Height-age model and site index curves for *Acacia mangium* and *Eucalyptus pellita* in Indonesia

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ABSTRACT

Height-age growth models and site index curves were developed for the site quality evaluation of *Acacia mangium* Willd and *Eucalyptus pellita* F. Muel stands in Korintiga Hutani plantation, Pangkalan Bun, Central Kalimantan, Indonesia. In this study, the Chapman-Richards growth function was used in the guide curve method to generate anamorphic site index curves for the two species. In order to evaluate the developed models, coefficient of determination ($R^2$), root mean square error (RMSE), bias ($\bar{z}$), absolute mean difference (AMD), and mean percent bias (MPB) were used as statistical criteria. In addition, a simple linear regression and simultaneous $F$-test was performed to evaluate the relationship of the observed and the predicted dominant height of each species. Based on the statistical evaluations, simple linear regression and $F$-test models developed for the two species showed satisfactory results. Furthermore, the developed models explained about 98.35% and 98.60% of the total variation in the estimate of total dominant height for *Acacia mangium* and *Eucalyptus pellita*, respectively. The developed site index curves are expected to be significant for forest managers in predicting the growth patterns and classifying the site productivities of the different stands in Korintiga Hutani plantation.

Introduction

*Acacia* (*Acacia mangium* Willd.) and eucalyptus (*Eucalyptus pellita* F. Muell.) are the two main species used in the tropical forest plantation of Pangkalan Bun, Central Kalimantan, Indonesia, which accounts for more than 93% of the total forested area (Korea Forest Research Institute 2008). From 1998 to 2004, a total of 18,132 ha and 9355 ha of *Acacia mangium* and *Eucalyptus pellita*, respectively, were planted (Pirard and Cossalter 2006). It was reported that trees with more than 18 cm diameter would be utilized for plywood production while trees with smaller diameters and trees with lower quality would serve as a supply for pulp mill (Pirard and Cossalter 2006). Tropical forest plantations and tree farms are becoming more important because they reduce pressures from the natural and residual forest resources by increasing the supply of wood and other forest-based raw materials. They can also increase employment generation while improving the ecological conditions of the denuded forest areas (Lumbres et al. 2012b). Tropical forests are also attracting attention in climate change mitigation due to their crucial role as carbon sinks (Avitable et al. 2012) and the large emissions associated with their disappearance (Houghton 2007).

Haywood (2009) reported that accurate estimates on forest productivity are essential in order to sustainably manage the forests. Site quality evaluation is considered an important aspect in forest management whereby forest managers can assess potential forest stand timber production for a particular species or forest type (Clutter et al. 1983). Several authors state that site quality evaluation can guide critical decision-making through predicting the growth and yield of a forest stand (Spurr 1952; Spurr & Barnes 1980). Site index is considered one of the better measures to evaluate site quality and is the most direct and most widely used in forestry (Clutter et al. 1983; Fonweban et al. 1995; Onyekwelu 2005; Dieguez-Aranda et al. 2006). It is used to quantify site quality for pure, even aged, forest stands in growth and yield modeling (Lee 2002; Corral-Rivas et al. 2004; Dieguez-Aranda et al. 2006).

Various studies have been conducted to develop site index equations in tropical areas. Amongst others, site index prediction equations were developed for *Acacia mangium* in Colombia (Torres Velez and Del Valle 2007) and Bangladesh (Newaz and Millat-e-Mustafa 2004), *Pinus kesiya* (Lumbres et al. 2012a), *Tectona grandis* (Akindele 1991), *Gmelina arborea* (Onyekwelu and Fuwape 1998), *Nauclea diderrichii* (Onyekwelu 2005), and *Fagus orientalis* (Ahmadi et al. 2017). However, site quality evaluation using site index equations is still insufficient for *Acacia mangium* and *Eucalyptus pellita* in Pangkalan Bun, Central Kalimantan, Indonesia. Thus, the objectives of this study are to develop the height-age model for *Acacia mangium* and *Eucalyptus pellita* and to develop anamorphic site index curves using the Chapman-Richards growth function (Richards 1959; Chapman 1961).

Materials and methods

Study site

The Korintiga Hutani plantation is located in Pangkalan Bun, Central Kalimantan, Indonesia with an approximate total area of 95,429 ha. Its boundaries lie between 1°62′30″ to 2°20′00″ latitude and 111°28′00″ to 111°55′00″ longitude.
Most of the areas in this plantation (73.70%) are flat and gently sloping land or with a slope of 0%–15% (Pirard and Cossalter 2006). Furthermore, the elevation ranges from 25 m to 500 m above sea level while the mean annual precipitation is above 2400 mm and the mean annual temperature is 26.4 °C.

