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# Common allometric equations for estimating the tree weight of mangroves

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**Abstract:** Inventory data on tree weights of 104 individual trees representing 10 mangrove species were collected from mangrove forests in South-East Asia to establish common allometric equations for the trunk, leaf, above-ground and root weight. We used the measurable tree dimensions, such as *dbh* (trunk diameter at breast height), $D_{R0.3}$ (trunk diameter at 30 cm above the highest prop root of *Rhizophora* species), $D_B$ (trunk diameter at lowest living branch), and $H$ (tree height) for the independent variable of equations. Among the mangrove species studied, the trunk shape was statistically identical regardless of site and species. However, $\rho$ (wood density of tree trunk) differed significantly among the species. A common allometric equation for trunk weight was derived, when $dbh^2H$ or $D_{R0.3}^2H$ was selected as the independent variable and wood density was taken into account. The common allometric equations for the leaf and the above-ground weight were also derived according to Shinozaki's pipe model and its extended theory. The common allometric relationships for these weights were attained with given $\rho$ of each species, when $D_B^2$ or $dbh^2$ or $D_{R0.3}^2$ was selected as the independent variable. For the root weight, the common equation was derived from the allometric relationship between root weight and above-ground weight, since these two partial weights significantly correlated with each other. Based on these physical and biological parameters, we have proposed four common allometric equations for estimating the mangrove tree weight of trunk, leaf, above-ground part and root.

**Key Words:** Above-ground biomass, pipe model, root biomass, South-East Asia, wood density

## INTRODUCTION

In the context of global warming, carbon absorption by forest ecosystems receives considerable attention now. Mangrove forests are widely distributed along the coasts of tropical and subtropical areas. As mangroves grow on muddy and anaerobic soils which suffer from tidal inundation, they show a unique pattern of biomass allocation. In a *Ceriops tagal* forest, nearly 50% of total biomass was allocated to roots (Komiyama *et al*. 2000). The large amount of carbon fixed by mangroves gets accumulated and stored for a long period in underground parts. With the threat posed by the sea-level change, there is an urgent need for us to collect information on mangrove biomass. The biomass of mangrove forests has been studied for the past 20 years (Clough & Scott 1989, Clough *et al*. 1997, Komiyama *et al*. 1988, 2000, 2002; Ong *et al*. 1995, 2004; Tamai *et al*. 1986) by using allometric relationships.

Allometry is a powerful tool for estimating tree weight from independent variables such as trunk diameter and height that are quantifiable in the field. However, a demerit in using allometric relationships as a tool is that they often show varying relationships for different tree species and sites. It is too laborious for researchers to weigh a number of trees for establishing a series of allometric relationships for all tree species and sites. Thus, the need exists for identifying a common allometric relationship that can be applied for various tree species and within a wide geographical location of the forest.

A common allometric relationship can be predicted when the construction of a tree body is based on biological or physical theories. To date, the pipe model theory (Shinozaki *et al*. 1964a,b) has succeeded in eliminating the site segregation from leaf and branch allometric relationships. The basic idea of this model is that the partial weight of the trunk at a certain height physically sustains weights of upper tree body. Oohata & Shinozaki (1979) have extended this model and showed that the above-ground weight of a tree was a function of the squared diameter at trunk base and wood density. Common

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allometric relationships have been reported for above-ground weight of trees (Brown *et al.* 1989, Ketterings *et al.* 2001) and also for trunk weight of mangroves (Komiyama *et al.* 2002), by adding wood density to coefficients of the equation.

In this study, we have established common allometric relationships for the weight of mangrove trees growing both in primary and secondary stands, based on the pipe model theory and difference in wood density among the species. We also discuss the physical and biological aspects of the common allometric relationships, and propose common equations for estimating mangrove tree biomass.

