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Growth of *Dryobalanops beccari* Dyer in Restored Forest and Influences in Soil Properties in Sarawak, Malaysia

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ABSTRACT

Forest restoration through enrichment planting may, in the long term, substantially enhance the soil productivity. The time for a forest to be restored depends on productivity of the tree species and treatments applied during the planting process. Throughout the forest restoration period, planted tree species growth may either positively or negatively affect the soil condition. Thus, it is essential to study the relationship between the changes in soil properties and growth rate of trees at different ontogenetic phases in a rehabilitated forest. Observation on D. beccarii showed tree height growth rate increasing rapidly at the early stage, followed by apparent bulking up in stem diameter in 9–year–old stand. The higher tree density in 14–year–old stand contributes to high LAI value. The expansion of canopy size was rapid in 20–year–old stand. Tree height showed sigmoid growth pattern, while growth rate of stem diameter, canopy size, and LAI were still constantly increasing up to 20 years. The soil pH level in all tree stands became less acidic while bulk density and soil moisture content were decreased as the tree age increased. Except for exchangeable Mg and Ca, significant reduction ($P<0.05$) in soil total N, available P, and exchangeable K were observed in the older stands. In 20 years, D. beccarii stand was able to reduce soil acidity as well as increase exchangeable Mg and Ca despite the loss of soil total N, available P, and exchangeable K.

Keywords: Dryobalanops beccarii, forest restoration, ontogenetic phase, selected soil properties, tree growth rate

INTRODUCTION

Forest is a major source of subsistence that is essential for the survival and well–being of humankind by providing a wide range of economic, social, health, and environmental goods and services (Agrawal *et al*. 2013; Fritz–Vietta 2016). Besides human benefits, forest is also important in preventing soil erosion, formation of topsoil, and functionally serve as carbon sink (Wittmer & Gundimeda 2012). At present, forest covers approximately 31% of the world's land area, which consists of primary and relatively undisturbed forests. However, forest cover is being rapidly degraded as 13 million ha of forest are being cleared each year in order to make way for land use and human settlements and other land uses (FAO 2010).

Forest degradation leads to disruption of natural forest ecosystems, which adversely affects the changes in soil chemical and biological properties (Islam & Weil 2000; Chakravarty 2012). In terms of chemical properties, soil degradation is described either as acidification, salinization, nutrient depletion, reduction of cation exchange capacity (CEC), increased Al or Mn toxicities, Ca or Mg deficiencies, or leaching of nitrate or other essential plant nutrients (Lal 2015). The degradation of soil is severe in the tropics and sub–tropics (León & Osorio 2014). It has been reported that accelerated soil degradation affected approximately 500 million ha of land in the tropics (Lamb *et al*. 2005). The vast coverage of soil degradation would negatively impact agronomic production and eventually dampen economic growth, especially in countries where agriculture is one of the main sectors of economic development (Scherr 2001).

In order to reduce the severity of soil degradation, there have been efforts to improve the soil condition by restoring the degraded forest. Forest restoration was carried out to return the degraded forest land back to a condition dominated by trees through different methods and technologies (Stanturf *et al*. 2012). In Malaysia, recovering degraded forests have been successfully implemented under several forest restoration programs such as the ecosystem rehabilitation using enrichment planting technique in Sarawak (Ishizuka *et al*. 2000) and Peninsular Malaysia (Arifin *et al*. 2008; Affendy *et al*. 2009). These forest rehabilitation projects emphasized the planting of indigenous tree species especially Dipterocarps. The efforts focused mostly on improving the soil conditions (physical, chemical, and biological), seed preservation, hybridization, and enrichment planting (Daisuke *et al*. 2013; Thomas *et al*. 2014).

Various studies have been conducted on the effect of tree growth on different soil properties (physical, chemical, and biological) in the restored forest (Krzic *et al*. 2009; Arifin *et al*.

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2010; Holubík *et al*. 2014). In the tropical forest of Brazil, Amazonas *et al*. (2011) found that improvement of N cycling was achievable through ecological restoration. Akbar *et al.* (2010) reported that rehabilitation of tropical forest resulted in increased macro nutrients (P, K, Ca and Mg) as compared to the nearby natural forest. However, studies on the effect of tree growth at different ontogenetic phases of soil physical and chemical properties are still limited. In the current study, *Dryobalanops beccarii* Dyer was used as this species was planted at the different times over 20 years of continuous restoration project in Sarawak, Malaysia. This enabled chronosequence assessment of *D. beccarii* growth over a period of 18 months in the multi–cohort stands to test the hypothesis that tree has sigmoidal growth. The current study also assessed changes in selected soil physical and chemical properties over 18 months in different stand ages to establish relationship between tree growth and soil properties.

METHODOLOGY

Study sites and sampling

The study site is located in the UPM–Mitsubishi forest restoration area in the UPM Bintulu Sarawak Campus, Sarawak, Malaysia (3°12'N, 103°04'E) as shown in Figure 1. The site is situated at 60–110 m above sea level with mean annual rainfall of 2,327 mm. The soil is classified as Isohyperthermic Typic Dystropept known as Nyalau soil series (Ong *et al*. 2012). The forest area covers approximately 47.5 ha.

Universiti Putra Malaysia (UPM) and the Yokohama University of Japan conducted a research partnership since 1990 with financial support from the Mitsubishi Corporation, Japan to restore an abandoned or degraded area (Ong *et al.* 2012). This project adopted Prof. Akira Miyawaki's ecological technique to create a multiple species natural forest using indigenous tree species from the nearby forests (Miyawaki 1999). Selection of tree species used for planting was based on vegetation analyses of nearby areas. The degraded area was cleared and seedlings were densely planted with at least two seedlings in one square meter Soil surface was then covered with thick mulch after planting without application of any fertilizer.