**Data collection and analysis**

A total of 81 and 187 temporary plots, with a size ranging from 0.32 ha to 0.40 ha were established in the area planted with *Acacia mangium* and *Eucalyptus pellita* stands, respectively. Age information was obtained based on the plantation records whereas the total height of the dominant tree in each plot was measured to the nearest decimeter (10 cm) using a Haglof Vertex III and Transponder. The average age for both records whereas the total height of the dominant tree in each plot was 22.00 m (6.30–32.20 m range) as shown in Table 1.

To develop age-height model for the two species, the Chapman-Richards growth function was used where the form of the function is:

\[ H = a \left[1 - \exp\left(-bA\right)\right]^c \]  

(1)

where \( H \) = total height of the dominant tree in m, \( A \) = stand age in year, and \( a, b, \) and \( c \) = model parameters.

This equation has been extensively used in forest growth and yield studies to characterize site index curves, height-age, diameter-age, basal area-age, and growth rate-age relationships (Pienaar and Turnbull 1973; Clutter et al. 1983; Somers and Farrar 1991; Payandeh and Wang 1994; Corral-Rivas et al. 2004; Kim et al. 2014; Pyo 2017). It has been widely used because it defines sigmoid curves having three parameters that characterize the different growth stages as influenced by biological processes and behaviors (Peng et al. 2001).

For the model evaluation, the coefficient of determination (\( R^2 \)), root mean square error (RMSE), bias (\( \bar{E} \)), absolute mean difference (AMD), and mean percent bias (MPB) were used. These statistical evaluations were computed as follows:

\[ R^2 = 1 - \frac{\sum_{i=1}^{n} (H_i - \hat{H}_i)^2}{\sum_{i=1}^{n} (H_i - \bar{H})^2} \]

\[ RMSE = \sqrt{\frac{\sum_{i=1}^{n} (H_i - \hat{H}_i)^2}{n}} \]

where \( H_i \) = observed dominant height for the \( i \)th tree, \( \hat{H}_i \) = predicted dominant height for the \( i \)th tree, and \( \bar{H} \) = observed mean dominant height.

A simple linear regression (Zar 1999) was also performed to compare the observed and predicted dominant height of the tree for each species. The observed and the predicted dominant height were related according to the following linear model: Predicted dominant height = \( b_0 + b_1 \times \)Observed dominant height.

The regression line indicates that if the age-height model of the species correctly estimated the dominant height of the tree, then the intercept which is the \( b_0 \) would not be significantly different from 0 and the slope which is \( b_1 \) would not be significantly different from 1. A simultaneous F-test to evaluate the hypothesis: \( H_0: (\beta_0, \beta_1) = (0, 1) \), \( Ha: (\beta_0, \beta_1) \neq (0, 1) \) was also performed.

In this study, site index curves were developed using a mathematical model instead of a graphical method. The latter is less preferred due to the subjectivity and difficulties in conducting statistical tests on the goodness of fit of the curve (Akindele 1991; Onyekwelu and Fuwape 1998; Onyekwelu 2005). Moreover, the guide curve was used in this study because it could be applied to even-aged single species forest stands (Nanang and Nunifum 1999) and it was suitable for stands with temporary sampling plots (Akindele 1991).

**Results and discussion**

**Model fitting and evaluation**

The Statistical Analysis System Non Linear (SAS NLIN) procedure (SAS Institute Inc. 2004) and the nonlinear regression technique were used to fit the height-age data using the Chapman-Richards height growth function for *Acacia mangium* (Figure 1) and *Eucalyptus pellita* (Figure 2). The parameter estimates and associated standard errors are shown in Table 2. The results indicated that none of the asymptotic 95% confidence intervals contained 0 for each

![Figure 1](image)

**Table 1. Summary of observed statistics of the data used in the development of height-age model for Acacia mangium and Eucalyptus pellita in Pangkalan Bun, Central Kalimantan, Indonesia.**

| Statistics                          | \( n \) | Mean (standard deviation) | Range  |
|-------------------------------------|---------|---------------------------|--------|
| *Acacia mangium*                    |         |                           |        |
| Age (year)                          | 81      | 5 (2)                     | 1–9    |
| Dominant height (m)                 |         | 21.12 (8.35)              | 4.80–35.80 |
| *Eucalyptus pellita*                |         |                           |        |
| Age (year)                          | 187     | 5 (2)                     | 1–9    |
| Dominant height (m)                 |         | 22.00 (5.67)              | 6.30–32.20 |
parameter estimate; therefore, it was concluded that the equation parameters were significant.

