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Growth of *Acacia mangium* at Different Stand Ages and Soil Physicochemical Properties in Sarawak, Malaysia

Afifi Nazeri, Ismail Jusoh* and Mohd Effendi Wasli

Faculty of Resource Science and Technology, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

ABSTRACT

The information on soil physicochemical properties is vital for the optimum wood biomass production in forest plantation management. The objective of this study was to determine the topsoil physicochemical properties under different *Acacia mangium* stand ages and their effect on the growth parameters. Five plots were established randomly within each five different stand ages. In all sample plots, the diameter at breast height (DBH) and the total height of standing trees were measured. Soil samples were collected at a depth of 0 to 20 cm at three random points in each plot, then mixed to get a composite before determining physical and chemical properties. DBH mean and the total height of *A. mangium* increased as stand age increased. The mean annual volume increment maximised at the 8.5 years old stand with 27.9 m^3 ha^{-1} yr^{-1}. Survival rate and stem density decreased as stand age increased. Principal component analysis (PCA) results showed that the most important soil physical properties were soil organic matter, silt and sand contents, bulk density, and moisture content. For soil chemical parameters, exchangeable magnesium (Mg), cation exchange capacity (CEC), total carbon (TC), total nitrogen (TN), and carbon-to-nitrogen (C/N) ratio were the influential soil variables. Soil pH, available phosphorus (P), and clay content were negatively correlated with the growth development of *A. mangium* trees. Observations suggest that multiple soil variables are essential for the success of the *A. mangium* plantation.

Keywords: *Acacia mangium* plantation, growth, principal component analysis, soil properties, stand age

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E-mail addresses:
afifinazeri92@gmail.com (Afifi Nazeri)
jismail@unimas.my (Ismail Jusoh)
wmeffendi@unimas.my (Mohad Effendi Wasli)
*Corresponding author

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INTRODUCTION

Acacia mangium is one of the major species used in the timber plantation industry in Malaysia. This species is a unique timber tree in the tropical forest. It is fast-growing, tolerant to poor soil, and can undergo nitrogen-fixing by itself (Lee et al., 2015). Due to better site adaptability and growth performance, more than 85% of the Compensatory Forest Plantation Project (CFPP) area had been planted with *A. mangium* (Hashim et al., 2015). The plantation in Sarawak is established mainly in the central lowland region, which generally comprises elevated wave-cut platforms developed from sedimentary rocks. The central region of the state area is primarily dominated by the red-yellow Podzolic soils (Lee et al., 2015). In forest plantations, this soil type is usually low in the water holding capacity. It has poor infertility that is likely to limit the tree to grow efficiently (Lee et al., 2015). The soil status in the plantation area commonly dictates the type of vegetation planted on the land (Binkley & Giardina, 1998; Bonifacio et al., 2008). Thus, only a few high tolerance tree species can be grown in the plantation areas.

The capability of the soil to store nutrients is vital for the tree to survive. The physicochemical properties of soil support trees stand to grow efficiently and productively in every condition, such as disease susceptibility and harsh weather. The growth and wood quality are also highly influenced by the physicochemical properties of the soil (Rigatto et al., 2004). According to Blake and Hartge (1986), generally, most of the total volume of surface soil consists of 50% solids (45% of soil particles with less than 5% of organic matter) and about 50% of pore space (occupied with water and air).

In forest plantation management, soil quality can be defined as biomass production due to soils capacity (Jamil et al., 2016). Soil provides roots to anchor, grow, contain pore spaces for air, and preventing the plants from becoming waterlogged. It supports the tree stands planted in a high degree of slope and during the harsh weather from collapsing. The physical properties of soil are responsible for the rooting activities, holding the water availability, and easing water absorption by plants. They hold the soil nutrients in exchangeable ions that are available for plant roots to absorb. Soil can also hold a certain amount of oxygen in pore spaces and other gasses (Binkley & Fisher, 2019). Soil chemical properties are also crucial for a plant to survive. The deficiency of certain nutrients in the soil makes them inaccessible and unavailable to the tree. The problem can increase the susceptibility of diseases and insects, leading to infections of the tree. The *Eucalyptus* forest in Mexico had experienced stunted growth due to phosphorus (P) and nitrogen (N) deficiencies in the soil resulting in low biomass production of eucalyptus (Fenn et al., 2006). The addition of phosphorus might contribute to the tree growth, carbon, and nitrogen storage to the litter and woody biomass. It was reported that the application of phosphorus fertilisers to the *A. mangium* stands resulted in an increase in stem diameter and volume at stands between 4 and 5 years old (Hardiyanto & Wicaksono, 2008). Phosphorus also is an essential nutrient which when lacking, will limit tree growth, especially in tropical areas (Zás & Serrada, 2003).

An increasing amount of nitrogen fertiliser in an *A. mangium* plantation in Sumatra, Indonesia, did not affect the growth. This is because there was the nitrogen-fixing ability for this tree species (Hardiyanto & Wicaksono, 2008). Furthermore, additional potassium (K) and calcium (Ca) did not affect diameter growth. They also recorded that applying lime (increasing the soil pH level) and potassium fertilisers to tree stands did not positively affect growth. The leguminous crop plantations, such as *A. mangium*, needs a good P and N in the soil (Bini et al., 2013).

PCA can provide insight to find the main factors affecting the classification of vegetation and soil (Li et al., 2018). This analysis is widely used in many studies to explain the expected effect of soil and vegetation on geography, ecology, forestry, and soil science (Eni et al., 2012). Several researchers had documented the interrelationship of soil and vegetation in rainforest and forest plantation using this analysis approach (Eni et al., 2012; Li et al., 2018; Matali & Metali, 2015; Salehi & Maleki, 2012).