## METHODS

### Field study

We selected five study sites in Thailand and Indonesia (Table 1), which included two mangrove forests in primary condition. These five sites are located from 1°10′N to 12°12′N in latitude, and from 98°36′E to 127°57′E in longitude. One hundred and four sample trees representing 10 mangrove species (*Rhizophora mucronata* Lamk., *R. apiculata* Bl., *Bruguiera gymnorrhiza* (L.) Lamk., *B. cylindrica* (L.) Bl., *Ceriops tagal* (Perr.) C. B. Robinson, *Avicennia alba* Bl., *Sonneratia alba* J. Smith., *S. caseolaris* (L.) Engler, *Xylocarpus granatum* König and *X. moluccensis* (Lamk.) Roem.) were felled and weighed (Table 2). In this study, sample trees with diameter (*dbh* or $D_{R0.3}$, see below) larger than 5.0 cm were used for the analysis.

For all sample trees, the trunk diameters at ground level ($D_0$), at 30 cm height ($D_{0.3}$), at each 1-m interval ($D_{1.3} = dbh$, $D_{2.3}$, $D_{3.3} \ldots$), and at the height of lowest living branch ($D_B$), the tree height ($H$), and the height of the lowest living branch ($H_B$) were measured. For *Rhizophora* species, trunk diameter at 30 cm above the highest prop root ($D_{R0.3}$) was also measured. Assuming the trunks to be conical in shape, the trunk diameters at each 1-m interval were used for calculating the trunk volume ($V_S$).

Each sample tree was cut at ground level using handsaws or chainsaws, and separated manually into trunk, branch, and leaf fractions. These organs were weighed fresh using electric balances, and then the trunk dry weight $W_S$, the branch dry weight $W_B$ and the leaf dry weight $W_L$ were derived. For this derivation, samples of *c.* 500 g of each organ were oven-dried (110 °C for 48 h) to acquire the dry matter ratios.

Within the 104 tree samples, 26 individual trees were studied for the root weight, consisting of *R. apiculata*, *R. mucronata*, *B. cylindrica*, *B. gymnorrhiza*, *X. granatum*, *C. tagal*, *S. caseolaris*, *S. alba* and *A. alba*. The root weight of an individual tree was investigated either by the trench method (Komiyama *et al.* 1987, 1988, 2000) or by complete excavation (Poungparn *et al.* 2002, Tamai *et al.* 1986, the current study). The prop roots of *Rhizophora* species and aerial roots of other species were included in the root weight instead of the above-ground weight. The dry root weight $W_R$ was calculated by the dry matter ratio.

The wood density of tree trunk $\rho$ (t m$^{-3}$) was measured for each mangrove species. For the 104 tree samples mentioned above, $\rho$ was calculated from the value of $W_S/V_S$.

**Table 1.** Mangrove forests where tree weights used for establishment of the common allometric relationships were studied.

| Site | Location | Stage of forest | Tree density (N ha$^{-1}$) | Basal area (m$^2$ ha$^{-1}$) | Max. $D$ (cm) | Max. $H$ (m) | Mean temp. (°C) | Precipitation (mm y$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Pang-nga (Thailand) | 8° 20′N, 98° 36′E | secondary | 1446 | 11.2 | 32.4 | 18.8 | 27.1 | 3634 |
| Trat (Thailand) | 12° 12′N, 102° 33′E | secondary | 1682 | 18.0 | 53.7 | 23.8 | 27.4 | 4810 |
| Satun (Thailand)[1] | 7 °22′N, 100 ° 03′E | secondary | 11 000 | – | – | – | 27.5 | 2263 |
| Ranong (Thailand)[2] | 9° 58′N, 98° 38′E | primary | 1246 | 24.0 | 55.0 | 30.9 | 26.9 | 4152 |
| Halmahera (Indonesia)[3] | 1° 10′N, 127° 57′E | primary | 206–761 | 14.0–36.2 | 47.7–85.6 | 26.6–41.7 | 27.2 | 3250 |

[1] Komiyama *et al.* (2000).
[2] Tamai *et al.* (1986).
[3] Komiyama *et al.* (1988); The trees greater than 8 cm in *dbh* were measured in seven plots.
The ranges of tree density, basal area, Max. $D$ and Max. $H$ of these seven plots are shown.

