Biomass and carbon accumulations of acacia trees planted on tropical peatlands

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Abstract. Acacia (Acacia crassicarpa) is a fiber source for pulp industries, adaptive on tropical peatlands and has been planted intensively since the early seventies. Considering the fragility of peat and its low nutrient content along with the complication to manage water conducive environment to the tree growth, the sustainability of this plantation is under rudimentary inquiry. Peat loss may occur due to subsidence, emission, and surface runoff whilst biomass accumulation will result in carbon enhancement. This study aims 1) to evaluate growths of Acacia trees planted on tropical peatlands with different peat thicknesses; 2) to obtain allometric model to represent the growth of the tree parts; and 3) to estimate biomass and carbon accumulations and their rate in a few rotations. Destructive samples were taken from three different sites with different peat thicknesses and separated into the root, knud (buttress root), stem, branch, and leaf. An allometric model was introduced to represent each growth of the tree parts and to estimate the accumulation of biomass and carbon. The result shows Acacia grew better in thick peatlands, larger than 1 meter. The model can relate the tree parts specifically to estimate the tree biomass. In one hectare of one rotation within 5 years, total biomass ranges 36.3–443.7 tonnes, and total carbon absorbed ranges 17.4–213.0 tonnes. Thus, successive rotations would potentially result in additional thickness of organic matter at the rate of 0.07–2.08 cm/y, and carbon enrichment at the rate of 1.74–19.98 tones/y. This biomass and carbon enrichments would lessen the losses and greenhouse gas emission from the peatlands.

1. Introduction

Acacia (Acacia crassicarpa) is a small to medium sized tree at 25 m (max. 30) tall; bole often straight and branchless for about 13-18 m; up to 50-60 cm in diameter; crown heavily branched and spreading. Bark dark or grey-brown, hard with deep vertical furrows; inner bark is red and fibrous. The species is found in warm to hot humid and sub-humid zones in the lowland tropics. Under favorable conditions, seedlings grow rapidly reaching 25-30 cm in 3-4 months. Acacia crassicarpa is considered as the fastest-growing tropical Acacia species. Aboveground dry biomass of 207 t/ha can be obtained in 3 years with a mean annual rainfall of 1,500 mm, and 40 t/ha in 3 years on poorer sites. Spacing of 3 x 3 m (1,100 trees/ha) to 4 x 4 m (625 trees/ha) is suitable for land reclamation, fuel wood, and pulpwod plantations. Acacia is found on gently undulating terrains on well-drained, strongly acid soils, and on imperfectly drained soils that flood in the wet season [1].

In Indonesia, this tree is adaptive on tropical peatlands and planted intensively since the early seventies, and this is an important fiber source for pulp industries. This species is preferable for pulp
and paper industries, well suited to making paper, packaging, cardboard, and other uses. Cultivating acacia also helps fixing the soil’s structure, and preventing floods and landslide [2]. Considering the fragility of peat and its low nutrient content along with difficulty to manage the water conducive environment to this tree growth, the sustainability of acacia-based plantation is under rudimentary inquiry. Peat may lose due to subsidence, emission, and surface runoff whilst biomass accumulation will result in carbon enrichments [3,4].

Tree biomass plays a key role in sustainable management and in forest carbon stocks estimation. As a fast-growing tree and planted in rotations, Acacia plantation is potential to absorb CO₂ from the atmosphere and store the entrapped carbon in the biomass left in the field. Data of sequestrated carbon is essential to estimate variations of the carbon stock in peat forests [5]. Characterizing biomass in tree’s parts is important to know their contribution to the total carbon stock [6]. A throughout analysis is then needed to characterize the tree growth process, and generated biomasses and carbon, particularly in peatlands where these trees commonly cultivated. Allometric model is a common tool to relate among the tree’s parts. Validated models is needed to calculate the tree’s biomass, and to estimate the stem’s weight or volume of the main product in the plantation.

The diameter or the circle of the trunk at breast height (DBH) is recommended for estimating total aboveground biomass because of the simplicity. This variable is easy to measure and a common variable for forest inventories [7]. At the tree level, DBH and tree height were significant determinants to estimate the biomass of stems, coarse roots, and small roots. Altogether, the allometric model can be used to estimate biomass of all above- and belowground compartments [7]. The simplest mathematical model to estimate stem’s weight (M) or volume (V) from the trunk’s diameter (D) takes a form of power function with two fitted parameters (M=aDᵇ). Other models are then developed from this model [8,9]. Involving tree’s height (H) and particle density (ρ) in the model to calculate M will gain more accuracy [10].