Four different age group stands were selected, *i.e.* newly planted 5 years old, 6–10 years old, 11–15 years old, and more than 16 years old. The study plots were established where *D. beccarii* was previously planted, *i.e.* P20, plot of 20 years old (established in 1992) located in Phase II and P1, P9 and P14, plots aged 1, 9, and 14 years old, respectively (established in 2011, 2003, and 1998) located in Phase IV of the restoration project area (Table 1). Size of each plot was 30 × 10 m. At each study plot, four seedlings (P1), saplings (P9 and P14), and mature trees (P20) of *D. beccarii* were selected for the study.

Table 1. Plot location and its establishment year.

Phase	Plot	Coordinate	Year of Estab-lishment	Stand Age	Stand Density (ha^{-1})
II	P20	3°12'46.28"N, 113° 3'47.28"E	1992	20	2,000
	P14	3°12'43.93"N, 113° 4'29.50"E	1998	14	2,400
IV	P9	3°12'46.93"N, 113° 4'28.57"E	2003	9	1,600
	P1	3°12'52.45"N, 113° 4'28.04"E	2011	1	3,200

Tree morphology

Measurement of tree growth was performed every six months for 18 months. Tree height (total height and merchantable height) and canopy depth for seedlings P1 were measured using a ruler, while trees in P9, P14, and P20 were measured using the trigonometric method (West 2015). The canopy diameter was measured using average crown spread (Blozan 2006). Measurement of diameter at breast height (DBH) for trees in P9, P14, and P20 was done at 1.3 m from the ground level using a diameter tape, while stem diameter for seedlings in P1 was done slightly above the collar root using digital caliper. The Leaf Area Index (LAI) of each tree and sapling was determined using the HEMIv9 equipped with 180° fisheye lens and a high resolution digital SLR CMOS camera and the images taken were analyzed using the HEMIv9 software.

Soil study

Soil study was conducted twice. This involved collection of soil samples 1 m from each tree and saplings at two different depths (0–15 cm and 15–30 cm) for analysis of pH, moisture content, bulk density, and nutrient contents (total N, available P, exchangeable K, exchangeable Mg, and exchangeable Ca). Four soil samples of different depths were collected, allowed to dry, grounded into fine powder, and stored at room temperature. Soil bulk density was determined using core method (Blake 1965). Soil pH was determined by mixing 5 g of air–dried soil with 10 mL distilled water. The solution was left overnight to allow the soil to settle and the clear solution was tested using calibrated

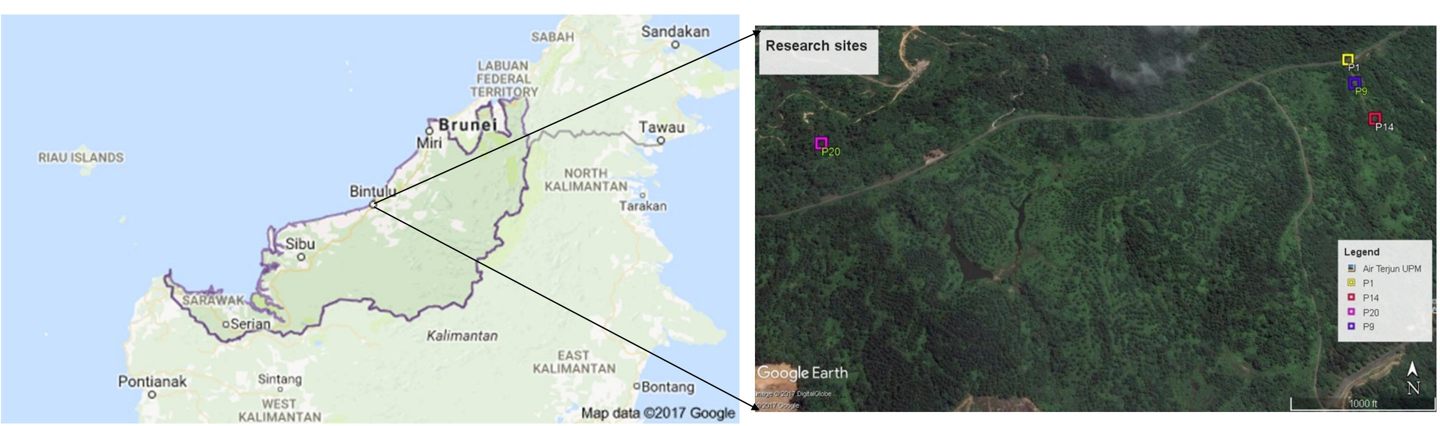

Figure 1. Site location of research plots (red box – P20; white – P14; blue – P9; yellow – P1)

Toledo® pH Meter (Hendershot 1993). Soil moisture content was determined by placing 10 g of air–dried soil in a crucible and oven–dried at temperature 105°C for 24 hours. Soil moisture percentage was calculated as the percentage of weight loss of moist soil over weight of dried soil (Peters 1965). Total N was determined using Kjeldahl method (Bremner 1965) and analyzed using AutoAnalyzer 3 HR (Seal Analytical, Mequon, WI). Available P was determined using Double Acid Method (Tan 2005) and analyzed using AutoAnalyzer 3 HR. Exchangeable cations (K, Ca, and Mg) were extracted using Double Acid Method (Tan 2005) and were determined using Atomic Absorption Spectrophotometer (AAS Analyst 800, Perkin Elmer Instruments, Norwalk, CT).

Data analysis

The differences between the mean values were evaluated using a one–way analysis of variance (ANOVA). Comparison among the means was performed using the Tukey's test and t–Test, calculated at $P<0.05$. Growth models were used in order to determine the most fitted and accurate model on each tree morphology parameter and selected soil properties related with age. The models were tested via Linear and Non–Linear (NLIN) procedures. Statistical analysis was performed using SAS for Windows Version 9.3. The relationship between the tree morphology parameters and selected soil properties was tested using Pearson correlation.