The most effective soil factor on the separation of two Poplar plantations in the north of Iran was also determined using PCA (Salehi & Maleki, 2012). They found the accumulation of clay content, soil organic matter, nitrogen, phosphorus, and potassium in the first axis of PCA, also known as principal component 1 (PC1). The clay content had a positive correlation to PC1. In contrast, the other four soil parameters had a negative correlation to PC1. Eni et al. (2012) studied the mangrove swamp in Tinapa, Nigeria, and analysed PCA soil parameters. They recorded that the soil parameters with the most variation in PC1 were exchangeable sodium (Na) and exchangeable magnesium (Mg). For principal component 2 (PC2) at their study site, they found that soil organic matter (SOM) and total nitrogen (TN) were heavily loaded on the axis to represent the second group, which was the most influenced variation of soil parameters.

In an *A. mangium* plantation in Andalau Forest Reserve, Sungai Liang, Brunei, it was reported that the total N and P have positively associated with PC1. In contrast, soil organic layer depth and exchangeable Ca were negatively associated with the axis (Matali & Metali, 2015). On the other hand, the total Mg, exchangeable K, available P, and gravimetric water content were positively correlated to PC2. Matali and Metali (2015) used PCA biplot to find the association of vegetation parameters to the soil nutrients concentration. They found that pH was the most influential component of the *A. mangium* plantation in Andalau Forest Reserve Brunei.

Previous studies on the effects of soil physicochemical properties on the growth parameters of *A. mangium* stands in natural and planted forest areas have been done in Sarawak by Hardiyanto and Wicaksono (2008), Perumal et al. (2015), and Tanaka et al. (2015). However, information on soil physicochemical properties within a large scale of a commercially planted forest of different stand ages, particularly on *A. mangium*, is still unavailable. This warrant a study to provide information regarding the soil status on *A. mangium* and its relation to growth performance, particularly in Sarawak. Thus, our study aimed to determine the topsoil physicochemical properties at different stand ages of *A. mangium* and their relationship with growth parameters.

MATERIALS AND METHODS

Study Site

The study was conducted at a forest plantation owned by Daiken Sarawak Sdn. Bhd., the Malaysian and Japanese joint venture companies, incorporated on February 15, 1994. The plantation area is located approximately 60 km from the town of Bintulu in Sarawak, Malaysia at 03˚21.347' N and 113°27.129' E and within 30 to 160 m asl (height above mean sea level). The site receives a total annual rainfall of 2749 mm, and the average temperature ranges from 23 °C to 32 °C (Soil Survey Report, 1996). The plantation was originally a secondary forest and was planted with *A. mangium*. In general, the soil type is a well-drained Bekenu series, subgroup Typic Hapludult, Paleudult, Kanhapludult, and Kandiudult characterised by fine, loamy, siliceous, isohyperthermic, and red-yellow to yellow. The main factor restricting the use of this soil is its low fertility status (Paramananthan, 2000). However, the initial soil conditions were considered to be similar for all stands. The terrain was undulating with a slope of less than 6˚ and covered by the same vegetation type. Planting spacing of 3 x 3 m is used, which resulted in 1,111 trees per hectare.

Field Sampling

A chronosequence approach was employed in this study. Five different stand ages, namely, 4.3, 5.8, 8.5, 10.8, and 12.7 years old, were chosen for this study. These stands were selected to represent growth performance spaced about two years apart. A total of five 30 m × 30 m (4,500 m^2) sample plots were established randomly within each of five different stand ages. Thus, a total of 25 plots are assigned to the plantation for this study. At the planting spacing of 3 x 3 m, there were 100 trees initially within a 30 m × 30 m plot size. Thus, the real trees are 500 for each stand age at the time of planting. The DBH of standing trees was measured by using diameter tape (Yamayo, Japan). The top or total height of the standing trees was measured using the trigonometry principle (Philip, 1994). The Suunto clinometer (Forestry Suppliers, Inc., Canada) and rangefinder (Bushnell®, USA) were used to measure a tree's slope and horizontal distance, respectively.

Determination of *Acacia mangium* Tree Growth

Growth is the increasing dimension of each tree in a forest stand for a given time. Growth can be measured by the mean annual increment (MAI) of the tree parameter. MAI is the dimension of a tree over the age of the tree. The basal area of the tree is the cross-sectional area of a tree stem measured at breast height which is 1.3 m from the ground. The geometrical shape of the *A. mangium* tree is considered a cone shape along the tree's stem. The form factor for a conical shape tree is 0.33 (Philip, 1994). Using basal area, total tree height, and form factor of 0.33, total tree volume was calculated as 0.33 multiply by basal area multiply by total tree height. MAI of growth parameters, including DBH, height, basal area, and volume of each tree, were calculated by dividing these parameters by the tree age. Stand density or stocking is calculated by counting the number of trees per ha. The survival rate is calculated by counting the number of trees survived divided by the number of seedlings planted initially and expressed as a percentage.