Allometric models combined with Moderate-Resolution Imaging Spectroradiometer (MODIS) land [11] data and aerial photographs [12] can be used to estimate branch and aboveground biomass. The aboveground biomass density matches well with the data at both state and pixel levels. Remote sensing is commonly used to detect land altitude and tree’s height (H). In this case, a function that can relate D and H in a form of D=f(H) is very essential. Allometric model is essential for inversion.

As for the Acacia tree, present allometric models are merely based on the simple power function that cannot be applied to represent sequential tree’s growth [3–5,13]. Ogawa model as reported elsewhere [7,14,15] meets the criteria but in this case the model showed unsatisfactory. It is necessary then to seek an allometric model to represent the growth of tree’s parts, mathematically differentiable over time, such as to determine the time of maximum growth rate, and explicitly invertible.

The objectives of this study are: 1) to evaluate the growth of Acacia planted in tropical peatlands with different peat thicknesses; 2) to obtain allometric model that can represent the growth of the tree’s parts; and 3) to estimate biomass and carbon accumulations and their rate in one or more rotations.

2. Materials and methods
A total of 78 tree samples were collected in three sites of Acacia plantations grown in peatlands in the Provinces of Jambi, Riau, and South Sumatra. The plantation is managed by Asia Pulp and Paper Company. The first site (Site1) represents peatland with a thin peat thickness (≤50 cm) from the soil surface, and the third site (Site3) has a peat thickness ≥of 100 cm, while the peat thickness in the second site (Site2) is between that of Site1 and Site3. Site3 is the first cycle of the growing tree while the rest is more than 3 cycles. All sites are managed with the same operating standard including that for the water management system. The most contrasting condition is that the peats in Site1 and Site2 are more matured, or more frequently exposed to the atmosphere than those in Site3.

Trees were sampled by a destructive method [4,9]. Randomly selected trees were felt and then cut into 5 parts: root, knud (buttress root), trunk, branch, and leaf. The number of the samples was 31, 27, and 20 for Site1, Site2 and Site3 respectively, around the tree ages of 1, to 5 years. Weight was measured in the field while a small sample from each part was oven-dried in a laboratory. Perimeter (rather than
diameter) at the breast height and length of the trunk were also measured using a tape. The minimum, maximum, average, and standard deviation of every part for each age were calculated from the samples.

The average of variables were graphed to describe the growth of the tree part over time, thus allometric model was available for each tree part. Then, a representative allometric model was selected to describe the growth. The growth rate function would be the first temporal derivative model that inform the maximum rate preceding a levelling off. The estimated time to reach the maximum growth rate would guide the age to cut trees. Estimated values of each variable was then correlated for further understanding.

Biomass accumulation in one-hectare plot over cycles was predicted to describe their trends over time. The biomass was classified into the surviving and dead trees for each cycle. The surviving trees data were available from the company for planning and yield estimation and for generating an allometric model. Biomass left in the field composed from accumulated dead trees and other parts of the trees except trunk or stem which was transported to the pulp and paper mill was converted into the thickness unit to potentially enrich organic matters. The thickness was measured by dividing the biomass weight, tree’s parts density and the area. The density of each tree part was estimated from the secondary data for further used to predict the thickness of organic matter based on the loosed (lowest density) and compacted (highest density) conditions.

Carbon content was converted from biomass specific for each tree part. The carbon content referred to a secondary data. Similar procedure and simulation were applied here to estimate carbon accumulation and its trend over time. Special attention was given to provide information on the potential carbon enhancement in the field.

All calculations were undertaken using spreadsheet and visual basic programming and the Solver available in MS Excel. The Root Mean Squared Error (RMSE) was the convergent indicator of generated error during the optimization process, while the coefficient of determination ($R^2$) was the precision indicator of the model.