RESULTS AND DISCUSSION

Tree growth

Tree growth increased constantly with stand age of *D. beccarii*. Height of *D. beccarii* showed a sigmoid growth pattern while growth of stem diameter, canopy size, and LAI increased continuously up to 20 years (Figure 2). Each parameter fits a model with high R^2 value as shown in Table 2.

From the observation, P9 and P20 recorded higher total height growth rate than P1 and P14 in the 1st half year. In the 3rd half year, total height growth rate was significantly higher in P1 ($P<0.05$) than other *D. beccarii* stands (Table 3). Comparison between half yearly observations showed that P20 recorded the highest total height growth rate in the 1st half year, while P1 recorded the opposite trend in the 3rd half year. Merchantable height growth rate of *D. beccarii* in P1 and P9 was significantly higher ($P<0.05$) compared to P14 and P20 in the 3rd half year (Table 3). Only *D. beccarii* in P1 recorded significant merchantable height changes ($P<0.05$) between half yearly observations, where the highest value was recorded in the 3rd half year (Table 3). Stem diameter growth rate of *D. beccarii* was the highest in P20 during the 1st half year and P9 during the 3rd half year (Table 3). Comparison between half yearly observations showed that P1 and P9 recorded significant changes ($P<0.05$) in the 3rd half than in the 1st and 2nd half year (Table 3).

Canopy depth growth rate in P1 and P9 were lower than in P14 and P20 in the 1st half year (Table 3). In the 3rd half year, P20 recorded significantly lower ($P<0.05$) canopy depth growth rate than the other stands. Between the half yearly observations, P20 showed significantly higher ($P<0.05$) canopy depth growth rate in the 1st half year than 2nd and 3rd half year observations, while P1 and P9 showed the opposite trend with the highest canopy depth growth rate in the 3rd half year (Table 3).

The observation in 1st half year revealed that canopy diameter growth rate in P14 and P20 was significantly higher ($P<0.05$) than in P1 and P9. The 2nd half year observation shows only P9 recorded significant ($P<0.05$) canopy diameter growth rate among the stands (Table 3). The half yearly observations showed canopy diameter growth rate of P1 was the highest in the 3rd half year, P9 was the lowest in the 1st half year, and P14 was the lowest in 2nd half year (Table 3). LAI for P1 was measured only in the 18th month. Comparison between half yearly observations shows that LAI of *D. beccarii* in P9 and P20 was significantly higher in the 1st half year as compared to other half year observations (Table 3).

Soil properties

Soils in the study plots were acidic (Figure 2). The relationship between soil pH and the stand age was high with $R^2=0.99$ (Table 2). Soil pH increased over time except in P9 (15–30 cm) and P14 (0–15 cm and 15–30 cm) (Table 4). Bulk density decreased with time. The relationship between bulk density and stand age was strong with $R^2=0.99$ (Table 2). Both soil pH and bulk density showed no significant difference ($P<0.05$) between different depths or *D. beccarii* stands with the same depth. The relationship between soil moisture content and stand age was significant with $R^2=0.98$ (Table 2). Comparison between the depth (0–15 cm) as well as between *D. beccarii* stand showed P1 recorded significantly lower ($P<0.05$) moisture content than other stands (Table 4).

Soil total N, available P, and exchangeable K decreased with stand age (Figure 3). Stand age showed strong relationship with total N and available P, $R^2=0.99$, and exchangeable K, $R^2=0.98$ (Table 2). The increment of total N increased except in P1 (0–15 cm), P14 (0–15 cm), and P20 (15–30 cm). However, there was

Table 2. Regression model and coefficient of determination for tree morphology and soil properties.

Parameter	Regression model	Coefficient Of Determination, R^2
Tree Morphology		
Total height	$14.888/(1+e^{3.636-0.352Stand\ Age})$	0.99
Merchantable height	$9.6359/(1+e^{3.7884-0.3233stand\ Age})$	0.99
Stem diameter	$50.75(1-e^{-0.00273Stand\ Age})^{1.547}$	0.99
Canopy depth	$13500e^{-e^{2.8565-0.015Stand\ Age}}$	0.99
Canopy diameter	$13325.2e^{-e^{2.8512-0.015Stand\ Age}}$	0.98
Leaf Area Index	$3.3686/(1+e^{2.1575-(0.161Stand\ Age)})$	0.98
Selected Soil Properties		
Soil pH	$4.959(1-e^{-0.66Stand\ Age})^{0.1335}$	0.99
Moisture Content	$-0.00615Stand\ Age^2+0.1067Stand\ Age+2.13$	0.99
Bulk Density	$-3.797(1+e^{-1.5688Stand\ Age})^{-0.412}$	0.98
Total Nitrogen	$4.0787e^{4.0787(-0.0207Stand\ Age)}$	0.99
Available Phosphorus	$-0.1042^{Stand\ Age}+12.29$	0.99
Exchangeable Potassium	$5.2e^{-0.02Stand\ Age}$	0.96
Exchangeable Magnesium	$19.85(Stand\ Age^{0.0541})$	0.99
Exchangeable Calcium	$-0.01(Stand\ Age^2)+0.5156StandAge+1.2589$	0.98

