論　文

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

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インドネシア東ジャワのアグロフォレストリーにおけるチーク人工林（*Tectona grandis*）の地上部バイオマスおよび葉面積量推定のための相対成長式

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Allometric equations were described for estimating stem, branch and leaf biomass from measurements of stem diameter at breast height (D), stem diameter at the lowest major living branch (D_B) and total height (H) in the teak tree (*Tectona grandis*) under both traditional and intensive *taungya* and alley cropping system of agroforestry management in moist deciduous forests of East Java, Indonesia. The results showed a diameter of 1.3m above the ground (D) alone was a good predictor of stem diameter at the lowest major living branch (D_B) and tree height (H). Leaf area (U) was a good predictor of leaf dry weight (W_L). When D was combined with H, r^2 was improved somewhat for stem and branch biomass. The relationships among measured tree dimensions drew a simple linear in log-log scale diagrams with r^2 over 0.969, suggesting the growth patterns of tree dimensions were closely inter-dependent, whereas the allometric equation between D and H was approximated by the hyperbolic relation with r^2 over 0.853. The individual tree equations appear to be applicable over a wide area of agroforestry management practices, and are usable for both young and old planted teak forests in East Java.
Key words: allometric equations, aboveground biomass, teak (*Tectona grandis*), agroforestry.

インドネシア東ジャワの湿潤落葉樹林地帯で行われているアグロフォレストリーである「伝統的タウンヤシステム」と「アレークロッピングシステム」で造成されたチーク人工林の幹，枝，葉のバイオマス量を推定するため，幹部胸高直径（D），枝下直径（D_B），樹高（H）を測定パラメータとする相対成長式を明らかにした．その結果，地上高1.3mでの直径（D）のみで枝下直径（D_B）と樹高（H）をよく予測しうることを明らかにした．葉面積（U）から葉乾燥重量（W_L）を精度良く予測することができた．パラメータHを組み入れることで，Dによる幹および枝バイオマス量推定精度の寄与率はいくぶん向上した．測定パラメータの関係は0.969以上の寄与率で，両対数スケール上に直線的にプロットされ，各パラメータの成長パターンが密接に相互依存的であることが示唆された．他方，DとHの間の相対成長式は寄与率0.853以上で双曲線関数により近似された．単木について得られた相対成長式が広範囲のアグロフォレストリー施業へ適用可能であり，また，東ジャワの若齢，壮齢双方のチーク人工林に利用しうることを明らかにした．
キーワード：相対成長式 地上部バイオマス量，チーク人工林，アグロフォレストリー

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 *taungya*, 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*, *Schleichera oleosa*, *Gmelina arborea*, *Paraserianthes falcataria*, *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℃. 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 × 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, *Leucane 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 (D_B). Stem weight (W_S) of 31 trees, branch weight (W_B) of 17 trees, leaf weight (W_L) 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℃. 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

$$Y = aX^b \tag{1}$$

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:

$$\frac{1}{H} = \frac{1}{AD^h} + \frac{1}{B}, \tag{2}$$

where, H (tree height, m), D (diameter at 1.3 m above the ground, cm), h, 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:

$$\frac{1}{H} = 0.8983\frac{1}{D^{1.1}} + 0.0260 \quad (n = 316, \ r^2 = 0.853) \tag{3}$$

Stem diameter of a tree was an excellent predictor of tree height, as shown in Fig. 1., and explained more than 80 % of the variability in tree height. The remaining variability may be attributed to the inherent characteristics of tree, stand (densities and age class distribution), and/or site condition (soil and hydrological parameters).

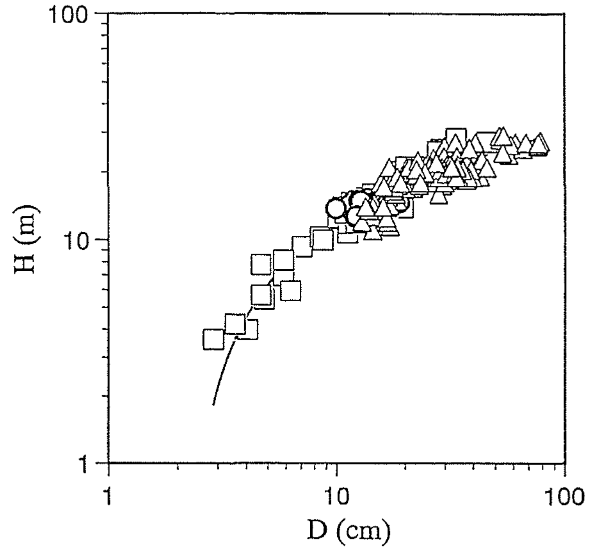

Fig. 1. Hyperbolic relationships between stem diameter at 1.3m aboveground (D) and tree height (H) for planted teak forests under agroforestry management in the study area. Square, the intensive alley cropping; circle, the intensive *taungya*; triangle, the traditional *taungya* system. The hyperbolic curve represents Eq. (3)