Determination of Soil Physical Properties

The soil properties of each stand age were determined by collecting soil samples. Each stand age was represented by one plot. Three random points within each selected plot were identified for soil sampling. Soil samples were collected at a 0 to 20 cm depth (topsoil) using a hand auger (Eijkelkamp, Netherland). The field sampling method for soil sampling in all the study plots was adapted from Wasli et al. (2009). The soil samples from each point were mixed to get a composite sample for each soil layer. Particle size distribution was determined using the pipette method (Gee & Bauder, 1986). In this method, the inorganic soil particle was separate into the sand, silt, and clay fractions (Soil Survey Staff, 1999). Soil bulk density was on the 100 cc core sampler (Eijkelkamp, Netherland) with the dry mass ratio to the bulk volume of the soil core. This experiment was carried out by drying the soil samples at 105 °C overnight (Blake & Hartge, 1986). The soil organic matter (%) was determined using the loss on ignition method (Schulte et al., 1991). Soil moisture was determined by the American Society for Testing and Materials (ASTM) D2216-19 (2019) laboratory standard test method. Soil moisture content (%) of each sample was calculated as the ratio of soil moisture to the mass of the oven-dry soil.

Determination of Soil Chemical Properties

Soil pH was measured in distilled water (H_2O) in the soil to a solution ratio of 1:5 using the glass electrode method (denoted as 'pHw' and 'pHk'). Total carbon (TC) content was determined using the loss on ignition method. Total nitrogen (TN) content was determined by Kjeldahl acid digestion using Digesdahl® (USA) and tested with Hach DR/890 Portable Colorimeter (Hash, USA) (Bremner, 1996). The CEC and the contents exchangeable bases (Ca, Mg, K, and Na) were measured after successive extraction (three times) using 1 M ammonium acetate (NH_4-OAc) adjusted to pH 7.0 and 10% sodium chloride (NaCl), respectively (Gee & Bauder, 1986). The concentrations of Ca, Mg, K, and Na were determined with the atomic absorption spectrophotometer (AAS) (Thermo Scientific, Ice Series 3500, USA). Available phosphorus content was measured using the Bray II method (Bray & Kurtz, 1945) with a V-630 ultraviolet-visible (UV) spectrophotometer at a wavelength of 710 nm (JASCO, USA).

Data Analysis

The data of soil physicochemical properties were statistically analysed using one-way analysis of variances (ANOVA) to determine any significant differences between stand ages. Tukey's HSD (honestly significant difference) tests were used to analyse the differences among means. PCA with varimax rotation was performed to identify the variables that accounted for the most variations in the datasets of soil physicochemical properties. PCA was also performed to establish the correlation between soil properties and stand growth parameters. This analysis is used to find the linear combinations of the soil physicochemical properties to make the interpretation of the results easier to be observed. The PCA identifies the principal components (PCs) that are the dominant factors to determine the correlative effect among soil physicochemical properties and between physicochemical properties and growth parameters. PC with eigenvalues of 1.0 or more will be selected for the dominant factors. The PCA is also used to determine the most influential factors of soil physicochemical properties contributing to the growth of different analysis parameters. Finally, the correlation analysis was concluded to determine which variables among the soils physicochemical properties and growth parameters correlate and measure the strength of their associations.

All analyses were conducted using IBM SPSS Statistics 24.0.

RESULTS

Growth Characteristics of *Acacia mangium*

The survival rate and stem density decreased as stand age increased. The mean survival rate and stem density of 3.7 years stand was 60.8% and 676 stem ha^{-1}, respectively, while in the 12.7 years old stand, only 27.4% survived or 304 stem ha^{-1} left standing (Table 1). Mean DBH and the total height of *A. mangium* increased as stand age increased. MAI of volume initially increased with stand age and reached the maximum at 27.9 $m^3 ha^{-1} yr^{-1}$, then it decreased from stand age 8.5 years onwards (Figure 1).

Table 1
Mean of DBH, height, stem density, and survival rate of different Acacia mangium *stand ages*

Stand age (year)	DBH (cm)	Ht (m)	Mean density (stems ha^{-1})	Survival rate (%)
3.7	15.5[a]*	17.6[a]	676[b]	61
5.8	19.4[b]	20.7[b]	473[ab]	43
8.5	26.5[c]	26.3[c]	367[a]	33
10.8	26.9[c]	26.6[d]	324[a]	29
12.7	28.2[d]	27.6[d]	304[a]	27

Note. *Means within the column with the same letter are not significantly different; DBH = Diameter at breast height; Ht = Height

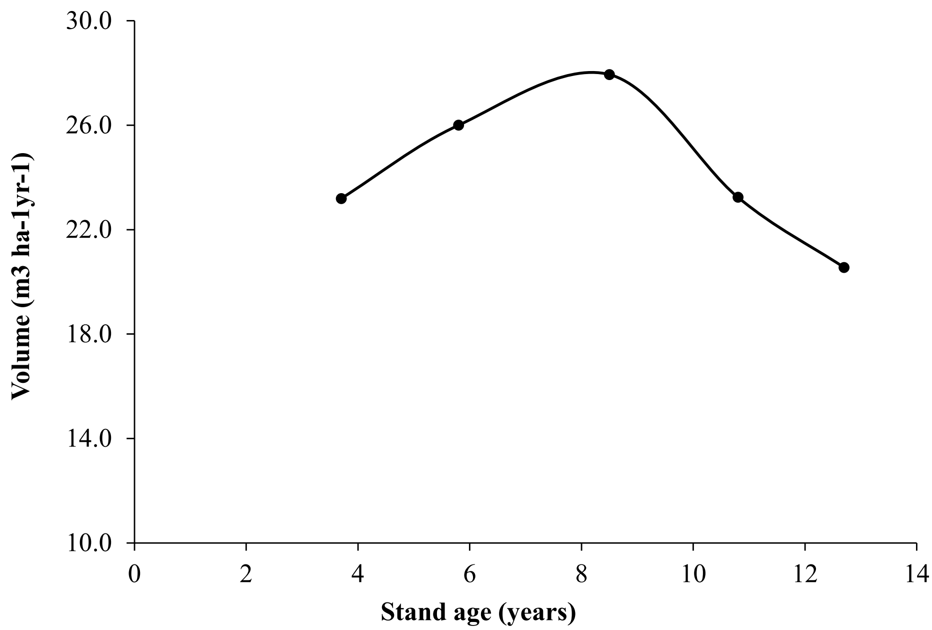

Figure 1. Mean annual wood volume increment of *Acacia mangium* according to stand ages

