocks in soil.

Thus, the results obtained from AM soil were inconsistent with those of previous studies, which reported positive effects of planting *Acacia* on soil conditions but agreed with several studies conducted in a tropical humid climate (Norisada et al. 2005, Nykvist & Sim 2009, Vijayanathan et al. 2011).

On the other hand, in AH sites, the level of exchangeable Ca in the 0–5 cm layer was higher than those in AM and CF sites (Table 3). The levels of total C and N, exchangeable Ca, Mg and K in the 0–5 cm layer for AH4–AM6 were significantly higher or tended to be higher than those for AH1–AH3. These results seemed to be ascribed to gradual release from harvest residues due to low level of decomposition and low uptake rate caused by poor vegetation regrowth. However, the levels of MBC and MBN were not different between AM and AH or between AH1–AH3 and AH4–AH6, suggesting that sufficient amounts of C and N were constantly supplied to sustain soil microbial biomass in spite of severe conditions.

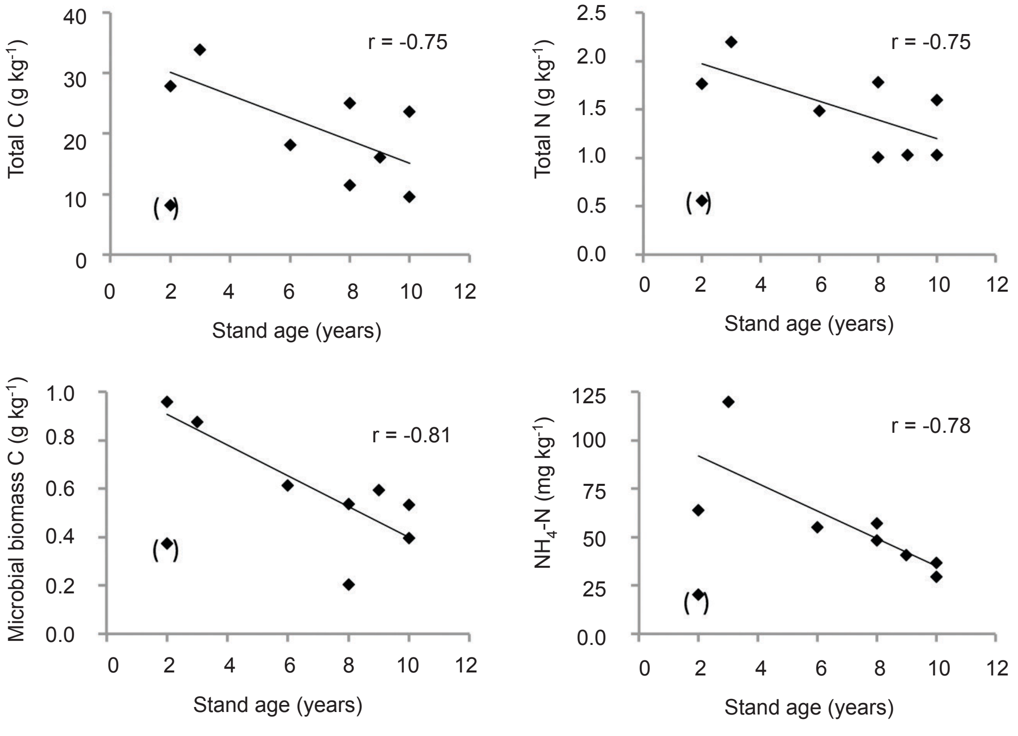

Figure 3 Relationship between soil C- as well as N-related properties in the 0–5 cm layer and stand ages in the AM sites; correlation coefficients were calculated excluding data for the AM1 soil (clay content was extremely low; plots in parentheses); statistically significant at $p < 0.05$

Table 5 Correlation coefficients of soil C- and N-related properties in the 0–5 cm layer with stand ages for *Acacia mangium* (AM) sites

Parameter	All AM[@] (n = 9)	AM2–AM9[+] (n = 8)	Percentage clay basis[#] (n = 9)
Total C	-0.29	-0.75*	-0.77*
Total N	-0.16	-0.75*	-0.76*
C/N	-0.48	-0.47	
Microbial biomass C	-0.51	-0.81*	-0.86**
Microbial biomass N	-0.38	-0.59	-0.92**
NH_4-N + NO_3-N	-0.41	-0.89	-0.75*
NH_4-N	-0.40	-0.78*	-0.76*
NO_3-N	-0.04	-0.29	-0.34

[@]Correlation coefficients were calculated using data from all the AM sites; [+]correlation coefficients were calculated excluding data from the AM1 soil (i.e. clay content was extremely low); [#]correlation coefficients were calculated using data expressed on percentage clay basis; *significant at $p < 0.05$, **significant at $p < 0.01$