The developed model was further evaluated using the statistical evaluation (Table 3). The $R^2$ for Acacia mangium was 0.9835 and the $R^2$ for Eucalyptus pellita was 0.9860. The developed models explained about 98.35% and 98.60% of the total variation in the estimate of total dominant height for Acacia mangium and Eucalyptus pellita, respectively. The bias was 0.0280 m and the AMD was 2.2440 m for the Acacia mangium model. On the other hand, the bias and AMD were 0.0013 m and 2.0830 m for the Eucalyptus pellita model. Peng et al. (2001) explained that a negative value of bias indicates that the model overpredicts total dominant height while a positive value indicates underprediction. The results showed that the bias values were near 0, which indicates that the developed models are a good predictor. A lower AMD value means that the model is more accurate in terms of overall prediction. The computed RMSE was 2.9707 and 2.7116 and the MPB was 1.96% and 2.30% for Acacia mangium and Eucalyptus pellita, respectively. The developed models were further evaluated by determining the bias in different age classes. A graph showing the bias in the height estimations in each age class for Acacia mangium and Eucalyptus are illustrated in Figure 3.

The relationships of the observed and the predicted dominant height of the Acacia mangium and the Eucalyptus pellita were plotted using a simple linear regression. The linear regression line for the Acacia mangium is shown in Figure 4 while the regression line of the Eucalyptus pellita is shown in Figure 5. The dominant heights of the Acacia mangium trees were determined to be related according to the following linear model: Predicted dominant height = $0.9065 \times \text{Observed dominant height} + 1.4374$. The regression showed that the height model gave overestimated results for heights $< 20.0$ m and gave underestimated results for heights $> 20.0$ m. A $p$-value of 0.0772 was determined through simultaneous $F$-test to evaluate the hypothesis: $H_0: (\beta_0, \beta_1) = (0, 1)$, $H_a: (\beta_0, \beta_1) \neq (0, 1)$. On the other hand, the dominant heights of the Eucalyptus pellita trees were determined to be related according to the following linear model: Predicted dominant height = $0.8056 \times \text{Observed dominant height} + 4.0004$. The regression showed that the height model gave overestimated results for heights $< 20.0$ m and gave underestimated results for height $> 20.0$ m, the same with the regression line of Acacia mangium trees. A $p$-value was determined to be 0.13500 through simultaneous $F$-test to evaluate the hypothesis: $H_0: (\beta_0, \beta_1) = (0, 1)$, $H_a: (\beta_0, \beta_1) \neq (0, 1)$.

Table 2. Parameter estimates, approximate standard error, and confidence intervals for the fitted Chapman-Richards growth function.

| Parameters | Estimate | Standard error | Lower 95% confidence level | Upper 95% confidence level |
|------------|----------|----------------|---------------------------|---------------------------|
| Acacia mangium | a | 33.226 | 2.1823 | 28.8813 | 37.5707 |
| | b | 0.3212 | 0.0782 | 0.1656 | 0.4768 |
| | c | 1.5782 | 0.3436 | 0.8092 | 2.2622 |
| Eucalyptus pellita | a | 30.9678 | 1.2965 | 28.4096 | 33.5258 |
| | b | 0.3372 | 0.0624 | 0.2140 | 0.4603 |
| | c | 1.2474 | 0.2164 | 0.8205 | 1.6742 |

Figure 2. Comparison of the observed and predicted height using the developed height-age model for Eucalyptus pellita in Pangkalan Bun, Central Kalimantan, Indonesia.

Figure 3. Mean bias of the developed model in height estimation by age classes for Acacia mangium and Eucalyptus pellita in Pangkalan Bun, Central Kalimantan, Indonesia.

Figure 4. Simple linear regression for the Acacia mangium in Pangkalan Bun, Central Kalimantan, Indonesia.

Table 3. Fit statistics and evaluation statistics of the fitted Chapman-Richards model.

| Species | $R^2$ | RMSE | $F$ | AMD | MPB |
|---------|-------|------|-----|-----|-----|
| Acacia mangium | 0.9835 | 2.9707 | 2.2440 m | 1.96% |
| Eucalyptus pellita | 0.9860 | 2.7116 | 2.0830 m | 2.30% |

$F$-value was determined to be 0.13500 through simultaneous $F$-test to evaluate the hypothesis: $H_0: (\beta_0, \beta_1) = (0, 1)$, $H_a: (\beta_0, \beta_1) \neq (0, 1)$. On the other hand, the dominant heights of the Eucalyptus pellita trees were determined to be related according to the following linear model: Predicted dominant height = $0.8056 \times \text{Observed dominant height} + 4.0004$. The regression showed that the height model gave overestimated results for heights $< 20.0$ m and gave underestimated results for height $> 20.0$ m, the same with the regression line of Acacia mangium trees. A $p$-value was determined to be 0.13500 through simultaneous $F$-test to evaluate the hypothesis: $H_0: (\beta_0, \beta_1) = (0, 1)$, $H_a: (\beta_0, \beta_1) \neq (0, 1)$.
Site index curves