Soil Physicochemical Properties in Different Stand Ages

Topsoil (0 cm to 20 cm) is the most important layer for plant growth. It consists of O and A horizons containing accumulated humus or organic matter and is available for plant nutrients. Soil physical properties of different stand ages of *A. mangium* plantation are shown in Table 2. Although not significant, there was an increasing trend of SOM with the stand age. Our results indicated that the organic content in the soil increased gradually with age from 5.8 to 12.7 years old stand. The increased level of organic contents in the older stand soil might be influenced by the development of the root mat at the surface horizon (Ishizuka et al*.,* 1998). The soil moisture content ranged from 13.99% to 16.92% and did not differ among the stand ages. The clay, silt, and sand contents range from 24.70% to 28.49%, 13.53% to 19.41%, and 58.55% to 61.95%, respectively, with no significant variation throughout the stand ages.

The soil chemical properties within the topsoil depth in various ages of *A. mangium* plantation are shown in Table 3. We observed that pH values dropped (more acidic) as stand age increased from 4.67 to 3.19. Bulk density in all stand ages was similar in all stand ages except for 8.5 years old stand. The topsoil of 8.5 years old stand recorded significantly low bulk density than the other stand ages.

The CEC values in all study areas were relatively low, ranging from 6.84 to 8.53 cmolc kg^{-1}. The oldest stand of 12.7 years old was observed to have a significantly low CEC value compared to other stand ages except for 3.7 years old stand age. The value of TC and TN content in the planted area appeared to be similar for all stand ages. The TC and TN contents in all stand ages ranged from13.67 g kg^{-1} to 24.16 g kg^{-1} and 0.41 g kg^{-1} to 1.02 g kg^{-1}, respectively. In general, TC and TN values decrease with the increment of stand ages but increase back at 12.7 years old stand age. The C/N ratio was within 30.12 to 41.79, where the values did not differ between stand ages.

Table 2

Soil physical properties within different stand ages of Acacia mangium *plantation*

Stand age (year)	SOM (%)	Moisture content (%)	Clay (%)	Silt (%)	Sand (%)	Bulk density (g mL^{-1})
3.7	3.86±0.61^{ab}	15.11±3.03^{a}	28.49±0.91^{a}	15.92±0.54^{a}	58.55±2.58^{a}	1.55±0.28^{b}
5.8	2.82±0.44^{a}	13.99±3.06^{a}	25.39±2.01^{a}	14.34±1.70^{a}	60.27±3.65^{a}	1.54±0.22^{b}
8.5	2.97±0.32^{a}	16.34±3.03^{a}	24.96±12.20^{a}	13.53±6.32^{a}	61.51±16.37^{a}	0.31±0.12^{a}
10.8	2.35±0.33^{a}	16.25±1.16^{a}	24.70±2.30^{a}	15.65±2.74^{a}	59.65±0.50^{a}	0.73±0.84^{b}
12.7	4.16±1.12^{a}	16.92±1.06^{a}	25.65±4.15^{a}	17.54±1.06^{a}	61.95±5.11^{a}	0.69±0.30^{b}

Note. Means ± standard deviation = Values in the same column followed by different letters indicate significant differences between stand ages at $P < 0.05$ using Tukey's HSD test; SOM = Soil organic matter

Table 3

Soil chemical properties within different stand ages of Acacia mangium *plantation*

Stand age (year)	pH (H_2O)	CEC (cmolc kg^{-1})	TC (g kg^{-1})	TN (g kg^{-1})	C/N ratio	Exch. Ca (cmolc kg^{-1})	Exch. Mg cmolc kg^{-1})	Exch.K (cmolc kg^{-1})	Exch. Na (cmolc kg^{-1})	Available P (mg kg^{-1})
3.7	4.67±0.17^{b}	7.13±0.81^{ab}	22.43±3.52^{a}	0.67±0.25^{a}	37.39±16.04^{a}	1.04±0.65^{a}	0.23±0.99^{b}	0.10±0.35^{a}	0.06±0.01^{a}	12.81±1.96^{b}
5.8	3.66±0.02^{a}	8.53±0.67^{b}	18.38±2.59^{a}	0.60±0.22^{a}	30.63±16.11^{a}	0.28±0.03^{a}	0.17±0.36^{a}	0.10±0.15^{a}	0.06±0.01^{a}	9.00±0.96^{b}
8.5	3.54±0.25^{a}	8.48±0.50^{b}	17.26±1.86^{a}	0.41±0.32^{a}	31.51±9.555^{a}	0.66±0.17^{a}	0.45±0.17^{b}	0.18±0.15^{b}	0.06±0.00^{a}	6.05±0.38^{a}
10.8	3.25±0.11^{a}	7.92±0.82^{b}	13.67±1.88^{a}	0.48±0.45^{a}	28.98±4.83^{a}	0.54±0.41^{a}	0.33±0.59^{b}	0.11±0.21^{a}	0.07±0.01^{a}	8.36±1.11^{b}
12.7	3.19±0.32^{a}	6.84±0.73^{a}	19.15±1.05^{a}	0.80±0.61^{a}	31.39±16.56^{a}	0.42±3.38^{a}	0.22±0.21^{b}	0.11±0.23^{a}	0.05±0.01^{a}	10.17±4.69^{b}