### 3. Results and discussion

#### 3.1. Statistical parameters

Table 1 shows statistical parameters of the tree’s parts comprising tree perimeter, height, root, knud, stem (trunk), branch, leaf, and the whole weight of the tree for every age. The sampling number should be sufficient for generating small variance and high consistency [16]. The resulted standard deviation was relatively small due to sufficient samples. Deviation is commonly smaller at an early age and increasing by time which is normal as trees are growing variably in size by ages. Trees of Site3 produced the highest weight followed by Site2 then Site1 indicating that the deeper and the fresher peats resulted in better tree growth. As shown in Table 1, the weight of the tree after 4 years reached 38.4±7.38 kg in Site1, 153.4±38.01 kg in Site2, and 271.5±78.10 kg in Site3. It indicates the decreasing fertility of peat after being cultivated for several rotations. Whilst the fertilization is merely given at the early stages and limited at the surrounding tree stand. The average height in Site2 likes that reported by Puspitasari [4] around 17.57 m with the average diameter of 16.65 cm.
3.2. Allometric models

There are many allometric models available for estimating tree biomass in the form of polynomial, power, or logarithmic functions [5,6,14–19]. The allometric model is specific for a tree species and needs to be calibrated preceding implemented for other sites. The simple allometric models commonly relate tree diameter with height and stem weight. After several trials, those models generally confirmed well with the data in the earlier ages but failed to represent the data approaching maximum vegetative stage. Here, we introduce an allometric model that is specific to represent each part of a tree. The model takes the following formula:

\[ Y = Y_m \left[ 1 - \left( \frac{X}{a} \right)^b \right]^c \]

(1)

Where, \( Y \) is the size of the tree’s part, \( Y_m \) is the maximum size, \( X \) is the tree’s age while \( a, b, \) and \( c \) are fitted parameters. The growth rate is the first derivation which forms the following formula:

\[ \frac{dY}{dt} = Y_m \left( \frac{X}{a} \right)^{b-1} \left[ c \left( 1 + \left( \frac{X}{a} \right)^b \right)^{-c-1} \right] \]

(2)

The inverse function of the model is:

\[ X = a \left( \frac{Y_m}{Y} \right)^{1/c} - 1 \]

(3)

The parameters could be found by using the Solver available in MS Excel subjected to minimize RMSE for every part of the tree. Table 2 shows those parameters with the RMSE and \( R^2. \) \( Y_m \) is the maximum value such as shown in Table 2. Most \( R^2 \) are close to 1 except those for the Leaf in Site1 and Site2. However, since their weight fractions are small (less than 7% for each site), they are not significantly affecting the total weight of the tree.

### Table 1. Statistical parameters of the tree’s parts.

| Sites  | Age (y) | Circle (cm) | Height (m) | Root (kg) | Knud (kg) | Stem (kg) | Branch (kg) | Leaf (kg) | Tree (kg) |
|-------|---------|-------------|------------|-----------|----------|-----------|-------------|-----------|-----------|
| Site1 | 1.0     | 0.15       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.21      |
|       | n = 31  | 0.11       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.19      |
|       | n = 22  | 0.11       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.19      |
|       | Site2   | 0.11       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.19      |
|       | 0.8     | 0.15       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.21      |
|       | 1.0     | 0.15       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.21      |
|       | 2.0     | 0.01       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.21      |
|       | 4.0     | 0.01       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.21      |
|       | 5.0     | 0.01       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.21      |
|       | Site3   | 0.11       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.21      |
|       | 0.8     | 0.15       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.21      |
|       | 1.0     | 0.15       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.21      |
|       | 2.0     | 0.01       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.21      |
|       | 4.0     | 0.01       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.21      |
|       | 5.0     | 0.01       | 0.01       | 0.01      | 0.11     | 0.11      | 0.01        | 0.11      | 0.21      |