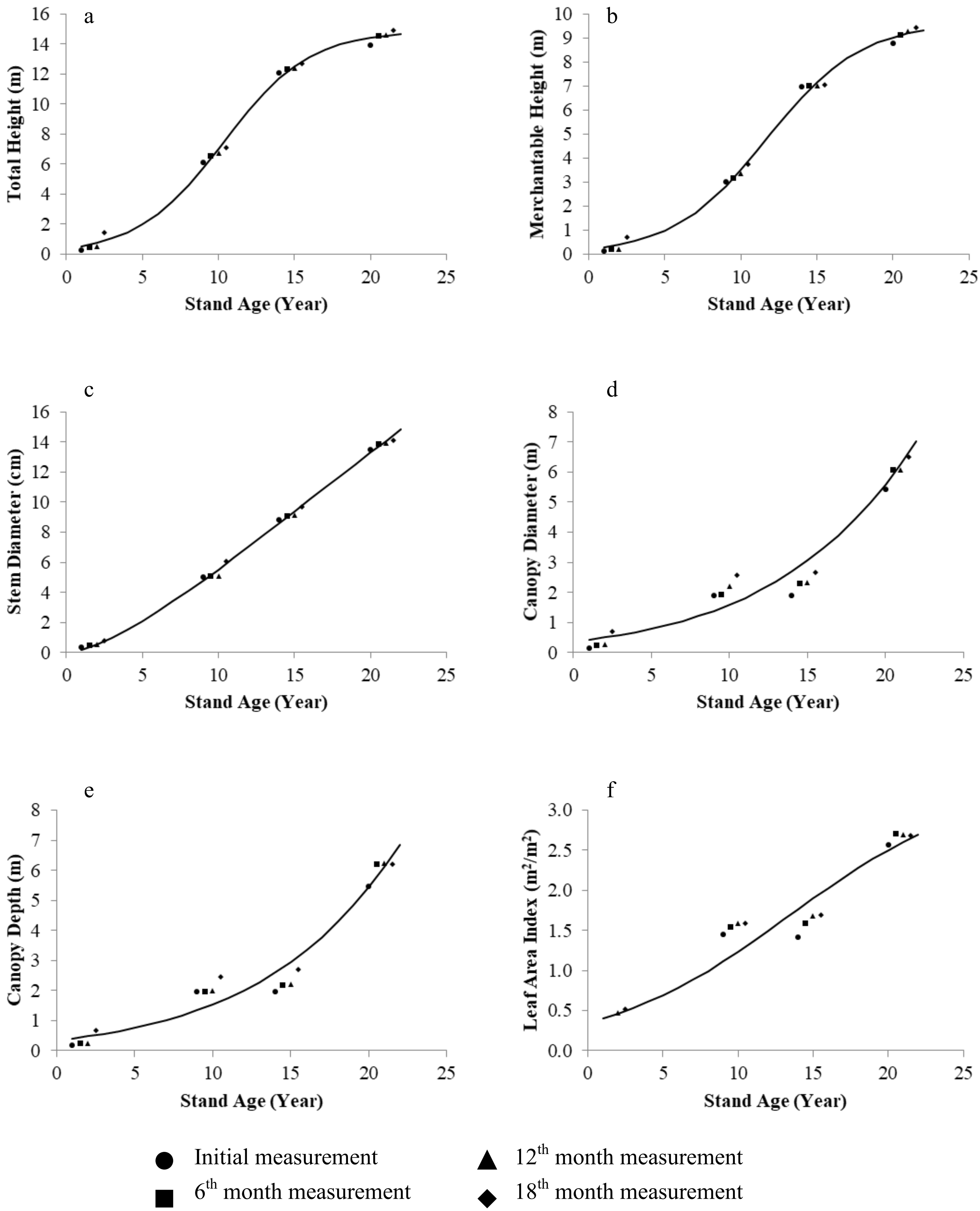

Figure 2. Relationship between tree morphological parameters and *Dryobalanops beccarii* stand age