CONCLUSIONS

In AM sites, soil C- and N-related properties reduced with stand age, while the levels of exchangeable bases and available P remained very low irrespective of stand age. This was due to the favourable condition for decomposition and vegetation uptake under tropical humid climate. This implied the depletion of soil organic matter and nutrients by continual disturbance and timber extraction during the course of rotation. On the other hand, increasing tendencies of total C and N and exchangeable bases in AH with time, in contrast to AM, suggested that the intensity of disturbance and condition of vegetation cover might control physical conditions such as temperature and moisture regimes on forest floor and in surface soil and, as a result, control biological conditions of fauna and microorganisms, affecting organic matter and nutrient dynamics in the ecosystem. In addition, the improved correlation coefficients of soil C- and N-related properties in AM on percentage clay suggested the importance of clay contents in soil organic matter dynamics. Thus, to understand soil–plant relationship in tropical forest plantation in short rotation systems and to develop its sustainable management, comprehensive long-term studies are required, which take into consideration influences of physical and biological field conditions, and of clay contents in the case of the terrain of relatively heterogeneous soil condition.

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REFERENCES

Brookes PC, Landman A, Pruden G & Jenkinson DS. 1985. Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass nitrogen in soil. *Soil Biology and Biochemistry* 17: 837–842.

Inagaki M, Kamo K, Titin J, Jamalung L, Lapongan J & Miura S. 2010. Nutrient dynamics through fine litterfall in three plantations in Sabah, Malaysia, in relation to nutrient supply to surface soil. *Nutrient Cycling in Agroecosystems* 88: 381–395.

Inagaki M & Titin J. 2009. Evaluation of site environments for agroforestry production. Pp 26–31 in Gotoh T & Yokota Y (eds) *Development of Agroforestry Technology for the Rehabilitation of Tropical Forests*. JIRCAS Working Report 60. Japan International Research Center for Agricultural Sciences, Tsukuba.

Kenzo T, Ichie T, Hattori D, Kendawang JJ, Sakurai K & Ninomiya I. 2010. Changes in above- and belowground biomass in early successional tropical secondary forests after shifting cultivation in Sarawak, Malaysia. *Forest Ecology and Management* 260: 875–882.

Lim MT. 1988. Studies on *Acacia mangium* in Kemasul Forest, Malaysia. I. Biomass and productivity. *Journal of Tropical Ecology* 4: 293–302.

Mackensen J, Klinge R, Ruhiyat D & Fölster H. 2003. Assessment of management-dependent nutrient losses in tropical industrial tree plantations. *Ambio* 32: 106–112.

Norisada M, Hitsuma G, Kuroda K et al. 2005. *Acacia mangium*, a nurse tree candidate for reforestation on degraded sandy soils in the Malay peninsula. *Forest Science* 51: 498–510.

Nykvist N & Sim BL. 2009. Changes in carbon and inorganic nutrients after clear felling a rainforest in Malaysia and planting with *Acacia mangium*. *Journal of Tropical Forest Science* 21: 98–112.

Soil Survey Staff. 2010. *Keys to Soil Taxonomy*. 11th edition. US Department of Agriculture and Natural Resources Conservation Service, Washington DC.

State Government of Sarawak. 2009a. *Master Plan For Community Development Programme for the Communities in Sarawak Planted Forest (Pulp & Paper) Project, Bintulu, Sarawak*. Main Report Volume 3. State Government of Sarawak, Kuching.

State Government of Sarawak. 2009b. *Master Plan For Community Development Programme for the Communities in Sarawak Planted Forest (Pulp & Paper) Project, Bintulu, Sarawak*. Main Report Volume 4. State Government of Sarawak, Kuching.

Tanaka S, Funakawa S, Kaewkhongkha T & Yonebayashi K. 1998. Labile pools of organic matter and microbial biomass in the surface soils under shifting cultivation in northern Thailand. *Soil Science and Plant Nutrition* 44: 527–537.

Vance ED, Brookes PC & Jenkinson DS. 1987. An extraction method for measuring soil microbial biomass C. *Soil Biology and Biochemistry* 19: 703–707.

Vijayanathan J, Yahya AZ, Yaacob A, Kassim AS & Chik SW. 2011. Impact of thinning of *Acacia mangium* plantation on soil chemical properties. *Malaysian Journal of Soil Science* 15: 75–85.

Yamashita N, Ohta S & Hardjono A. 2008. Soil changes induced by *Acacia mangium* plantation establishment: comparison with secondary forest and *Imperata cylindrica* grassland soils in South Sumatra, Indonesia. *Forest Ecology and Management* 254: 362–370.

Yang L, Liu N, Ren H & Wang J. 2009. Facilitation by two exotic *Acacia*: *Acacia auriculiformis* and *Acacia mangium* as nurse plants in South China. *Forest Ecology and Management* 257: 1786–1793.