### Table 2. Parameters of the allometric models for each part of the tree.

| ModelX | Parameters | Site1 | Site2 | Site3 |
|--------|------------|-------|-------|-------|
|        | Circle | Height | Root | Knud | Stem | Branch | Leaf | Circle | Height | Root | Knud | Stem | Branch | Leaf | Circle | Height | Root | Knud | Stem | Branch | Leaf |
| Ym     | 0.23   | 30.37 | 4.12 | 4.29 | 34.90 | 3.776 | 1.846 | 0.23   | 21.60 | 19.07 | 27.04 | 106.48 | 30.66 | 20.08 | 0.337 | 29.00 | 34.35 | 39.62 | 335.65 | 48.76 | 32.14 |
| a      | 54.32  | 5.07  | 12.41 | 10.75 | 14.44 | 497.3 | 5780 | 529.6 | 199.9 | 28.61 | 51.71 | 12.25 | 68.79 | 186.19 | 258.6 | 160.6 | 28.76 | 51.71 | 15.44 | 37.64 | 1810 |
| b      | 1.220  | 1.414 | 4.227 | 4.518 | 3.626 | 1.647 | 1.134 | 1.177 | 1.466 | 2.209 | 2.245 | 3.745 | 1.526 | 4.027 | 1.612 | 1.750 | 3.430 | 2.245 | 4.221 | 2.356 | 2177 |
| c      | 37.00  | 0.21  | 212.3 | 94.56 | 104.35 | 3074 | 3807 | 530.5 | 795.3 | 42.6 | 281.9 | 225.1 | 51.33 | 3.003 | 1051 | 963.5 | 508.6 | 281.9 | 246.7 | 127.9 | 0.036 |
| R²     | 0.974  | 0.983 | 0.971 | 0.987 | 0.970 | 0.833 | 0.783 | 0.982 | 0.954 | 0.946 | 0.967 | 0.991 | 0.967 | 0.486 | 0.803 | 0.986 | 0.974 | 0.971 | 0.991 | 0.965 | 0.982 |
| RMSE   | 0.004  | 0.382 | 0.119 | 0.100 | 0.699 | 0.154 | 0.095 | 0.003 | 0.624 | 0.112 | 0.527 | 1.960 | 0.497 | 0.621 | 0.005 | 0.689 | 0.655 | 1.108 | 5.084 | 0.973 | 0.825 |

Figure 1 shows fluctuating weight percentage of the tree parts by age. At the initial stage, the percentages of leaf of Site1 and Site2 and root of Site3, but root and branch in Site3 were higher than those of Site1 and Site2. It indicates that, in the deeper peats, root proliferates unhindered in all directions. In contrast, root in shallow peat, with hardpan or high-water level at its beneath, expanded more radially and tends to form Knud (buttress root). In all sites, stem steadily increased with
time until reaching a levelling-off stage occupying between 60% and 75% out of the total weight in five years. The total weight of one tree in Site1 was 44.5 kg, in Site2 is 169.9 kg, and in Site3 is 408.6 kg. As a comparison, trees in natural forests of 4.5–5.6 m tall with average diameter of 7.16 cm produced 13.38 kg of biomass [7]. Out of that, 33.9% was allocated to the stem, 25% to the branches, 22% to the needles, 17.8% to the coarse roots, and 1.3% to the small roots. The ratio of belowground biomass to aboveground biomass amounted to 0.26. [7]. In this sense, Acacia trees in the sites generated more biomass than the forest tree with the same diameter/circle size.

![Figure 1](image1.png)

**Figure 1.** Weight percentages of the tree’s components.

### 3.3. Correlations among tree parts

Figure 2 shows correlations between perimeter, height, and stem which compares the data with estimated values of the allometric model. These models that relate perimeter to height and relate perimeter x height to stem generated $R^2$ larger 0.95 for estimating height and stem by measuring perimeter. In another application, the inverse function expressed by Equation 3 can be used to estimate perimeter by measuring height such as possibly done using remote sensing or aerial photograph. The maximum height is around 30 m, but the maximum perimeter is different over three sites. Perimeter of Site1 and Site2 never reached 25 cm while in Site3 could be close to 35 cm in five years. Thus, perimeter combined with the allometric model can be used to estimate stem with a rationale result. Furthermore, stem in Site1 and Site2 rarely reached 25 kg but in Site3 could be up to 30 kg in five years.
Figure 2. Correlations between circle, height, and stem.

3.4. Stem’s growth and survival trees
Figure 3 shows rates of stem growth and surviving trees in one hectare. The rate was calculated using Equation 2. The rates form a bell curve, in which different sites resulted different maximum values. Site3 produced the highest value around 103 kg/y at 3.9 years followed by Site2 around 47 kg/y at 2.6 years then Site1 around 10 kg/y at 3.6 years. By considering other aspects tree cutting is undertaken every four years or more. Though, it is expected to cut the tree earlier, if possible. Producing a faster-growing Acacia with better maintenance in the fields is a continuous pursuit.