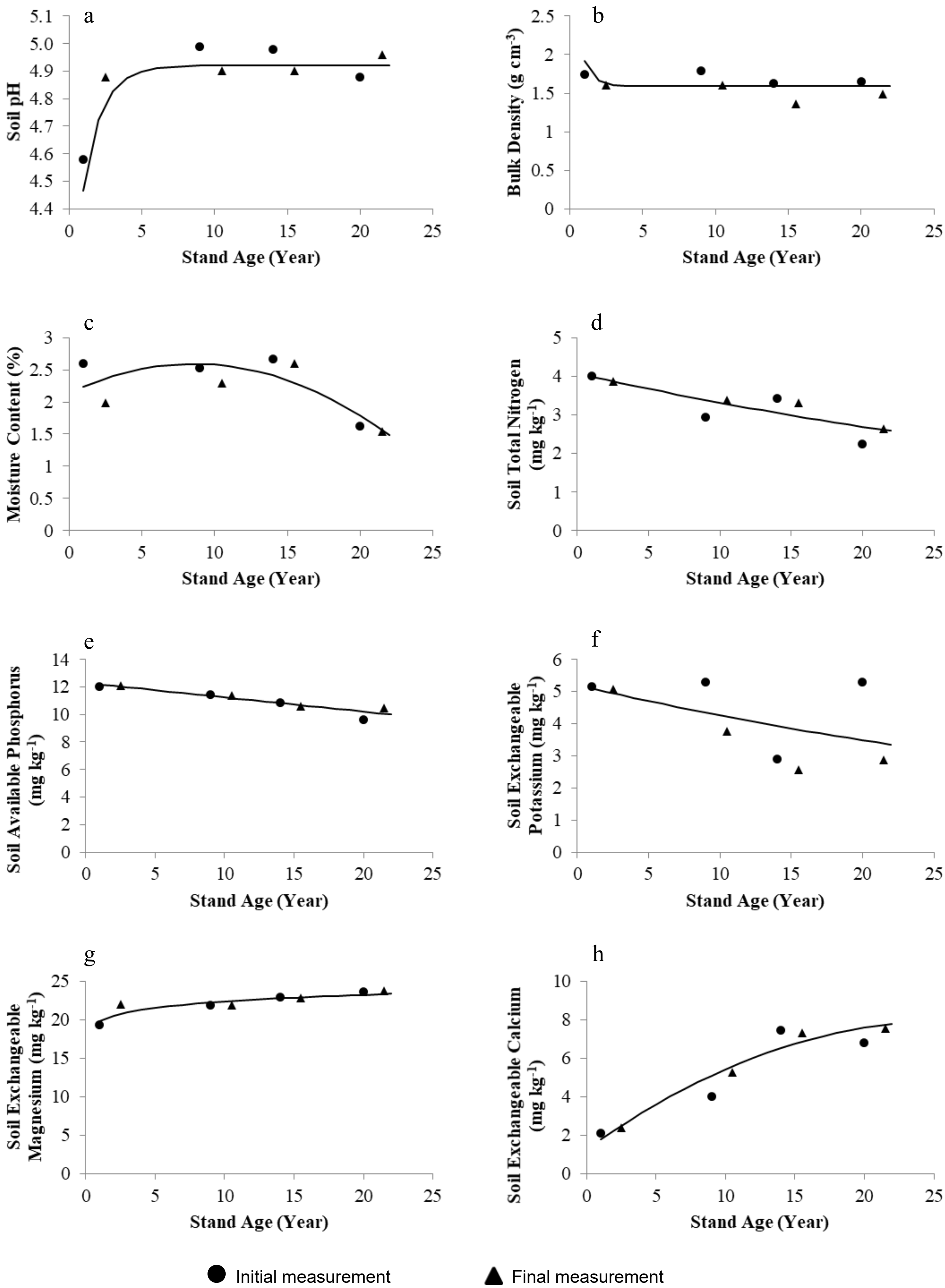

Figure 3. Relationship between soil properties and *Dryobalanops beccarii* stand age

Table 3. Growth rate of tree morphological properties.

Tree Morphology	Half Yearly Observation	Plot			
		P1	P9	P14	P20
Total Height (m mth^{-1})	1st	0.007^{2b}	0.075^{1a}	0.038^{12ab}	0.098^{1a}
	2nd	0.007^{2a}	0.027^{1a}	0.012^{2a}	0.017^{2a}
	3rd	0.160^{1a}	0.058^{1b}	0.052^{1b}	0.050^{2b}
Merchantable Height (m mth^{-1})	1st	0.005^{2a}	0.025^{1a}	0.005^{1a}	0.055^{1a}
	2nd	0.002^{2a}	0.030^{1a}	0.005^{1a}	0.025^{1a}
	3rd	0.078^{1a}	0.067^{1a}	0.005^{1b}	0.025^{1b}
Stem Diameter (cm mth^{-1})	1st	0.003^{2b}	0.007^{2b}	0.047^{12ab}	0.070^{1a}
	2nd	0.003^{2a}	0.007^{2a}	0.003^{2a}	0.008^{2a}
	3rd	0.042^{1c}	0.160^{1a}	0.093^{1b}	0.027^{12c}
Canopy Depth (m mth^{-1})	1st	0.007^{2b}	0.005^{2b}	0.033^{12ab}	0.123^{1a}
	2nd	0.002^{2a}	0.005^{2a}	0.007^{2a}	0.003^{2a}
	3rd	0.073^{1a}	0.073^{1a}	0.080^{1a}	0.002^{2b}
Canopy Diameter (m mth^{-1})	1st	0.003^{2b}	0.010^{2b}	0.063^{1a}	0.108^{1a}
	2nd	0.007^{2b}	0.045^{1a}	0.007^{2b}	0.002^{2b}
	3rd	0.072^{1a}	0.058^{1a}	0.057^{1a}	0.072^{12a}
Leaf Area Index (m^{2} m^{-2} mth^{-1})	1st	.	0.017^{1a}	0.022^{1a}	0.023^{1a}
	2nd	.	0.007^{2a}	0.017^{12a}	0.002^{2a}
	3rd	0.017*	0.007^{2a}	0.002^{2a}	0.002^{2a}

–Growth rate represented by superscript lowercase alphabets indicate significant difference in measurement between D. beccarii of different ages (P1, P9, P14, and P20) by Tukey's test.
–Growth rate represented by superscript numbers indicate significant difference in measurement between observations by Tukey's test.

no difference in total N increment with variation between –12.87 to 18.28% (Table 5). Soil available P revealed significant difference (P<0.05) between depths in P20. At the soil surface, P20 recorded 17.42% increase, while P14 recorded 8.66% reduction in available P. This variation resulted to significant differences between both stands. At a deeper soil level, positive increment was recorded by P14 and P20 while reduction was recorded in P1 and P9 (Table 5). Soil exchangeable K recorded positive increments in P1 and P9, both at 15–30 cm soil layer, while others showed reduction, with P9 (0–15 cm) and P20 (0–15 cm and 15–30 cm) with the most reduction (Table 5). Significant differences (P<0.05) were observed between soil layers in P9 (Table 5).

The soil exchangeable Mg and Ca increased as the *D. beccarii* stand aged (Figure 3). Both soil exchangeable Mg and Ca showed strong relationship with the stand age, with R^2=0.99 and R^2=0.98, respectively (Table 5). From the observation, soil exchangeable Mg increment in P1 was significantly higher (P<0.05) than other *D. beccarii* stand of different ages. The most reduction of exchangeable Mg increment was recorded in soil surface of P9 and 15–30 cm depth soil in P14 (Table 5). Concentration of exchangeable Ca at the soil surface was reduced except in P20 (Table 4). Thus, significant differences (P<0.05) was found between *D. beccarii* of different ages at the soil surface (Table 5). At the lower soil layer, P9 recorded significantly larger (P<0.05) increment compared to P14 and P20 (Table 5). Significant differences (P<0.05) were also observed between soil layers in P1, P9, and P14 (Table 5).