Note. Means ± standard deviation = Values in the same row followed by different letters indicate significant differences between stand ages at $P < 0.05$ using Tukey's HSD test; CEC = Cation exchange capacity; TC = Total carbon; TN = Total nitrogen; C/N ratio = Carbon-to-nitrogen; ratio; Exch. Ca = Exchangable calcium; Exch. Mg = Exchangable magnesium; Exch. K = Exchangable potassium; Exch. Na = Excahangable sodium; Available P = Available phosphorus

The exchangeable Ca and Na mean values among all stand ages were statistically similar. *Acacia mangium* planted areas were observed to have similar exchangeable Mg mean values in all stand ages except for 5.8 years old stand. For exchangeable K, the 8.5 years old stand age topsoil was significantly higher than the other stand ages. The available P mean values in 8.5 years old stand age area was found to be significantly lower than the other stand ages. The available P increased back after 8.5 years old, probably due to the accumulation of P when the *Acacia mangium* stands reached their maturity at 8.5 years after planting. The demand for phosphorus is high during the initial years of plant growth. It decreases in later years due to internal recycling (Fernandez et al., 2000).

Correlation among the Soil Physicochemical Properties

The principal component analysis generated the three most significant principal component scores (PC1, PC2, and PC3), which explains 70.03% of the total variability. Table 4 shows the loading values of the first three principal components. These loadings explain the contribution of each variable in a principal component. Variables with coefficients ≥ ±0.70 were selected and considered significant (Eni et al., 2012). The underline number refers to the variable loads on that component that are significant (coefficients ≥ ±0.70). For example, the first component score, PC1, has five soil physicochemical characteristics that exhibited high positive factor loadings. The parameters included SOM (0.855), TC (0.855), exchangeable Mg (0.805), CEC (0.796), and available P (0.774) that was accounted for 28.14% of the total variance in all parameters.

The second component score, PC2, was loaded heavily with four soil parameters that accounted for 25.27% of the total variance. Two of them exhibit negative factor loadings, which were C/N ratio (-0.899) and sand content (-0.843). In comparison, other two-factor loadings were silt content (0.865) and TN (0.726) that were positive. It is indicated that the C/N ratio and sand content had an inverse effect on silt content and TN in the study area. The third component score, PC3, has three variables that accounted for 16.63% of the total variance parameters. One of them exhibited negative factor loading, which was moisture content (-0.949). At the same time, the rests were bulk density (0.860) and pH (0.704) that were positive. This suggests that soil moisture content is negatively correlated with bulk density and pH level. Overall, PCA results illustrated the basic soil physical properties that significantly influence SOM, silt, sand contents, bulk density, and moisture content. While, for soil chemical parameters, exchangeable Mg, CEC, TC, TN, and C/N ratio were sets of influential soil variables.

The loading plot of PC1 and PC2 were selected to show the degree of intercorrelation and association of the soil physicochemical properties of the study area. Loadings of PC1 and PC2 show that all the components were partitioned inordinate space (Figure 2). In the PC1 vector, soil organic matter and TC were shown to have the farthest point indicating that they had the most significant influence on the soil variables. Exchangeable Mg and CEC also showed that cation retention capacity also significantly affect soil properties.

Table 4
Rotated component of soil physicochemical properties in all Acacia mangium *stand ages*

Soil properties	Principal components		
	1	2	3
SOM	.855*		.400
TC	.855		.400
Exch. Mg	.805		-.332
CEC	.796		
Available P	.774		.381
Exch. Na	.633		-.364
Clay content	.533	.426	
C/N ratio		-.899	
Silt content		.865	
Sand content	.329	-.843	
TN		.726	
Bulk density			.860
Moisture content			-.949
pH			.704
Exch. K	.463	-.318	-.647
Exch. Ca			
Eigenvalues	**4.502**	**4.043**	**2.660**
% Variance	**28.136**	**25.267**	**16.627**
Cumulative explanation	**28.136**	**53.403**	**70.030**

Note. *Variables underlined with eigenvectors (coefficients) ≥ ±0.70 are considered significant; SOM = Soil organic matter; TC = Total carbon; Exch. Mg = Exchangable magnesium; CEC = Cation exchange capacity; Available P = Available phosphorus; Exch. Na = Exchangable sodium; C/N ratio = Carbon-to-nitrogen; ratio; TN = Total nitrogen; Exch. K = Exchangable potassium; Exch. Ca = Exchangable calcium

