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Allometric equations for estimating above ground biomass and leaf area of planted teak (Tectona grandis) forests under agroforestry management in East Java, Indonesia

Ris Hadi PURWANTO* and Masami SHIBA**

1. Introduction

Above ground biomass is the amount of standing organic matter per unit area at a given time. which is related to a function of productivity system, stand age, and organic allocation, and exportation strategies (Cintron and Novelli, 1984). The estimation of above ground biomass not only provides increasingly valuable means for evaluating world wide productivity patterns (Rodin and Bazilevich, 1967), but is also very important for the study of the functional aspects of forests such as primary productivity, nutrient cycling and energy flow (Hasse et al., 1985). Consequently, biomass data is important in order to understand forest ecosystem characteristics to establish the proper management system based on the sustainable yield principle.

The most common procedure for estimating tree biomass is through the use of regression. Trees are chosen through an appropriate selection procedure for destructive sampling, and weights or mass of the

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components of each tree are determined and related by regression to one or more dimensions of the standing tree. The tree is normally separated into three above ground components: (1) bole or main stem, (2) bole bark, and (3) crown (branches and leaves). Occasionally, a fourth component, below ground biomass is considered.

The process of collecting data and developing biomass relationships falls under the subject of allometry, the measure and study of growth or size of a part in relation to an entire organism (Parresol, 1999). The term of "allometry" was defined as an exponential or logarithmic relationships that characterize harmonious growth with changing proportions. In practice a set of sample trees are cut down and subjected to intensive measurement, so that biomass, production and other dimensions (as dependent variables) can be related to diameter (or other independent variables) in logarithmic regressions (Whittaker, et al., 1975). The amount of dry weight for above ground components of standing trees can be estimated non-destructively using appropriate equations for each component or proportional relationships with total biomass previously developed or determined through destructive sampling mentioned above.

Teak (Tectona grandis) as a dominant species in moist deciduous forests in Java has been planted for the past two hundred years in the lowlands of monsoon climate regions (Cordes, 1881; Whitmore, 1984). Extensive areas of these forests are being clear felled for sawn timber, woody furniture, and firewood. Regenerating teak forests in Java has been carried out successfully under agroforestry systems by traditional and intensive tallingya and intensive alley cropping.

Though teak forests have been grown in a large scale by the State Forest Enterprise, a database on teak biomass in Java is lacking. This paper presents the results of allometric equations for estimating above ground biomass and leaf area of planted teak forests under agroforestry.

2. Materials and methods

2.1. Study site

The study area is located at the eastern foot of Mt. Lawu (7°30'S and 112°30'E) in East Java, Indonesia, and is being managed by Madiun Forest District, a State Forest Enterprise under the control of Perhutani in Java. The total area of Madiun district is ca. 115,400 ha, and the Madiun Forest District covers an area of 30,395 ha, or 26% of the total area. Teak forests of various ages grow on volcanic soil in altitude from 50 m to 600 m a.s.l by agroforestry management to settle the social problems with the local forest farmers and increase forest productivity simultaneously. Madiun Forest District is classified into the moist deciduous forest climate. The moist deciduous forest grows in the region below 1,200 m a.s.l in Java. The rainfall is 1,500-4,000 mm, and there are 4-6 dry months. Moist deciduous forests are characterized by Acacia leucophloea (Legu.) and Salmalia malabarica (Bomb.), and distinct leafless period during dry season (Whitten et al., 1996). During the wet season, a minimum light reaches the ground because of the thick foliage. The moist deciduous forests exhibit a stratified vertical structure. Regarding horizontal structure, the forest type does not show any characteristic species association (Chandrasekharan, 1962). The dominant sylvan community is comprised of Tectona grandis, and many other species such as cajeput (Melaleuca leucadendron), Cassia siamea, Acacia spp, Swietenia spp, Schleicheria oleosa, Gmelina arborea, Paraserianthes falcatoria, Leucaena glauca, Melia azedarach, Dalbergia spp, Eucaliptus spp, etc. are commonly found either as mono or mixed species plantations.

Purwanto et al. (2003) reported the area has two distinct seasons: a dry season (May-September) and rainy season (October-April). Air temperature is relatively stable throughout the year with mean daily temperatures of 28.8°C. Mean annual precipitation during the past 20 years was 1900 mm. On Whitmore’s map of rainfall types for the tropical Far East, the area is classified into types C and D or as a seasonal type (Whitmore, 1984).

The ground vegetation cover in teak plantations during the rainy season consisted of ca. 31 species. Eupatorium pallescens is the dominant shrub species as undergrowth (Pudyatmoko, 1998). The accumulated litter in the forest floor together with shrubs and grasses is a potential fire risk during the dry season.

The geological structure in most of the area is
volcanic, the soil type is a red-brownish latosol, and the topography is gently undulating and slightly rocky (Margono et al. 1989).