Correlation between tree morphology and soil properties

In Table 5, three out of the eight soil properties showed significant (P<0.01 and P<0.05) correlation with tree morphological parameters. The tree morphology was positively correlated among each other with high significance at P<0.01 (Table 6). Total N and available P (except canopy size) were negatively correlated with all tree morphological parameters (Table 6). Meanwhile, exchangeable Ca was positively correlated with the tree morphological parameters (Table 5). The correlation among the soil nutrient content showed available P was positively correlated (P<0.01) with total N (Table 6). The exchangeable Mg was positively correlated with the soil pH (P<0.01), but showed opposite result for total N (P<0.05) and available P (P<0.01) (Table 6). In Table 6, the exchangeable Ca showed positive correlation with Mg (P<0.01), but negatively correlated with available P (P<0.01) and exchangeable K (P<0.05).

Table 4. Soil physical properties of *D. beccarii* at different ages and two soil depths.

Age	Depth (cm)	Soil pH		Bulk Density (g cm^{-3})		Moisture Content (%)	
		Initial	Final	Initial	Final	Initial	Final
P1	0–15	4.65^{1aA}	4.98^{1aA}	1.69^{2aA}	1.55^{2aA}	2.88^{1aA}	1.91^{1abA}
	15–30	4.50^{1bA}	4.78^{1aA}	1.80^{1aA}	1.64^{1aA}	2.39^{1aA}	2.07^{1abA}
P9	0–15	5.03^{1aA}	5.07^{1aA}	1.65^{2aA}	1.48^{2aA}	2.43^{1aA}	2.51^{1aA}
	15–30	4.96^{1aA}	4.73^{1aA}	1.92^{1aA}	1.71^{1aA}	2.10^{1aA}	2.12^{1abA}
P14	0–15	4.88^{1aA}	4.78^{1aA}	1.49^{2aA}	1.12^{2aA}	2.47^{1aA}	2.28^{1abA}
	15–30	5.08^{1aA}	5.02^{1aA}	1.78^{1aA}	1.60^{1aA}	2.87^{1aA}	2.93^{1aA}
P20	0–15	4.80^{1aA}	4.92^{1aA}	1.56^{2aA}	1.42^{2aA}	1.69^{1aA}	1.63^{1bA}
	15–30	4.96^{1aA}	5.00^{1aA}	1.73^{1aA}	1.55^{1aA}	1.55^{1aA}	1.45^{1bA}

–Means represented by different superscript lowercase alphabets indicate significant differences between D. beccarii of different ages in same depth by Tukey's test at P<0.05.
–Means represented by different superscript numbers indicate significant differences between different depth (P14 and P20) by t–Test.
–Means represented by different superscript uppercase alphabets indicate significant differences between assessment dates by t–Test.

Table 5. Soil nutrient content of *D. beccarii* at different ages and two soil depths.

Age	Depth (cm)	Total N (mg kg^{-1})		Available P (mg kg^{-1})		Exchangeable K (mg kg^{-1})		Exchangeable Mg (mg kg^{-1})		Exchangeable Ca (mg kg^{-1})	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
P1	0–15	4.22^{1a}_{A}	3.78^{1a}_{A}	11.90^{1a}_{A}	12.25^{1a}_{A}	5.75^{1aA}	5.13^{1aA}	17.68^{1bA}	22.28^{1aA}	2.44^{1bA}	2.32^{1bA}
	15–30	3.81^{1a}_{A}	3.96^{1a}_{A}	12.15^{1a}_{A}	11.95^{1a}_{A}	4.54^{1aA}	5.00^{1aA}	20.88^{1bA}	21.63^{1aA}	1.81^{1bA}	2.45^{1bA}
P9	0–15	2.68^{1b}_{A}	3.17^{1a}_{A}	11.25^{1a}_{A}	11.30^{1a}_{bA}	5.47^{1aA}	2.31^{1bA}	22.10^{1aA}	20.24^{1aA}	5.20^{1bA}	4.82^{1abA}
	15–30	3.20^{1a}_{A}	3.58^{1a}_{bA}	11.65^{1a}_{bA}	11.45^{1a}_{bA}	5.11^{1aA}	5.21^{1aA}	21.72^{1abA}	22.08^{1aA}	2.79^{1bA}	5.75^{1abA}
P14	0–15	3.25^{1a}_{bA}	3.51^{1a}_{A}	11.08^{1a}_{A}	10.12^{1b}_{A}	3.06^{1aA}	2.59^{1bA}	22.50^{1aA}	22.60^{1aA}	8.57^{1abA}	7.67^{1abA}
	15–30	3.34^{1a}_{A}	2.91^{1a}_{bA}	10.68^{1b}_{A}	11.04^{1a}_{bA}	2.71^{1aA}	2.52^{1bA}	23.30^{1abA}	22.90^{1aA}	6.36^{1aA}	6.92^{1aA}
P20	0–15	2.56^{1b}_{A}	2.90^{1a}_{A}	8.84^{1bA}	10.38^{1a}_{bA}	5.47^{1aA}	3.09^{1abA}	23.80^{1aA}	23.62^{1aA}	7.57^{1aA}	8.39^{1aA}
	15–30	2.57^{1a}_{A}	2.29^{1b}_{A}	10.40^{1b}_{A}	10.58^{1b}_{A}	5.11^{1aA}	2.64^{1bA}	23.50^{1aA}	23.86^{1aA}	6.05^{1aA}	6.66^{1abA}

–Means represented by different superscript lowercase alphabets indicate significant differences between D. beccarii of different ages in same depth by Tukey's test at P<0.05.
–Means represented by different superscript numbers indicate significant differences between different depth (P14 and P20) by t–Test.
–Means represented by different superscript uppercase alphabets indicate significant differences between assessment dates by t–Test.