Diameter at the lowest major living branch or at the base of crown (D_B) was the simplest and most stable parameter for estimating the leaf dry weight in individual trees. Diameter at the lowest major living branch (D_B, cm) was closely correlated with stem diameter at breast height (D, cm) as follows:

$$D_B = 0.9258(D)^{0.9524} \quad (n = 144, r^2 = 0.969) \tag{4}$$

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

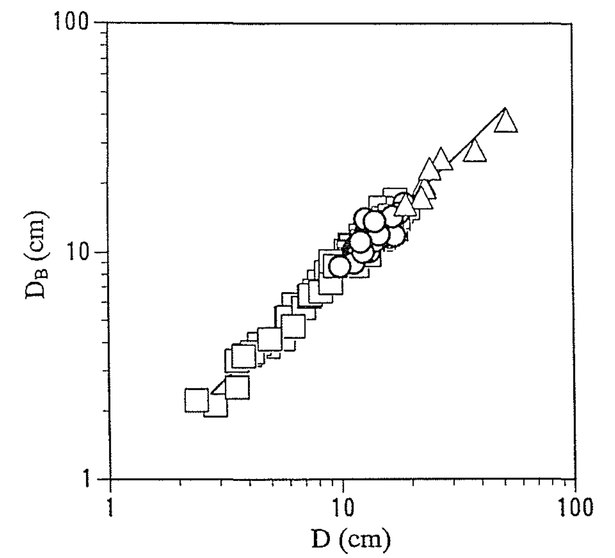

Fig. 2. Relation between stem diameter at 1.3m aboveground (D) and stem diameter at the lowest major living branch (D_B) for planted teak forests under agroforestry management in the study area. Square, the intensive alley cropping; circle, the intensive taungya; triangle, the traditional *taungya* system. The straight line represents Eq. (4).

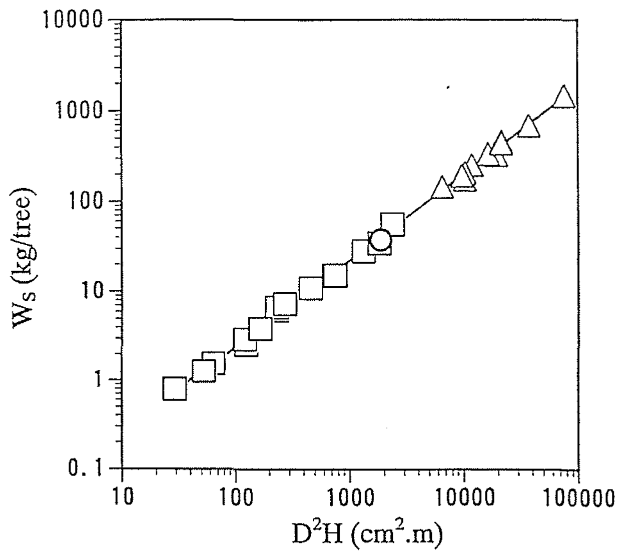

Fig. 3. Stem weight (WS) − D^2H allometry in planted teak forests under agroforestry management in the study area. Square, the intensive alley cropping; circle, the intensive *taungya*; triangle, the traditional *taungya* system. The straight line represents Eq. (5).

Fig. 3. The regression was written as:

$$W_S = 0.0287(D^2H)^{0.9586} \quad (n = 31,\ r^2 = 0.997) \quad (5)$$

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:

$$W_B = 0.0058(D^2H)^{1.0380} \quad (n = 17,\ r^2 = 0.979) \quad (6)$$

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 WB − 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.