**Table 2.** Sample trees in five study sites.

| Site | Sample trees | Species | Range of $D$ (cm) | Range of $H$ (m) |
|---|---|---|---|---|
| Pang-nga (Thailand) | 24 | Rm, Bc, Xg, Sa | 5.1–12.7 | 4.49–13.44 |
| Trat (Thailand) | 36 | Aa, Sa, Sc, Ra, Rm, Bg | 5.0–14.1 | 5.10–17.61 |
| Satun (Thailand) | 1 | Ct | 5.3 | 5.12 |
| Ranong (Thailand) | 26 | Ra, Bc, Bg | 5.3–39.7 | 6.15–31.2 |
| Halmahera (Indonesia) | 17 | Bg, Ra, Sa, Xm, Xg | 5.7–48.9 | 7.30–34.3 |
| Total | 104 | – | – | – |

Rm = *Rhizophora mucronata*, Bc = *Bruguiera cylindrica*, Xg = *Xylocarpus granatum*, Sa = *Sonneratia alba*, Aa = *Avicennia alba*, Sc = *S. caseolaris*, Ra = *R. apiculata*, Bg = *B. gymnorrhiza*, Ct = *Ceriops tagal*, Xm = *X. moluccensis*.

For the other additional 22 trees, $\rho$ was calculated from 3–5 wood samples that were cut from base to top per tree in an approximate length of 10 cm. Trunk diameters at both ends and length of each wood sample were measured by using a vernier caliper in undried condition. Then, each sample was oven-dried (110 °C for 48 h), and dry weight was determined by using an electric balance with an accuracy of 0.1 g (Bonso Co. Ltd., model 339). The frustum volume of each trunk sample was calculated from diameters and length.

### Backgrounds for common allometric equations

A common allometric equation for trunk weight was developed by us (Komiyama *et al.* 2002) for a range of trees in secondary mangrove forests. We found that the trunk weight was a function of the external shape and wood density. The external shape of the trunk can be evaluated from the relationship between $V_S$ and $dbh^2H$. We also found that the external shape could be assumed to be identical among mangrove species growing in the secondary mangrove forests.

In this study, the common allometric relationship for estimating trunk weight was established by using $D$, $H$ and $\rho$ shown in Equation 1:

$$W_s = a\,\rho(D^2H)^b \quad (1)$$

where $D$ stands for $D_{R0.3}$ in the case of *Rhizophora* species and for $dbh$ in the case of other species. To determine the constants a and b of Equation 1, the linear relationships between $W_S/\rho$ and $D^2H$ were examined on logarithmic coordinates. The value of $\rho$ was assumed to be constant for each species.

A common allometric relationship for leaf weight can be obtained from the simple pipe model of Shinozaki *et al.* (1964a). This model is based on the assumption that the body of the tree can be equalled to an assemblage of unit pipes. Thus, the leaf weight above horizon z, $F$(z), shows a proportional relationship with the trunk weight at height z, $C$(z):

$$F(z) = L\,C(z) \quad (2)$$

where $L$ is a proportional constant known as the specific pipe length (Shinozaki *et al.* 1964a). $C$(z) in Equation 2 can be expressed by the cross-sectional area of trunk at the height z, $S$(z), by using the constant relating trunk shape (c), the thickness of each horizon ($\Delta$z) and $\rho$.

$$F(z) = Lc\,\rho\,\Delta z\,S(z) \quad (3)$$

$\Delta$z is set as a constant value of 1 m in this study. Finally, the total leaf weight of a tree $W_L$ is expressed by Equation 4 taking into account the trunk diameter at the lowest living branch $D_B$:

$$W_L = L\,c\,\rho\,(\pi/4)D_B^2 \quad (4)$$

$W_L$ will be proportional to $D_B^2$, if $L$, c, and $\rho$ are assigned specific values for each species.