RESULTS AND DISCUSSION

Based on a tree life span cycle, a tree goes through unidirectional series of ontogenetic stages (Meinzer *et al*. 2009). Each stage is characterized by discontinuous and discrete changes. The growth of tree in different ontogenetic stages typically increases with time (Karlsson *et al*. 2005). Similar to other tree species, the increment of *D. beccarii* growth also exhibits a sigmoidal curve over time. In the sigmoidal curve, tree growth accelerated in the juvenile stage, constantly linear in the mature stage, and declining in the senescence stage (Weiskittel *et al*. 2011). However, sigmoid growth pattern in this study was only applicable for total height and merchantable height, while stem diameter, canopy depth, and canopy diameter still have potential to increase even after 20 years.

In the early stage of *D. beccarii* growth, transition from seedling to sapling exhibits active apical (primary) development. Young *D. beccarii* requires a full overhead light by maximizing the allocation to vertical growth, maintaining the foliage above the shade of competitors (Metslaid *et al*. 2007). Hence, seedlings of *D. beccarii* mostly focus on the apical meristem development that leads to outstanding growth in total height, surpassing other stands' growth performance in the final observation.

The transition from seedling to sapling phase revealed significant changes on the tree physical forms. The growth rate of saplings was generally higher than seedlings. Similar to seedlings, the growth rate of *D. beccarii* saplings accelerating over time. Saplings of *D. beccarii* recorded high development rate of apical meristem (merchantable height) and lateral meristem (stem diameter) under the influence of different stand densities. Low stand density provides adequate growing space for saplings to bulk up rapidly (Etigale *et al*. 2014) which reduces competition for resources from other trees. High stand density with dense canopy leads to high LAI, while sparse canopy leads to low LAI (Hardwick *et al*. 2015). The competition for light in the crowded stand resulted in vigorous canopy size and LAI growth (Kull & Tulva 2000), resulting to high LAI growth rate of *D. beccarii* saplings.

Growth performance in height, canopy size, and stem diameter were still high in mature *D. beccarii*. Growth increment normally increased with time but there were some cases where increment in the canopy depth and LAI reached a plateau or decreased, respectively. There is a probability that growth rate of canopy expansion and LAI will reach an equilibrium and decrease as the stand grows old (Pallardy 2008) in a condition where development of leaves equals the speed of cladoptosis (continuous natural thinning) process (Vertessy *et al*. 2001).

Soil pH in all *D. beccarii* stands was acidic and ranged from 4.50 to 5.08. There was no significant difference found in both soil depths. The soil in seedling stand was more acidic due to the fact that seedlings produce less litterfall for organic matter decay and possessed no dense canopy. This allows heavy rainfall to directly carry lime into the soil, which then effectively removes the basic cations and lets the nutrients leach further down into the soil. The leached soluble bases were replaced by H^+ ions of the carbonic acid and other acids (Al^{3+}) in the soil. Eventually, pH of soil will increase as either $CaCO_3$, CaO, or Ca (OH_2) combine with CO_2 and water in the soil to yield bicarbonates (HCO^{3-}) that are able to take H^+ and Al^{3+} out of the solution (McCauley *et al*. 2009). The pH level was almost similar in saplings and mature *D. beccarii* stands. These stands had large canopies which contribute a large amount of litterfall. The large canopy size and litterfall prevented rain water to penetrate into the soil directly (Bernhard–Reversat *et al*. 2001; Celentano *et al*. 2011). Hence, soil pH was less acidic in sapling and mature *D. beccarii* stands. The well–established root system of saplings and mature *D. beccarii* penetrated deeper into the soil and absorbed the CO_2 and water efficiently compared to newly established roots of seedlings. The efficient absorption limits of CO_2 and water by the well–established roots cause soil pH be reduced or reach a plateau (Sparks 2003; Forman 2014).

Bulk density is influenced by the frequent activities that cause soil compaction and organic matter decay (Chaudhari *et al*. 2013). The bulk density for all stands ranged from 1.12 to 1.92 g cm^{-3}. The bulk density was high in seedling and sapling (P9) stands as these stands produce a few amount of organic matter, which increases soil compaction (Arshad *et al*. 1996). Sapling (P14) and mature *D. beccarii* stands produce a lot of organic

Table 6. Correlation between soil properties and tree morphological parameters.

	Total Height (m)	Merchantable Height (m)	Diameter at Breast Height (cm)	Canopy Diameter (m)	Canopy Depth (m)	Leaf Area Index	Soil pH	Bulk Density (g cm^{-3})	Moisture Content (%)	Total Nitrogen (mg kg^{-1})	Available Phosphorus (mg kg^{-1})	Exchangeable Potassium (mg kg^{-1})	Exchangeable Magnesium (mg kg^{-1})	Exchangeable Calcium (mg kg^{-1})
Total Height (m)	1.00													
Merchantable Height (m)	0.99**	1.00												
Diameter at Breast Height (cm)	0.98**	0.99**	1.00											
Canopy Diameter (m)	0.84**	0.88**	0.93**	1.00										
Canopy Depth (m)	0.85**	0.89**	0.94**	0.99**	1.00									
Leaf Area Index	0.91**	0.92**	0.96**	0.95**	0.96**	1.00								
Soil pH	0.35	0.26	0.25	0.11	0.13	0.36	1.00							
Bulk Density (g cm^{-3})	–0.56	–0.53	–0.49	–0.40	–0.39	–0.41	–0.27	1.00						
Moisture Content (%)	–0.52	–0.58	–0.56	–0.59	–0.58	–0.44	–0.19	0.19	1.00					
Total Nitrogen (mg kg^{-1})	–0.78*	–0.80*	–0.86**	–0.89**	–0.91**	–0.93**	–0.53	0.11	0.62	1.00				
Available Phosphorus (mg kg^{-1})	–0.85**	–0.80*	–0.75*	–0.52	–0.54	–0.72*	–0.41	0.40	0.47	0.86**	1.00			
Exchangeable Potassium (mg kg^{-1})	0.38	0.43	0.43	0.37	0.38	0.27	–0.39	0.78	–0.13	0.05	0.33	1.00		
Exchangeable Magnesium (mg kg^{-1})	0.69	0.67	0.59	0.36	0.37	0.48	0.81**	–0.52	–0.57	–0.77*	–0.80**	–0.45	1.00	
Exchangeable Calcium (mg kg^{-1})	0.98**	0.96**	0.92**	0.74*	0.75*	0.84**	0.59	–0.60	–0.22	–0.65	–0.86**	–0.74*	0.83**	1.00