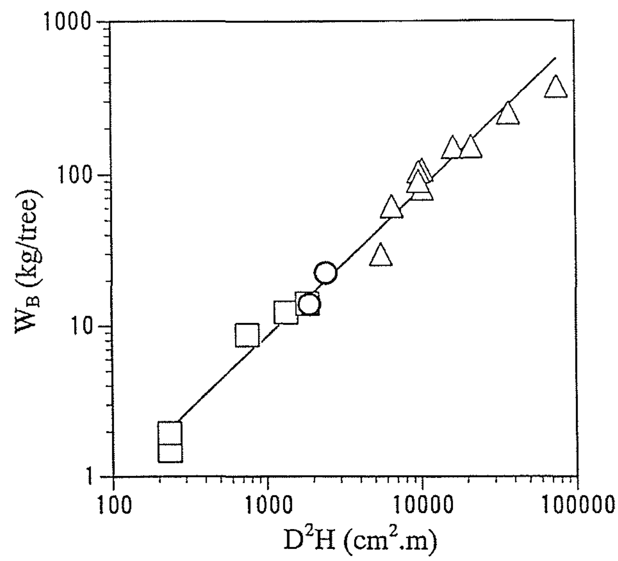

Fig. 4. Relation between branch dry weight per tree (W_B) and the product of the square of stem diameter at 1.3m aboveground (D) and tree height (H) or D^2H for planted teak forests under agroforestry management in the study area. Square, the intensive alley cropping; circle, the intensive *taungya*; triangle, the traditional *taungya* system. The straight line represents Eq. (6).

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 weigh was closely correlated with the square of stem diameter at the lowest major living branch (D_B), as follows:

$$WL = 0.0660(D_B^2)^{0.8759} \quad (n = 9, r^2 = 0.996) \quad (7)$$

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.

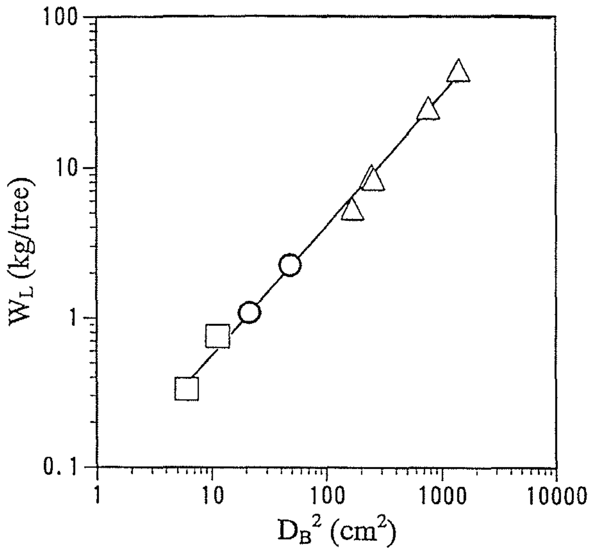

Fig. 5. Simple allometry between W_L and D_B^2 for planted teak forests under agroforestry management in the study area. Square, the intensive alley cropping; circle, the intensive *taungya*; triangle, the traditional *taungya* system. The straight line represents Eq. (7).

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:

$$U = 7.9528(W_L)^{1.0416} \quad (n = 10, r^2 = 0.997) \quad (8)$$

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

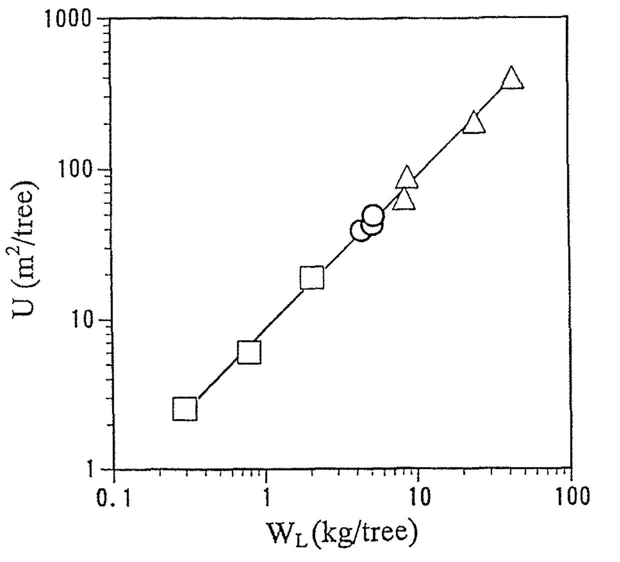

Fig. 6. Relation between leaf dry weight (W_L) and leaf area (U) in individual tree for planted teak forests under agroforestry management in the study area. Square, the intensive alley cropping; circle, the intensive *taungya*; triangle, the traditional *taungya* system. The straight line represents Eq. (8).

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 equals 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 (Ogawa *et al.*, 1965; Ogawa and Kira, 1977), generally contributes to a much better explanation of the variation. In the research, we used D^2H as independent variable to estimate the stem and branch dry weight. The D^2H-W_S and D^2H-W_B 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, i.e.:

$$W_S = 0.0333(D^2H)^{0.9586}$$

$$W_B = 0.0060(D^2H)^{1.0270}$$

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.

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 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.

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