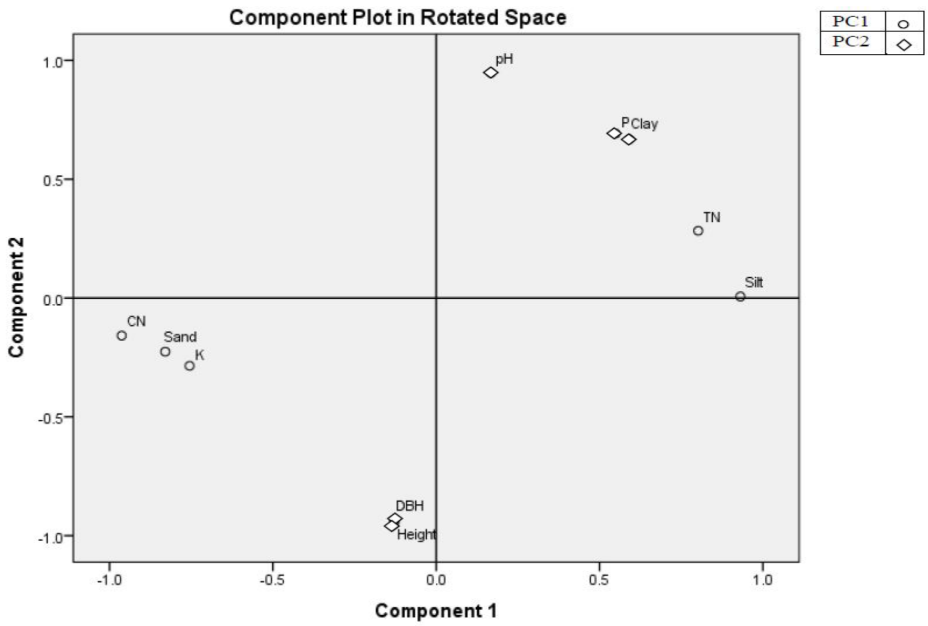

Figure 2. Distribution of soil variables of all stand ages concerning PC1 and PC2

Correlation between Soil Physicochemical Properties and Growth Parameters

The PCA of the physicochemical properties in topsoil (0 cm to 20 cm depth) incorporating stand growth parameters in five different stand ages was performed to determine the association between physicochemical properties and growth parameters (DBH and height). The analysis generated the three most significant principal component scores (PC1, PC2, and PC3), explaining 73.137% of the total variability (Table 5). The first component, PC1, was loaded heavily with five soil physicochemical parameters that accounted for 42.60% of the variation. It exhibited three positive factor loadings, which were C/N ratio (0.961), sand content (0.843), and exchangeable K (0.750). There were two negative factor loading exhibits in PC1: silt content (-0.935) and TN (-0.795).

The second component score, PC2, was loaded heavily with three-factor loadings, consisting of two growth parameters and one soil chemical property that accounted for 17.07% of the variation. In addition, they were stand DBH (0.951), height (0.948), and soil pH level (-0.861). Finally, the third principal component, PC3, was loaded with two soil physicochemical properties that accounted for 13.47% of the variance include TC (0.969) and SOM (0.969).

The soil physicochemical and stand growth parameters in PC1 and PC2 were selected to construct the loading plot in Figure 3. The available phosphorus and clay content in PC2 was also selected as they showed a significant correlation to the growth parameters (Table 5). There was a negative effect on available P and clay content toward DBH and height. This loading plot helped show the degree of intercorrelation and association of those soil physicochemical properties to the growth parameters in the study area. The distance between variables in the loading plot depicted the strength of correlation among variables. The farther the distance represents, the stronger correlation.

Table 5

Rotated component of soil physicochemical properties and growth parameters in all Acacia mangium *stand ages*

Soil and growth parameters	Principal component				
	1	2	3	4	5
C/N ratio	.961*	.117			-.147
Silt content	-.935				-.120
Sand content	.843	.240	.165	-.148	-.146
TN	-.795	-.141	.406	-.132	
Exch. K	.750	.253	.198	.415	-.273
CEC	.657	.130	-.446	.266	.207
Clay content	-.570	-.481	.407	.136	.462
Available P	-.552	-.511	.508		.238
DBH	.165	.951		.150	-.146
Height	.166	.948		.149	-.151
pH (DIW)	-.200	-.861	.354		.189
TC			.969		.171
SOM			.969		.171
Exch. Mg	.196	.285		.877	-.260
Exch. Na		.221	-.325	.863	.125
Exch. Ca		-.479	.308	.730	
Moisture content	-.116	.349	-.111	.169	-.874
Bulk density	-.347	-.116	.415		.811
Eigenvalues	**7.667**	**3.073**	**2.425**	**2.053**	**1.302**
% Variance	**42.593**	**17.074**	**13.470**	**11.407**	**7.236**
Cumulative explanation %	**42.593**	**59.666**	**73.137**	**84.543**	**91.779**

Note. *Variables underlined with eigenvectors (coefficients) ≥ ±0.70 are considered significant; C/N ratio = Carbon-to-nitrogen ratio; TN = Total nitrogen; Exch. K = Exchangable potassium; CEC = Cation exchange capacity; Available P = Available phosphorus; DBH = Diameter at breast height; DIW = Deionised water; TC = Total carbon; SOM = Soil organic matter; Exch. Mg = Exchangable magnesium; Exch. Na = Exchangable sodium; Exch. Ca = Exchangable calcium

In the loading plot, it shows that all the components were partitioned inordinate space. It was observed that the soil pH level, available P, and clay content were correlated. The vast opposite distance between pH, available P, clay content, DBH, and height in the loading plot (Figure 3) revealed that these variables are significantly negatively correlated to the growth parameters. The pH level is observed to have the farthest point from the growth parameters compared to the other soil properties. Hence, the soil pH level has the most significant influence on the DBH and height in the study (Table 5; Figure 3).