*The correlation coefficients with * are significant at P<0.05 and ** are significant at P<0.01*

A sample of *D. beccarii* tree used in the study.

A 14–year old *D. beccarii* stand with a staff member climbing the tree to get leaf samples.

matter and have overlapping root systems which loosen the soil and reduce soil bulk density in the stand (Bengough *et al*. 2006; Chaudhari *et al.* 2013).

There were distinct differences in soil moisture content among the *D. beccarii* stands along the age sequence. Mature *D. beccarii* stands recorded the lowest soil moisture for both depths. Excessive water loss due to transpiration and uptake rate by the roots (Patriquin 2004) was closely related to mature *D. beccarii*, since mature *D. beccarii* have larger sized crowns than younger stands. The movement of water vapor out of leaf during the transpiration process creates suction on the open ends of the xylem, which will force water to move toward the leaf. The suction extends right to the intake ends at the thousands of root tips where most of water intake occurs, and out into the surrounding soil. Roots are constantly growing at their tips, and branching to produce more growing tips as water is pulled out of one region of the soil; roots then grow into other regions. Hence, more well–established root system in older stands will cause more water loss from the soil (Patriquin 2004).

Soil functions as the reservoir for plant–available water and nutrients (Comerford 2005). The nutrient supplied to the tree is determined by the concentrations of nutrients available in soil and soil solutions, microbial activity, and nutrient uptake kinetics of the roots (Bassirirad 2000). Soil total N, available P, and exchangeable K decreased with the increasing age of *D. beccarii*. Among these three soil nutrient elements, only total N and available P were negatively correlated ($P<0.01$ and $P<0.05$ respectively) with *D. beccarii* growth. The range of total N at the initial assessment was from 0.23 g kg^{-1}, recorded in mature *D. beccarii* stand (15–30 cm), to 0.42 g kg^{-1}, recorded in seedling sstand (0–15 cm). The high total N in seedling stand was due to high soil moisture content (Table 4) that helps to increase N mineralization (Stark & Firestone 1995; Hungate *et al*. 1997; Hungate 1999). The lowest available P recorded in the mature *D. beccarii* stand (0–15 cm) was 8.84 mg kg^{-1} while highest available P of 12.25 mg kg^{-1} was recorded in the seedling stage (0–15 cm). Soil exchangeable K also decreased with age of the stand. The range of exchangeable K varies from 2.31 to 5.75 mg kg^{-1}. Seedling stand recorded the highest exchangeable K (5.75 mg kg^{-1}). Results obtained in the present study contradict with the findings of Jong–Hwan (2003) where K increased steadily with the increase in amount of litterfall decomposition. The higher N, P, and K contents at the seedling stage (P1) were also due to decomposition of mulch materials and plant residuals from site preparation. During planting, thick layer of mulching was applied to cover the planting site.

According to Lal (2015), Ca or Mg deficiencies occurred in the degraded forest. However, the study showed soil exchangeable Mg and Ca increased with the age of *D. beccarii*. The exchangeable Ca was highly correlated with the *D. beccarii* growth. This proved that the soil in *D. beccarii* stand was improving from the degraded state. The range for exchangeable Mg was 17.68 to 23.86 mg kg^{-1} and exchangeable Ca was 1.81 to 8.57 mg kg^{-1}. This is probably due to established root systems in the older stands that are able to absorb Mg and Ca at larger, and in deeper areas (van Noordwijk *et al.* 1996). Older stands usually produce more litterfall (Hardiyanto & Wicaksono 2008), and in turn result to higher nutrient turnover from decomposition. Leaching losses of exchangeable bases like Mg and Ca are less in well–established extensive root systems (van Noordwijk *et al*. 1996). This increases rate of nutrient uptake. There are similarities between Mg and Ca where both of these nutrient elements are influenced by the soil pH (Miyazawa *et al.* 2001; Whittinghill & Hobbie 2012). Soil pH affected the soil Mg concentration. Lower soil pH (more acidic) reduces Mg and thus lowers the Ca concentration (Miyazawa *et al*. 2001) since Mg correlated positively with Ca. The soil in seedling stand was more acidic than other stands and causes the exchangeable Mg and Ca concentration to be low. Since the soil pH became less acidic as the *D. beccarii* stand age increased, the exchangeable Mg and Ca increase at slow pace.

CONCLUSION

Dryobalanops beccarii reached its peak height growth at year 20 while stem diameter and canopy are still growing as indicated from the growth curve. Only available P decreased with stand age while exchangeable Ca increased with time in the current study indicating that early site preparation is important to sustain tree growth. These results support current Sarawak State policy that encourages all logging companies to restore logged forest using local indigenous tree species to conserve its biodiversity.

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