The simple pipe model of Shinozaki *et al.* (1964a) approximates the tree form only in the crown range. Subsequently, Oohata & Shinozaki (1979) extended the model into the range under the crown with the static model of plant form. They found that the linear relationship held between the total tree weight above z horizon, $T$(z), and the weight of trunk at height z, $C$(z), both in a single tree and a stand level.

$$T(z) = L'C(z) = L'c\,\rho\,\Delta z\,S(z) \quad (5)$$

Then, the total above-ground weight of a tree, $W_{top}$, is expressed by the trunk diameter $D$. In Equation 6, $L'$ represents a proportional constant known as the specific stress length (Oohata & Shinozaki 1979).

$$W_{top} = L'c\,\rho(\pi/4)D^2 \quad (6)$$

Based on the physical or biological theories applied, these common allometric equations (Equation 1 for the trunk weight, Equation 4 for the leaf weight and Equation 6 for the above-ground weight) have different independent variables.

## RESULTS

### Trunk weight

The relationship between $V_S$ and $D^2H$ did not vary among Rhizophoraceae and other species (ANCOVA, $P > 0.05$), though there was a significant difference in $\rho$ between the mangrove species studied (0.340–0.770 t m$^{-3}$, Table 3). There was no difference in $\rho$

**Table 3.** Mean wood density ($\rho$ in t m$^{-3}$) of mangroves.

| Species | $\rho$ (mean ± *SD*) | No. of sample (trees) | Source of samples |
|---|---|---|---|
| Rhizophoraceae | | | |
| *Bruguiera cylindrica* | 0.749 ± 0.042 | 13 | 1, 2 |
| *Bruguiera gymnorrhiza* | 0.699 ± 0.121 | 18 | 1, 2, 3 |
| *Ceriops tagal* | 0.746 ± 0.012 | 6 | 1, 4 |
| *Rhizophora apiculata* | 0.770 ± 0.093 | 33 | 1, 2, 3 |
| *Rhizophora mucronata* | 0.701 ± 0.033 | 13 | 1 |
| Other species | | | |
| *Avicennia alba* | 0.506 ± 0.016 | 9 | 1 |
| *Sonneratia alba* | 0.475 ± 0.047 | 13 | 1, 3 |
| *Sonneratia caseolaris* | 0.340 ± 0.054 | 8 | 1 |
| *Xylocarpus granatum* | 0.528 ± 0.048 | 11 | 1, 3 |
| *Xylocarpus moluccensis* | 0.531 ± 0.010 | 2 | 1, 3 |

$\rho$ of Rhizophoraceae and other species were used for establishment of the common allometric relationship.
[1] The current study.
[2] Tamai *et al.* (1986).
[3] Komiyama *et al.* (1988).
[4] Komiyama *et al.* (2000).

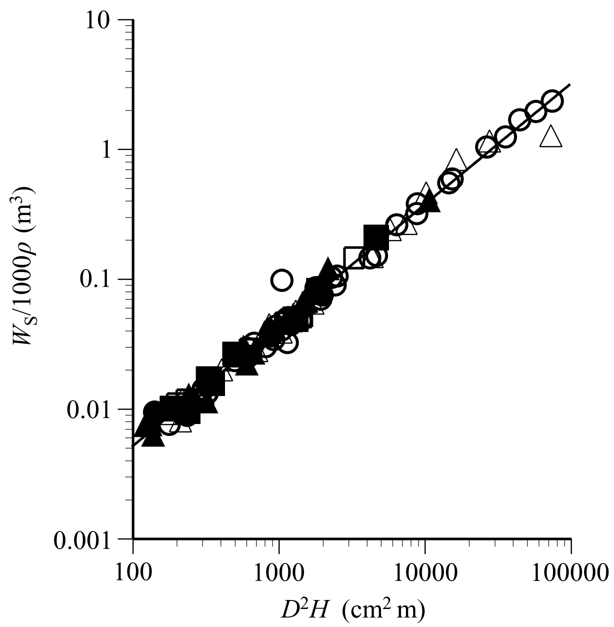


**Figure 1.** Common allometric relationship for trunk weight of mangroves. The relationship shown is between $W_S/1000\rho$ and $D^2H$. The wood density of each species in each site was applied for $\rho$. The trunk diameter $D$ stands for $D_{R0.3}$ for *Rhizophora* species and *dbh* for other species. The tree samples were 104 individuals including ten species. Symbols: (○) = *Rhizophora apiculata* and *R. mucronata*; (●) = *Ceriops tagal*; (△) = *Bruguiera gymnorrhiza* and *B. cylindrica*; (▲) = *Sonneratia alba* and *S. caseolaris*; (□) = *Avicennia alba*; (■) = *Xylocarpus granatum* and *X. moluccensis*.