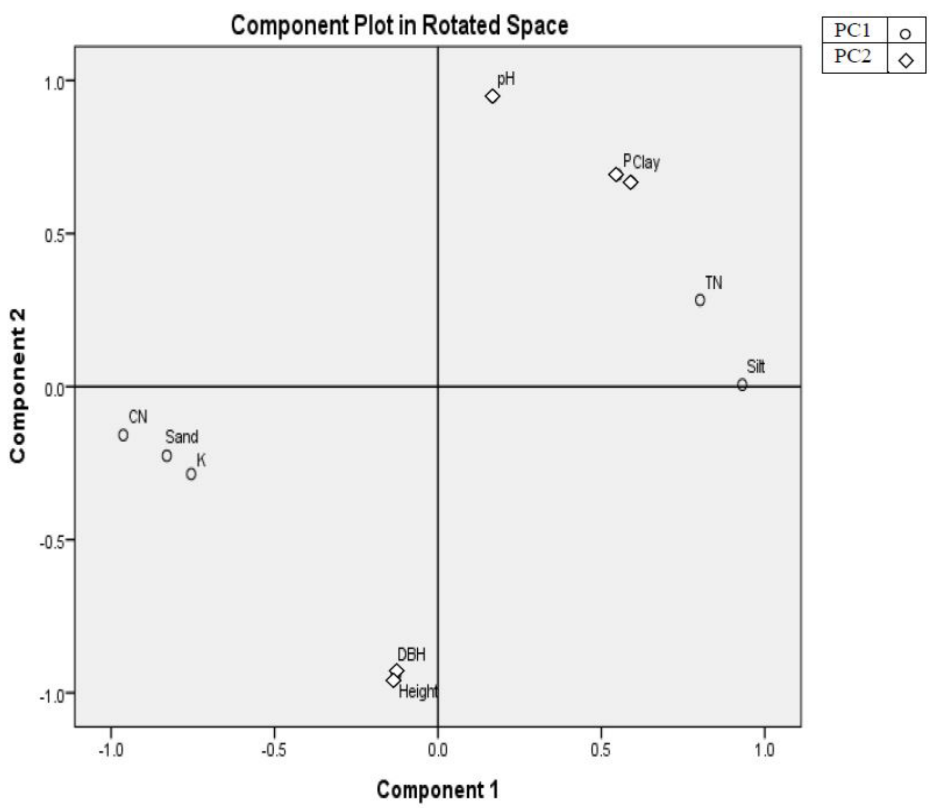

Figure 3. Distribution of soil variables and growth parameters of all stand ages concerning PC1 and PC2

Pearson correlation coefficient was used to determine the correlation among physicochemical properties and growth parameters and measure the strength of the association (Table 6). The result showed the soil pH was strongly ($P < 0.01$) negatively correlated to DBH ($r = -0.852$) and height ($r = -0.848$). Soil available P was also observed to show significant negative correlation ($P < 0.05$) to stand DBH ($r = -0.609$) and height

(r = -0.607). Similarly, clay content was negatively correlated to DBH (r = -0.595) and height (r = -0.597). It suggests that an excessive amount of available P and clay content in the soil might affect DBH and height.

Table 6

Pearson correlation coefficient of soil physicochemical and stand growth parameters

Parameters	DBH (cm)	Height (m)
DBH (cm)	1.000	
Height (m)	1.000	1.000
pH	-0.852**	-0.849**
SOM (%)	-0.100	-0.100
TC (g kg-1)	-0.100	-0.100
TN (g kg-1)	-0.280	-0.282
C/N ratio	0.307	0.308
CEC (cmolc kg-1)	0.189	0.182
Exch. Ca (cmolc kg-1)	-0.305	-0.300
Exch. Mg (cmolc kg-1)	0.479	0.479
Exch. K (cmolc kg-1)	0.431	0.430
Exch. Na (cmolc kg-1)	0.303	0.300
Available P (mg kg-1)	-0.609*	-0.607*
Clay (%)	-0.595*	-0.597*
Silt (%)	-0.172	-0.173
Sand (%)	0.372	0.375
Bulk density (g mL-1)	-0.291	-0.293
Moisture content (%)	0.439	0.441

Note. **Correlation significant at $P < 0.01$. *Correlation significant at $P < 0.05$; DBH = Diameter at breast height; SOM = Soil organic matter; TC = Total carbon; TN = Total nitrogen; C/N ratio = Carbon-to-nitrogen ratio; Exch. Ca = Exchangable calcium; Exch. Mg = Exchangable magnesium; Exch. K = Exchangable potassium; Exch. Na = Exchangable sodium; Available P = Available phosphorus

DISCUSSION

The DBH and height of *A. mangium* increased with age, suggesting the robustness of *A. mangium* growing rapidly and continuously in a plantation but up to a certain age as the growth decreased after 8.5 years old. It is normal to see the high growth rate of *Acacia* trees at an early age then diminish at a later age. Growth rates of *Acacia* tree are very rapid at a young age and begin to slow down after the fifth or after 8 years (Krisnawati et al., 2011). The same goes for stand basal area and volume per ha of *A. mangium* as the tree increased with stand age; however, after 8.5 years, it started to decrease (Heriansyah et al., 2007). Lee et al. (2015) stated that the growth rate of *A. mangium* would decline rapidly at 7 or 8 years after planting. Our results also showed that 8.5 years old stand recorded the maximum growth rate. The growth of *A. mangium* levels off after 8.5 years of planting.