2.2. Plant materials

The research was conducted in teak plantations under agroforestry of traditional and intensive taungya and intensive alley cropping system. In the traditional taungya system, landless farmers usually receive 0.25 hectares of forest land on which they have to sow teak seeds by a spacing of 3 m x 1m. Wide inter-spaces, having no shade, are utilized for planting the agricultural crops as groundnut, soybeans, mung bean, chilies, cassava, maize and rice. Leguminous species (Leucaena glauca), which supply fodder and green manure, are grown by line planting between teak rows in the initial stage. Because of its nitrogen fixing ability, Leucaena glauca trees are usually pruned cut at 10 cm above ground level half-year after sowing, and used for mulching the land surface and improve soil conditions. The farmers also do periodical weeding and hoeing during the first two years. Because the traditional taungya system are not always optimal for both the harvest of agricultural crops and teak trees, the intensive taungya and alley cropping system are attempted. Through those systems the farmers are encouraged to get the wider area for cash crop cultivation, subsidies to buy agricultural tools, fees for land preparation, and fertilizers (both chemical and manure). Duration of cultivation agricultural crops is also extended until the stands become mature, especially in the alley cropping system, and an effort is made to involve the local people in forestry activities as planting, weeding, thinning and fuel-wood utilization. In return, they have to plant and maintain neighboring forests. The alley cropping system is a land use system whereby food crops are grown in alleys formed by trees or shrubs that are pruned to provide green manure and mulch to restore soil fertility on degraded land maintain productivity (Cobbina et al. 1989).

Thinning was done to immature stands in order to stimulate the growth of teak trees and increase the total yield. The first thinning is carried out four and half years after sowing, and the thinning ratio was more or less 50% of original stock, depending upon the growth, density and site quality of the plantations.

2.3. Tree sampling

Field observation suggested that there no clear the relationships between average size of the partials biomass in individual teak trees and agroforestry practices, but the practices had effects on the growth, i.e. the more intensive management, the faster growth occurred. Thus, this research aimed to develop generalized allometric equations for planted teak forests, under different agroforestry systems, i.e., traditional and intensive taungya, and intensive alley cropping system. A total of 316 teak trees from the Madiun Forest District were measured to develop the relationships between stem diameter at 1.3 m above the ground (D) and tree height (H). Of the 316 sample trees, 195, 33 and 88 trees were obtained from the traditional taungya, intensive taungya, and intensive alley cropping system, respectively. The stands were primarily even aged, ranging from 3 to 79 years old, and both the D and H spanned nearly the complete range of this species.

For establishing the allometric equations, 144 sample trees were measured to determine allometry relationships between D and stem diameter at the lowest major living branch (Dm). Stem weight (Ws) of 31 trees, branch weight (Wd) of 17 trees, leaf weight (Wi) of 9 trees, and leaf area (U) of 10 trees.

Field studies were conducted during in April of 2000 (growing season), and this complementary survey was conducted in September of 2000 (end of the dry season) using the stratified tree sampling method for biomass estimation (Negi and Sharma, 1985). Sample trees were felled and divided into leaves, branches and stem. The total fresh weight of each component was measured in the field. The leaf samples were taken from various height levels, and that the leaf area be estimated separately for every stratum. Leaf area was directly measured in the field by area grid method. A grid of squares is placed over the leaf and the squares covered by the leaf are summed to obtain the total leaf area (Larsen and Kershaw, 1991). Representative sub-samples were brought back to the laboratory and oven-dried to constant weight at 80°C. The total dry-weight of each component was calculated from the ratio
of dry weight to fresh weight of the corresponding sub-samples.

2.4. Estimation method of above ground biomass

It is well known that the allometry formulates the quantitative correlation between two different parts of a plant. When one part of an individual plant is Y as the dependent variable and X for another part of the independent variable, the relationships between both parts is usually satisfied by the allometric equation of

\[ Y = aX^b \]  

where, \( a \) and \( b \) are constant, and \( b \) is known to be relatively growth constant. The equation can be expressed linear regression on logarithmic scale. Whereas, the relationships between \( H \) and \( D \) was approximated by the hyperbolic relation as proposed by Ogawa and Kira (1977), as follow:

[1] \[ \frac{1}{H} = \frac{1}{AD^b} + \frac{1}{B} \]  

where, \( H \) (tree height, m), \( D \) (diameter at 1.3 m above the ground, cm), \( A \), and \( B \) are coefficients specific to the forest.

Thus, a quantity of each component of individual teak tree was estimated by the allometry relationships calculated by Eq. (1), and for the relation of \( H \) to \( D \) was used Eq. (2).

3. Results

The quantities estimated were tree height (\( H \)), stem diameter at the lowest major living branch (\( D_b \)), stem dry weight (\( W_s \)), branch dry weight (\( W_b \)), leaf dry weight (\( W_l \)), and leaf area (\( U \)) per tree.