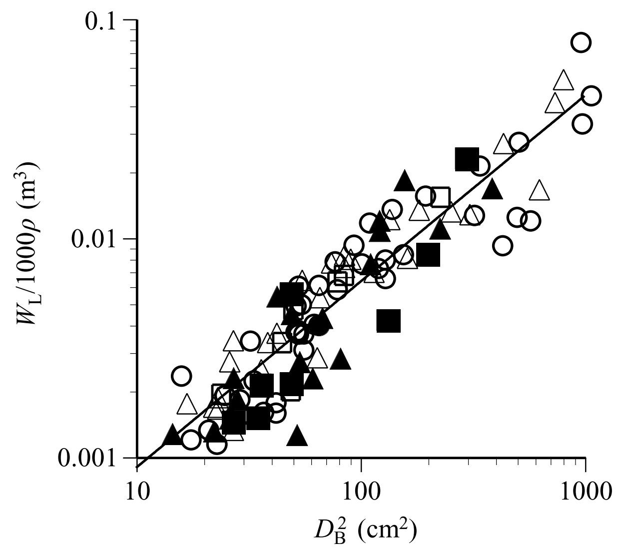


**Figure 2.** Common allometric relationship for leaf weight of mangroves. The relationship shown is between $W_L/1000\rho$ and $D_B^2$. The wood density of each species in each site was applied for $\rho$. The tree samples were 104 individuals including 10 species. Symbols: (○) = *Rhizophora apiculata* and *R. mucronata*; (●) = *Ceriops tagal*; (△) = *Bruguiera gymnorrhiza* and *B. cylindrica*; (▲) = *Sonneratia alba* and *S. caseolaris*; (□) = *Avicennia alba*; (■) = *Xylocarpus granatum* and *X. moluccensis*.

among diameter size classes (5–10 cm, 10–20 cm, and > 20 cm) for any species within any site (ANOVA, $P > 0.05$). No significant difference was observed in $\rho$ between sites for *B. cylindrica* and *R. mucronata* (ANOVA, $P = 0.449$ and $0.120$, respectively). However, for *B. gymnorrhiza* and *R. apiculata*, the difference in $\rho$ was detected among sites (*ANOVA*, $P < 0.001$). In this study, $\rho$ obtained in each study site was used to analyse the relationship for a species (Figures 1–3, and 5).

A close linear relationship was recognized between $W_S/1000\rho$ and $D^2H$ ($R^2 = 0.986$, Figure 1) on logarithmic coordinates. Transforming this relationship between $W_S/1000\rho$ and $D^2H$, the relationship between $W_S$ and $\rho D^2H$ was derived (Table 4). Then, the correction factor CF in Table 4 (the so-called Y0 EST method, Beauchamp & Olson 1973) was adopted to remove the bias in the regression estimate after logarithmic transformation. Finally, the common allometric equation for trunk weight of mangroves was determined as shown in Equation 7.