MAI reported in this study is relatively low compared to other studies due to the form factor used to calculate tree volume, which was 0.33. It was reported that the total standing volume of *A. mangium* in Sarawak was 177.40 m^3 ha^{-1} with MAI of 26 m^3 ha^{-1} yr^{-1} at a stand age of 7 years. The estimated productivity of 7 years old *A. mangium* plantation in Planted Forest Zone in Bintulu was 185 - 229 m^3 ha^{-1}. It averaged at 205 m^3 ha^{-1} to 8 cm top diameter with MAI at 29 m^3 ha^{-1} yr^{-1} (Gardner, 2009). The regular growth rate of *A. mangium* in Sumatra, Indonesia, ranged between 22 m^3 ha^{-1} yr^{-1} and 35 m^3 ha^{-1} yr^{-1}, depending on stand age (Harwood & Nambiar, 2014).

The organic matter within the soil is essential for soil and its overall health as it is accumulated with a large number of nutrients, moisture, and assistive bio-organisms (Bot & Benites, 2005). It helps the soil properties be in good condition to store the nutrients and water available for the tree to grow efficiently. The soil chemical variables, such as TC, exchangeable Mg, CEC, and available P, are also essential components in soil properties of the different stand ages. The soil TC is essential for *A. mangium* plantation as it is the main component of stand wood biomass (Nykvist & Sim, 2009). The CEC and exchangeable bases in the soil are directly proportional to the soil organic matter and clay content (Berry et al., 2007). The electrical charges in the soil influence the soil ability to hold the nutrients and provide buffering against soil acidification. The soil nutrients primarily exist as cations, which may increase soil fertility (McKenzie et al., 2004). Available P is essential for the growth of the stand as the lack of P element within the soil properties will result in an adverse effect on the growth and productivity, especially for leguminous plant type in tropical rainforest (Bini et al., 2013; Majid & Paudyal, 1999; Zás & Serrada, 2003).

Sand content was observed to significantly negatively affect the silt content and TN, which indicated that the soil's high amount of sand content would reduce silt content and nitrogen concentration in the study area. Soil properties dominated by high sand content lack nutrients, particularly nitrogen (Binkley & Fisher, 2019). Nath (2014) stated that the sand content is also negatively correlated to the water holding capacity in growing soil in Sivasagar, India. The negative association of moisture content to pH level suggested that high water content might increase the soil's acidity. It is inconsistent with Zhang and Wienhold (2002), which recorded that the high moisture content level will significantly alter the pH level to be higher in corn post-cropped soil.

Several soil characters may affect stand growth parameters (stand DBH and height). Results from correlation analysis and PCA were consistent regarding the negative effect of pH, available P, and clay content toward DBH and height. Soil pH showed it is the essential variable correlated to DBH and height. It indicates that the more acidic the soil, the greater the DBH and height (Figure 3). The pH values in *A. mangium* plantation in Andulau Forest Reserve, Sungai Liang, Brunei Darussalam ranged between 3.8 to 4.1 and is the most influential variable (Matali & Metali, 2015). The high density of litter and wood biomass within the older stands area might contribute to the high rate of nitrification leading to acidification. Soil pH reduction in the older stands could be related to vegetative coverage, which then caused extensive secretion of organic acids associated with accelerated organic matter decomposition (Lee et al., 2015).

Soil pH below 5.0 is ordinarily toxic to plant growth. Nutrient toxicity can occur in acid soils when the pH is 4.8 and lower due to aluminium (Al) and manganese (Mn) become more available in the soil solution and are harmful to plant roots (Slattery et al., 1999). However, *A. mangium* can survive well in acid soils, and the optimum soil pH range is 4 to 6 (Arentz et al., 1995). This tree species adapted well to acidic soils and grows satisfactorily in soils even with pH less than 4.0 (Franco & de Faria, 1997; Midgley & Turnbull, 2003).

Available P and clay content were shown to negatively correlate with DBH and height, suggesting that a high level of available P and clay can adversely affect the DBH and height growth rates. These results corroborate with Nurudin et al. (2013), stating that increased P adsorption negatively affects *Acacia* growth. An increase in P concentration resulted in a decrease in soil respiration under *A. mangium* plantation (Cao et al., 2011), indicating little or no aerobic microbial activity in the soil, resulting in poor growth. Clay has been shown to inversely correlate with Poplar plantation height growth (Salehi & Maleki, 2012). High clay content had been shown to cause limited root penetration and absence of *Acacia* fine roots (Kadir et al., 1998), thus limit tree growth. It was also reported that higher clay content correlates with low TC content (Nurudin et al., 2013), which negatively impacted wood productivity.

The results of this study can assist the plantation manager in the decision-making process in managing commercial *A. mangium* plantations. This study demonstrated that soil physical and chemical properties are vital in understanding the health condition of a plantation. Determining soil properties will ultimately help managers manage planted forests effectively because the soil physicochemical properties available for tree growth are affected by management practices that include site preparation plantation establishment, silvicultural treatment, and harvesting systems.

CONCLUSION

The growth rate of the *Acacia mangium* tree is very rapid at the early stage but slowed down as it gets old. Tree DBH, total height, basal area, and volume increased as stand age increased. However, the survival rate and mean annual increment decreased with age. The stand growth and yield culminate at the age of 8.5 years old. Information of the soil physicochemical properties status in forest plantation areas of various age stands is vital to understand the growth performance of the *A. mangium* plantation. The PCA analyses showed that the physical soil properties that are most influential were SOM, silt and sand contents, bulk density, and moisture content, while for chemical parameters, exchangeable Mg, CEC, TC, TN, and C/N ratio. In general, soil pH, available P, and clay content showed the most variables. They are significantly negatively correlated to DBH and height of *A. mangium* stand. The PCA helped to reveal some relationships between some soil properties and stand parameters. These results help broaden the understanding of the interrelationship and association of soil properties on the growth parameters of *A. mangium* plantation.

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