The relation of tree height (\( H \), m) to stem diameter at 1.3m above ground (\( D \), cm) was determined by the hyperbolic relation (Ogawa et al., 1965; Ogawa and Kira, 1977) as follows:

\[ \frac{1}{H} = 0.8983 \frac{1}{D^{0.0260}} \]  

More than 90 % of the stem diameter at the lowest major living branch variability is explained by \( D \). In this relation, one equation came out in spite of different management practices, as shown in Fig. 2.

Stem dry weight (\( W_s \), kg) is closely correlated with the square of stem diameter at 1.3m above ground (\( D \), cm) multiplied by their height (\( H \), m). The same trend was found in every agroforestry system, as shown in

![Fig. 1. Hyperbolic relationships between stem diameter at 1.3m aboveground (D) and tree height (H) for planted teak forests under agroforestry management in the study area. Square, the intensive alley cropping: circle, the intensive taungya: triangle, the traditional taungya system. The hyperbolic curve represents Eq. (3)]
The exponent of $D^2H$ was so close to 1.0 that stem dry weight may be regarded as being proportional to $D^2H$. The $D^2H$ is expected to be proportional to the volume or weight of stem, if the stem is approximately cone-shaped. In fact, the allometry constant (0.9586) in Eq. (5) has a close unity. Considering the large number of age and agroforestry management practices involved, it is rather surprising that the observed values fit a single regression so well.

The relation between branch dry weight ($W_B$, kg) and $D^2H$ per tree was approximated by the equation:

$$W_B = 0.0058(D^2H)^{0.9380} \quad (n = 17, r^2 = 0.979) \quad (6)$$

where $W_B$ included the branches of teak trees under traditional and intensive *taungya* and the alley cropping system. The exponent of $(D^2H)$ indicates a gradual increase in the ratio of branches to the $D^2H$ as tree size increases. Here, the $W_B - D^2H$ relation in the traditional and intensive *taungya* was also similar to that found for the intensive alley cropping system, as shown in Fig. 4.

Leaf dry weight ($W_L$, kg) was approximated by the square of stem diameter at the lowest major living
branch \((D_{b})\). The result showed that the leaf dry weight was closely correlated with the square of stem diameter at the lowest major living branch \((D_{b})\), as follows:

\[
WL = 0.0660(D_{b})^{0.8759} \quad (n = 9, \; r^2 = 0.996)
\]  

(7)

It showed the square of stem diameter at the lowest major living branch or \((D_{b})^{2}\) explained about 99% of the variability in leaf weight. The exponent of \((D_{b})^{2}\) slightly smaller than 1.0, suggesting an increase in the ratio of diameter at the lowest branch to leaves with an increase of tree size. The relationship between \(W_{L}\) and \(D_{b}^{2}\) is shown in Fig. 5.

![Fig. 5. Simple allometry between \(W_{L}\) and \(D_{b}^{2}\) for planted teak forests under agroforestry management in the study area. Square, the intensive alley cropping; circle, the intensive taungya; triangle, the traditional taungya system. The straight line represents Eq. (7).](image)

Leaf area (one side, \(U\), \(m^2\)) and the corresponding leaf dry weight \((W_{L}\), \(kg\)) are linearity correlated, as shown in Fig. 6. The relations are similar among teak trees under traditional and intensive taungya, and intensive alley cropping system, as follows:

\[
U = 7.9528(W_{L})^{0.1016} \quad (n = 10, \; r^2 = 0.997)
\]

(8)

It showed the leaf dry weight explained more than 90% of the variability in leaf area.

![Fig. 6. Relation between leaf dry weight \((W_{L})\) and leaf area \((U)\) in individual tree for planted teak forests under agroforestry management in the study area. Square, the intensive alley cropping; circle, the intensive taungya; triangle, the traditional taungya system. The straight line represents Eq. (8).](image)

4. Discussion

To establish allometric equations for estimating aboveground biomass and leaf area of planted teak \((Tectona grandis)\) forests in the three different agroforestry systems, Eq. (3)–(8) were formulated. Usually in planted forests, allometric relationships appear to be independent of site quality (Assmann, 1970; Drew and Flewelling, 1977). Site quality does not affect the relationship between average size and density, but it does effect the growth (Jack and Long, 1996). Miller (1981) applied this concept in his model about the effect of fertilization on forest stand development: fertilization increases yield by accelerating stand development temporally. This effect has been confirmed in slash pine \((Pinus elliottii)\) where fertilization had little effect on dimensional relationships (Jokela et al., 1989; Colbert et al., 1990). However, that allometries differ between genetic families of Loblolly Pine \((Pinus taeda L.)\), especially at young ages (Lee, 1989). This rises the question whether Eq. (3)–(8) are applicable for estimating plant biomass in the three different agroforestry systems.