$$W_s = 0.0696\,\rho\,(D^2H)^{0.931} \quad (7)$$

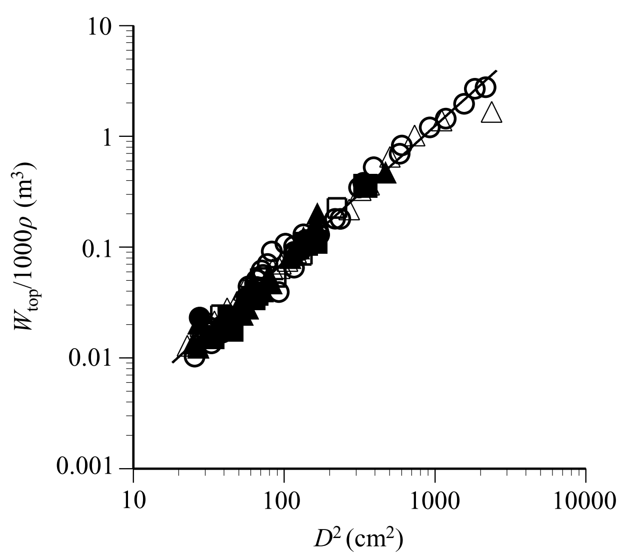


**Figure 3.** Common allometric relationship for above-ground weight of mangroves. The relationship shown is between $W_{top}/1000\rho$ and $D^2$. The wood density of each species in each site was applied for $\rho$. The trunk diameter $D$ stands for $D_{R0.3}$ for *Rhizophora* species and *dbh* for other species. In $W_{top}$, the prop roots of *Rhizophora* species are not included. The tree samples were 104 individuals including 10 species. Symbols: (○) = *Rhizophora apiculata* and *R. mucronata*; (●) = *Ceriops tagal*; (△) = *Bruguiera gymnorrhiza* and *B. cylindrica*; (▲) = *Sonneratia alba* and *S. caseolaris*; (□) = *Avicennia alba*; (■) = *Xylocarpus granatum* and *X. moluccensis*.

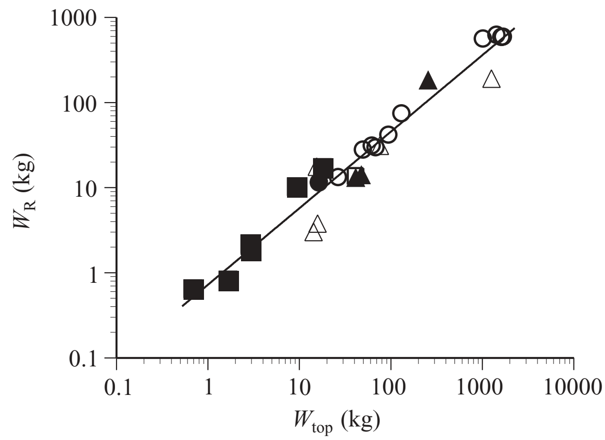


**Figure 4.** Common allometric relationship between root weight and above-ground weight of mangroves. The tree samples were 26 individuals including 9 species; *Rhizophora apiculata*, *R. mucronata*, *Ceriops tagal*, *Bruguiera gymnorrhiza*, *B. cylindrica*, *Sonneratia alba*, *S. caseolaris*, *Avicennia alba* and *Xylocarpus granatum*. Symbols: (○) = *Rhizophora apiculata* and *R. mucronata*; (●) = *Ceriops tagal*; (△) = *Bruguiera gymnorrhiza* and *B. cylindrica*; (▲) = *Sonneratia alba* and *S. caseolaris*; (□) = *Avicennia alba*; (■) = *Xylocarpus granatum* and *X. moluccensis*.

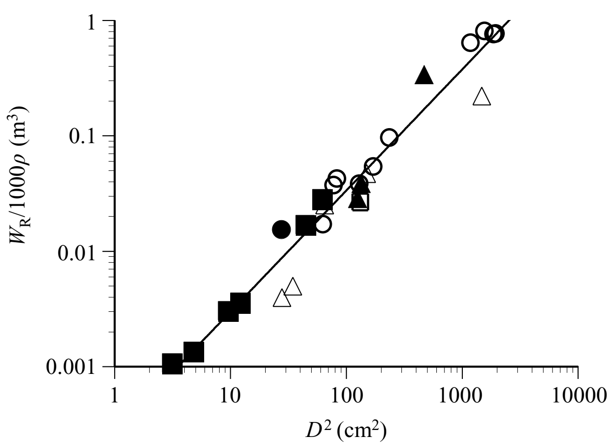


**Figure 5.** Common allometric relationship for root weight of mangroves. The relationship was shown between $W_R/1000\rho$ and $D^2$. The wood density of each species in each site was applied for $\rho$. The trunk diameter $D$ stands for $D_{R0.3}$ for *Rhizophora* species and *dbh* for other species. In $W_R$, the prop roots are included. The tree samples were 26 individuals as shown in Figure 4. Symbols: (○) = *Rhizophora apiculata* and *R. mucronata*; (●) = *Ceriops tagal*; (△) = *Bruguiera gymnorrhiza* and *B. cylindrica*; (▲) = *Sonneratia alba* and *S. caseolaris*; (□) = *Avicennia alba*; (■) = *Xylocarpus granatum* and *X. moluccensis*.