The loss of tree biomass over time can lead to underestimating above-ground net primary productivity if not accounted properly [18]. Here, the surviving trees even in the same plot fluctuated with time or rotation. New trees can be replanted to substitute the dead ones in the earlier stage, less than one year. When the wild bushes grow covering the lands, replanting is difficult. Even if it is done, a new tree is hard to survive due to limited exposure to the sunlight. Generally, the surviving tree is around 60% in one hectare planted with about 1100 trees in the interval of 3 m x 3 m [1]. Figure 3 shows the survival trees in a certain plot of this study. The curve displayed estimated value using Equation 1 the following formula:

\[ Y = 1 - Y_m \left[ 1 - \left( 1 + \frac{x}{a} \right)^b \right]^{-c} \] ..........................(4)

Where, \( Y_m = 13.32 \), \( a = 4.34 \), \( b = 1.00 \), and \( c = 0.03 \) with \( R^2=0.861 \) and RMSE=0.016. The model shows the decrease of the survival trees with time until 67% within five years. Initially, the decreasing rate is higher around 8.7% per year but then lower with time to reach 4.5% per year.

3.5. Biomass and carbon
Figure 4 shows total biomass and carbon gained from stem and those tree parts left in the field in one hectare. The weight of carbon was calculated from carbon content of each tree parts taken from secondary data [3,5], in which the carbon content of root is 45.18%, knud is 47.83%, Stem is 48.01%,
branch is 48.34% and leaf is 51.49%. Total biomass, as well as carbon, differ across site where Site3 has the highest values followed by Site2 and Site1. At five years, total biomass and carbon each reach 36.3 tonnes and 17.4 tonnes in Site1, 187.5 tonnes and 90.1 tonnes in Site2, and 443.7 tonnes and 213 tonnes in Site3. While left biomass and carbon in the field reach 19.1 tonnes and 9.1 tonnes in Site1, 108.1 tonnes and 51.9 tonnes in Site2, and 233.8 tonnes and 107.4 tonnes in Site3.

For comparisons, Dharmawan et al. [5] reported total carbon from understory was 73.08 tonnes, seedlings 4.93 tonnes, saplings 13.64 tonnes, and boles 26.13 tonnes. While NATR et al. [3] reported 30.53 tonnes in 2 years, and 43.19 tonnes in years. Both were closer to the Site2.

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![Figure 4. Biomass and carbon in one rotation.](image)

![Figure 5. Biomass and carbon accumulation.](image)

The left biomass will enrich organic materials to be converted into peat thickness by dividing with bulk density (say, 0.2 g/cc) for a loosed condition and by particle density (0.5 g/cc) for a compacted condition. By doing a simulation on four rotations (20 years), such as shown in Figure 5, the potential rate of additional peat thickness would range between 0.07–0.18 cm/y in Site1, 0.42–1.06 cm/y in Site2,
and 0.83–2.08 cm/y in Site3. Similarly, the absorption rate of carbon by the trees is about 3.33 tonnes/y in Site1, 17.92 tonnes/y in Site2, and 39.60 tonnes/y in Site3. Parts of these absorbed carbon would enrich the field at 1.74 tonnes/y in Site1, 10.18 tonnes/y in Site2, and 19.98 tonnes/y in Site3. This carbon enhancement to some extend would compensate for the losses due to carbon emission from the managed peatlands as being concerned by many parties.

4. Conclusions
Acacia tree grows better in peatlands having a thicker layer, larger than 1 meter. The growth of each part of tree such as root, knud, stem, branch, and leaf can be represented by a newly introduced allometric model. The model can relate tree parts to estimate the tree biomass. In one hectare of a rotation within 5 years, total biomass ranged 36.3–443.7 tonnes, and total carbon absorbed ranged 17.4–213.0 tonnes. Successive rotations would potentially result additional organic matter at the rate of 0.07–2.08 cm/y, and carbon enhancement at the rate of 1.74–19.98 tonnes/y. The increasing carbon thickness would lessen carbon losses from the peatlands.

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