Regarding the D-H relation of Eq. (3) obtained from
the data of sample trees in three different agroforestry systems, the data for the three systems have a similar dispersion around the regression curve of Fig. 1. Thus, Eq. (3) seemed to be applicable to all three agroforestry systems practiced in the teak plantations of East Java. The equation showed that the relative rate of stem elongation was nearly equal to that of diameter increase \((h = 1.1)\) in the initial stage of teak forest growth. Tree form changes from a stick-like form in early stages to an umbrella form after ten years old. In trees of the smallest size class the tree height increases in proportion to the stem diameter, but it approaches a plateau in very large trees. Using the equation, the maximum height was estimated as 38.5 meters.

To obtain stem diameter at the lowest major living branch \((D_B)\) estimates by means of regression, we used an exponential model Eq. (4), in which diameter at 1.3 m above ground \((D)\) was used as the independent variable. Such equations and the proportional relationships are based on easily measured parameters such as tree diameter. Despite measuring tree height \((H)\) is more time consuming, inclusion of height in the independent variable mostly as \(D^2H\) and \(D^2H - W_s\) relations are stable and do not generally differ among the different agroforestry systems. Furthermore, the trajectory of Eq. (5) \(- (6)\) in the log \(D^2H - \log W_s\) and log \(D^2H - \log W_b\) diagram, respectively, seemed to be similar to the \(D^2H - W_s\) relation obtained by Kato et al. (1978) at a lowland tropical rain forest in Pasoh, Malaysia, and the \(D^2H - W_b\) relation obtained by Ogawa et al. (1965) at tropical rain forest in Thailand, if the range of variables is limited as shown in Fig. 3 and Fig. 4. The fitness of the relations between the leaf amount and \(D\) or \(D^2H\) to the allometric regression is even less satisfactory as compared with the mentioned above case for stem and branch weight (Ogawa et al. 1965). Although Ogawa et al. (1965) reported the asymptote of \(W_l\) at \(W_s\) tropical forests of Thailand, it was not clear in our data. In other studies leaf weight has been more closely correlated with basal sapwood area (Grier and Waring, 1974) and stem diameter at the lowest major living branch \((D_B)\) than with basal area (Ford, 1982). In this study, we used the square of stem diameter at the lowest major living branch \((D_B)\) to estimate the leaf dry weight. The result showed one equation came out in spite of the data differing in agroforestry systems.

Ogawa and Kira (1977) suggested the relations between the total leaf area of a tree \((U)\) and weight of leaves per tree \((W_l)\) was correlated,

\[
U = A(W_l)^h
\]

is characterized by a value of \(h\) somewhat smaller than 1.0 (usually 0.85 - 0.95 in broadleaf trees). This means that the mean specific area in a tree \((U/W_l)\) tends to become smaller with increasing tree size (Ogawa and Kira, 1977). In this study the exponent of \(W_l\) was so close to 1.0 that leaf area was regarded to be proportional to leaf weight.

5. Conclusion

The generalized allometric equations were developed to estimate the above ground biomass and leaf area of planted teak \((Tectona grandis)\) under three agroforestry systems (traditional taungya, intensive taungya, and intensive alley cropping) in East Java, Indonesia. The quantities estimated were tree height \((H)\), stem diameter at the lowest major living branch \((D_B)\), stem dry weight \((W_s)\), branch dry weight \((W_b)\), leaf dry weight \((W_l)\), and leaf area \((U)\) per tree. By the measurement of harvested tree samples the relationships among tree dimensions were satisfied with hyperbolic relation to tree height, and a simple linear regression to stem diameter at the lowest major living branch, stem dry weight, branch dry weight, leaf dry weight, and leaf area. The results suggested

\[
W_s = 0.0333(D^2H)^{0.0386}
\]

\[
W_b = 0.0060(D^2H)^{0.0270}
\]

The amount of leaves produced by a tree is so sensitive to such factors as incident light intensity reaching its crown, stand density, tree age, etc. that its estimation is liable to greater error. The fitness of the relations between the leaf amount and \(D\) or \(D^2H\) to the allometric regression is even less satisfactory as compared with the mentioned above case for stem and branch weight (Ogawa et al. 1965). Although Ogawa et al. (1965) reported the asymptote of \(W_l\) at \(W_s\) tropical forests of Thailand, it was not clear in our data. In other studies leaf weight has been more closely correlated with basal sapwood area (Grier and Waring, 1974) and stem diameter at the lowest major living branch \((D_B)\) than with basal area (Ford, 1982). In this study, we used the square of stem diameter at the lowest major living branch \((D_B)\) to estimate the leaf dry weight. The result showed one equation came out in spite of the data differing in agroforestry systems.

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that the equations appear to be applicable over a wide area of agroforestry management practices, and are usable for both young and old planted teak forests.

References