### Leaf weight

A linear relationship was recognized between $W_L/1000\rho$ and $D_B^2$ (Figure 2) on logarithmic coordinates, though the value of $R^2$ (=0.850) was lower than that in the case of trunk weight. The specific pipe lengths $L$ of Equation 2 were calculated as 0.521 m and 0.510 m for Rhizophoraceae and other species, respectively. Between them, there was no significant difference (ANOVA, $P = 0.828$). Transforming the relationship between $W_L/1000\rho$ and $D_B^2$, the relationship between $W_L$ and $\rho D_B^2$ was derived (Table 4). After correcting the bias using CF, the common allometric equation for leaf weight of mangroves was determined as shown in Equation 8.

$$W_L = 0.135\,\rho\,D_B^{1.696} \tag{8}$$

**Table 4.** Allometric equation of each plant organ of mangroves. All of the equations were significant at $P < 0.0001$.

| Allometric equation† | $R^2$ | SE | CF†† |
|---|---|---|---|
| Trunk weight | | | |
| $W_S = 0.0687\rho\,(D^2H)^{0.931}$ | 0.986 | 0.072 | 1.013 |
| Leaf weight | | | |
| $W_L = 0.126\rho\,(D_B^2)^{0.848}$ | 0.850 | 0.163 | 1.069 |
| Above-ground weight | | | |
| $W_{top} = 0.247\rho\,(D^2)^{1.23}$ | 0.979 | 0.085 | 1.017 |
| Root weight | | | |
| $W_R = 0.196\rho^{0.899}(D^2)^{1.11}$ | 0.954 | 0.181 | 1.017 |

$D = D_{R0.3}$ for the species of Rhizophoraceae, $D = dbh$ for the other species.
† Equation before corrected by Correction factor (CF).
†† Correction factor to remove the bias of regression estimates after logarithmic transformation (so-called Y0 EST method by Beauchamp & Olson 1973). For the correction, CF is multiplied to the right side of each allometric equation. See the text for final equations.

### Above-ground weight

A close linear relationship was recognized between $W_{top}/1000\rho$ and $D^2$ ($R^2 = 0.979$, Figure 3) on logarithmic coordinates. As stated in Methods, the weight of prop roots was not contained in this $W_{top}$. The specific stress lengths $L'$ of Equation 6 were calculated as 5.75 m and 5.09 m for Rhizophoraceae and other species, respectively. No significant difference (ANOVA, $P = 0.0776$) was found between these values. Transforming the relationship between $W_{top}/1000\rho$ and $D^2$, the relationship between $W_{top}$ and $\rho D^2$ was derived (Table 4). After correcting the bias using CF, the common allometric equation for above-ground weight was determined as shown in Equation 9.

$$W_{top} = 0.251\rho D^{2.46} \tag{9}$$

### Root weight

For the 26 sample trees, there was a close linear relationship ($R^2 = 0.949$) between $W_R$ (containing the weight of prop-roots) and $W_{top}$ on logarithmic coordinates (Figure 4), where, $W_{top}$ was expressed by $\rho D^2$ as mentioned above. Thus, we examined the relationship between $W_R/1000\rho$ and the independent variable $D^2$ by the regression method ($R^2 = 0.954$, Figure 5), and then the equation between $W_R$ and $\rho D^2$ was derived (Table 4). After correcting the bias using CF, the common allometric equation for root weight of mangroves was determined as shown in Equation 10.