The guide curve method described by Clutter et al. (1983) was used in this study for the development of an anamorphic site index projection equation to estimate site index (SI) for any given index age of *Acacia mangium* and *Eucalyptus pellita*. The equation for the guide curve of *Acacia mangium* is:

\[
H = 33.226 \left[ 1 - \exp(-0.3212A) \right]^{1.5782}
\]

The equation for the guide curve of *Eucalyptus pellita* is:

\[
H = 30.9678 \left[ 1 - \exp(-0.3372A) \right]^{1.2474}
\]

In this study, the index or base age used was 6 years. Trousdell et al. (1974) and Goelz and Burk (1992) stated that an index age lower than the rotation age is commonly selected. For the Korintiga Hutani plantation, the rotation age is 10 years to sustainably support the production of plywood and pulpwod mills (Pirard and Cossalter 2006). Teshome and Petty (2000) reported that the selected index age must be near the average age to have a more accurate prediction. The index age of 6 years for both *Acacia mangium* and *Eucalyptus pellita* is near the average age of the different temporary plots and falls within the range of the dataset collected from the Korintiga Hutani plantation. The 6-year base age was also used in the different studies (Newaz and Millat-e-Mustafa 2004; Torres Velez and Del Valle 2007) for *Acacia mangium*. In order to derive curves for other site index values, the procedure described by Clutter et al. (1983) and applied in the different studies (Aguirre-Bravo and Smith 1986; Tewari and Kumar 2002; Mamo and Sterba 2006; Torres Velez and Del Valle 2007; Kitikidou et al. 2012) was also used. In this method, the rate parameter \( b \) and the shape parameter \( c \) of Equations 2 and 3 are constant while the asymptote parameter \( a \) varies in order to determine height \( H \) where stand age \( A \) is equivalent to base age \( A_0 \). The prediction equation created to estimate the site index for any given age of *Acacia mangium* is:

\[
SI = H \left[ \frac{1 - \exp(-0.3212A)}{1 - \exp(-0.3212A_0)} \right]^{1.5782}
\]

For *Eucalyptus pellita* the prediction equation created is:

\[
SI = H \left[ \frac{1 - \exp(-0.3372A)}{1 - \exp(-0.3372A_0)} \right]^{1.2474}
\]

Equations 4 and 5 can be rearranged algebraically to estimate \( H \) at some age for a given site index base age. The equation for *Acacia mangium* is:

\[
H = SI \left[ \frac{1 - \exp(-0.3212A)}{1 - \exp(-0.3212A_0)} \right]^{1.5782}
\]

For *Eucalyptus pellita* the equation is:

\[
H = SI \left[ \frac{1 - \exp(-0.3372A)}{1 - \exp(-0.3372A_0)} \right]^{1.2474}
\]

Site index curves were generated using Equation 6 for *Acacia mangium* stands (Figure 6) and Equation 7 for *Eucalyptus pellita* (Figure 7) stands ranging from 1 to 10 years of age. A total of seven site index curves with an interval of 4 m, ranging from 16 m to 40 m were generated to illustrate the potential forest stand productivities.

Newaz and Millat-e-Mustafa (2004) and Torres Velez and Del Valle (2007) developed anamorphic site index curves for *Acacia mangium* in Bangladesh and Colombia, respectively. After comparing these two studies with the present study, it was observed that the present study provided a higher prediction of total height of the dominant tree for the rotation age of 10 years. For instance, the estimated total height of the *Acacia mangium* with a site index of 24 m and harvesting age of 10 years was 26.76 m (Newaz and Millat-e-Mustafa 2004) and 25.30 m (Torres Velez and Del Valle 2007), whereas the estimated height using the developed model in this study was 28.83 m. This indicates that the models developed for *Acacia mangium* from other countries will underpredict the total height of the dominant trees in the Korintiga Hutani

![Figure 5. Simple linear regression for the *Eucalyptus pellita* in Pangkalan Bun, Central Kalimantan, Indonesia.](image)

![Figure 6. Site index curves developed for *Acacia mangium* in Pangkalan Bun, Central Kalimantan, Indonesia (base age: 6 years).](image)
Conclusion

In this study, the nonlinear regression technique of Chapman-Richards was used to fit the height-age data using the height growth function for *Acacia mangium* and *Eucalyptus pellita*. The parameters of the equation obtained from SAS were significant and based on the evaluations using fit statistics, the equation developed in predicting the height showed a good performance. As to the site index curves, the generated curves could predict the height-age development pattern of the different stands in the Korintiga Hutani plantation. Furthermore, based on the comparisons between the site index equations developed in the previous studies and our studies for *Acacia mangium*, and the insufficient information on the development of the site index equation for *Eucalyptus pellita*, the models developed in this study are acceptable and very suitable for the site classification and evaluation of the Korintiga Hutani plantation in Pangkalen Bun, Central Kalimantan, Indonesia. The site index model developed is a significant management tool in providing simple numerical values that can be easily measured and understood.

Disclosure statement

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