$$W_R = 0.199\rho^{0.899} D^{2.22} \quad (10)$$

## DISCUSSION

The external shape of trunk in the 104 sample trees growing in primary and secondary stands was similar among mangrove species. Therefore, as reported by Komiyama *et al.* (2002), trunk weight solely depends on the trunk volume and its wood density. Some authors have used $dbh^2H$ as the independent variable, and established site- or species-specific equations for mangroves (Komiyama *et al.* 2000, Ong *et al.* 2004, Suzuki & Tagawa 1983, Tamai *et al.* 1986). However, the variation of $\rho$ was wide among mangroves (Table 3). Clough & Scott (1989) also pointed out the significant difference of $\rho$ between *Rhizophora* species and *X. granatum*. Therefore, to obtain a common allometric relationship, it is necessary to incorporate $\rho$ with a given value for the species into the equation. Concurring with this view, Crow (1978) commented that $dbh^2H$ could become a common trunk-weight estimator if tree samples have a similar wood density and trunk form.

According to the pipe model, the specific pipe length $L$ is a proportional constant between the leaf weight and the branch/trunk weight sustaining it. In the present study, no statistical difference was observed in $L$ between Rhizophoraceae and other species. This suggests that the length of the pipe supporting a unit weight of leaves is similar among the mangrove species. Shinozaki *et al.* (1964a) listed the $L$ of some deciduous broad-leaved trees in Japan as 0.32–0.74 m. The result obtained by us for mean $L$ in the current study lies within this range. Thus, the specific pipe length was similar among the mangrove species. Since the external shape of the trunk can be assumed to be identical among mangrove species (Komiyama *et al.* 2002), the relationship between $W_L/1000\rho$ and $D_B^2$ shown in Equation 4 and Figure 2 was confirmed as the common allometric relationship for leaf weight. By the same logic, the relationship between $W_{top}/1000\rho$ and $D^2$ shown in Figure 3 was adopted as the common allometric relationship for above-ground weight.

For the allometric relationships concerning leaf weight of mangroves, many researchers have used either the variable $dbh^2H$ (Komiyama *et al.* 1988, Suzuki & Tagawa 1983) or simply $dbh$ (Clough & Scott 1989, Clough *et al.* 1997, Slim *et al.* 1996) to facilitate field measurements. In other temperate and tropical forests, allometric relationships based on the pipe model with $D_B^2$ as the independent variable have been reported (Chiba 1990, Gregoire *et al.* 1995, Hoffmann & Usoltsev 2002, Morataya *et al.* 1999, Oohata & Shinozaki 1979, Shinozaki *et al.* 1964b). However, the allometric relationship containing $\rho$ in a variable has seldom been used for the estimation of leaf weight. For above-ground weight of tropical trees in the central Amazon, Nelson *et al.* (1999) established a common equation by using trunk diameter and wood density.

We have found that the root weight $W_R$ had a close relationship with the above-ground weight $W_{top}$ for all mangrove species studied (Figure 4). This may reflect the severe problems forced on mangroves of standing upright in the soft mud. The common allometric relationship for root weight was derived from this relationship between $W_R$ and $W_{top}$, and from the relationship between $W_{top}$ and $\rho D^2$ as shown in Figure 3. Therefore, the root weight was finally expressed by the independent variable $\rho D^2$.

Wood density becomes a key to the common allometric relationship of tree parts. The difference in $\rho$ was detected by the study site for *B. gymnorrhiza* and *R. apiculata* in this study, therefore, we recommend the use of a site-specific $\rho$ for a species for the application of the common allometric equation.

In conclusion, we have established four common allometric equations for estimating the mangrove weights (Equations 7–10). Of these four equations, we believe that the two for the leaf weight and the root weight are useful mainly for academic purposes; the remaining two for trunk weight and above-ground weight are also of practical value in forest management. However, as a pre-condition for the use of these equations, determining the wood density for each species (Table 3) is a necessity, and also the measurement of rather-inaccessible diameter $D_B$ for leaf weight. Nevertheless, these four equations will provide useful and re-examinable information to the mangrove biomass, since they are established on physical and biological theories.

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