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Allometry and biomass distribution in replanted mangrove plantations at Gazi Bay, Kenya

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ABSTRACT

1. This study reports above-ground biomass of 5 and 8 years old mangrove plantations in Kenya. Trees with stem diameter greater than 5.0 cm inside 100 m^2 sample plots were harvested, and then separated into stems (trunks), branches, leaves and prop roots.
2. Mean above-ground biomass was calculated at 20.25 t dry matter ha^{-1} for *Rhizophora mucronata* Lam., 11.7 t dry matter ha^{-1} for *Avicennia marina* (Forsk.) Vierh., 6.7 t dry matter ha^{-1} for *Sonneratia alba* Sm. and 3.7 t dry matter ha^{-1} for *Ceriops tagal* (Perr.) C. B. Robinson. In *A. marina* and *R. mucronata*, stems (52.19%) and prop-roots (30.28%), respectively, accounted for the highest proportion of the above-ground dry weight. While in *S. alba* and *C. tagal*, branch biomass represented the highest percentage of biomass, 48.20% and 43.62%, respectively.
3. The total above-ground biomass of *R. mucronata* was best estimated from regression equations using a combination of height and diameter above stilt root as the independent variables. For *A. marina, C. tagal* and *S. alba* there was no simple correlation found between the above-ground biomass and tree height or stem diameter.
4. Comparison of the regression models with those developed elsewhere gave different biomass values in these plots, further reinforcing the need for the use of site-specific allometric equations for biomass estimation.

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KEY WORDS: mangrove reforestation; allometry; biomass accumulation; Gazi bay; Kenya

INTRODUCTION

As terrestrial forest resources become further depleted in many tropical countries, mangrove forest management is likely to increase. Already mangroves are being managed for timber production in a number of Indo-Pacific regions, notably Bangladesh (Chowdhury and Ahmed, 1994), Malaysia (Noakes, 1955; Tang *et al*., 1984; FAO, 1994; Saenger, 2002) and Thailand (Aksornkoae, 1987). Reliable estimates of biomass accumulation in mangroves are essential for assessing the yield of commercial products from forests, and for the development of sound silvicultural practices. Non-destructive allometric relations are used widely to estimate tree biomass in tropical and temperate forests (Brown *et al*., 1989). In mangrove forests, biomass above ground is normally estimated indirectly from measurements of stem diameter at a height of 1.3 m above ground (usually abbreviated to DBH or D_{130}, diameter at breast height) and tree height. Allometric relationship between DBH alone, or in combination with height (h), as the independent variables and the dry weights of different parts of the tree as dependent variables are then used to estimate biomass from measurements of DBH and height (Boto *et al*., 1984; Ong *et al*., 1985; Kirui *et al*., 2006; Kairo *et al*., 2008; Komiyama *et al*., 2008).

While working with natural stands of dwarf mangroves in Japan, Suzuki and Tagawa (1983) established a regression of the type $y = b(DBH^2.h)a$ for *Rhizophora mucronata* ($n = 9$) and *Bruguiera gymnorrhiza* ($n = 8$). Woodroffe (1985) reported the relationship $y = (a–bx)^{-3}$ for naturally growing *Avicennia marina* in New Zealand, where x is the diameter, the height of the trunk or the diameter of the crown ($n = 12$, $h < 4$ m, $DBH < 10$ cm). In Sri Lanka, Amarasinghe and Balasubramaniam (1992) established a relationship between DBH and biomass for natural *R. mucronata* and *A. marina* of the form, $\log y = a \log DBH + b$

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($n = 30$, $DBH < 12$ cm). The regression equation used for predicting the total above-ground biomass of naturally growing *R. mucronata* at Gazi bay, Kenya, was $y = 0.8069DBH^{2.5154}$, ($r^2 = 0.98$, $P < 0.05$) (Kirui *et al.*, 2006). In another study at Gazi bay, Kairo *et al.* (2008) developed biomass tables for the replanted *R. mucronata* using the equation $1.6 \times 10^{-5}(x^2y)^2 + 0.0454\ x^2y + 0.495$ (where $x = DBH$, $y = h$).

This paper provides biomass values of 5–8 years old mangrove plantations in Kenya. The data are discussed in comparison with similar studies elsewhere, particularly the managed mangroves forests of Asia (Ong *et al.*, 1985, 2004; Putz and Chan, 1986; Alongi *et al.*, 2004), and hence contribute to an understanding of the biomass accumulation rate in replanted mangrove systems. This study complements the work of Kairo *et al.* (2008) when the plantation was 12 years old.

Study site

Gazi bay, where the present study was based, is located on the south coast of Kenya in the newly created Msambweni district (4°25′S and 39°50′E). The bay has a surface area of 18 km^2 and is sheltered from strong waves by the presence of Chale Peninsula to the east and a fringing coral reef to the south (Figure 1). Mangroves at Gazi cover 615 ha (Doute *et al.*, 1981). In total, nine mangrove species occur in Gazi bay, although most publications (Kokwaro, 1985; Gallin *et al.*, 1989) mention only eight or even seven. *R. mucronata* and *Ceriops tagal* are the dominant species. There has been extensive exploitation of mangrove forest in Gazi over many years for various purposes (Dahdouh-Guebas *et al.*, 2000). The forest has been most affected by wood extraction for fuelwood and building poles. The natural stands are currently heavily fragmented with stand density, canopy height and basal area at only 678 stems ha^{-1}; 8.3 m and 3.91 m^2 ha^{-1}, respectively (Kairo *et al.*, 2001).

A pilot reforestation project to rehabilitate degraded mangrove areas was launched at Gazi bay in October, 1991 (Kairo, 1995). The plantations focused on four main species planted as monocultures, as follows; *R. mucronata*, *C. tagal*, *A. marina* and *Sonneratia alba*. Subsequent development of the reforested areas has been monitored by comparing forest structure and productivity (Kairo *et al.*, 2008), and by studying floral and faunal secondary succession (Bosire *et al.*, 2003, 2004, 2006). At the time of this study, canopy heights of the replanted forests averaged 3.9 ± 0.6 m for 5 years old *Rhizophora* (DBH: 5.3 ± 0.8 cm); 5.3 ± 0.7 m for 8 years old *Avicennia* (DBH: 7.5 ± 1.4 cm); 4.5 ± 0.3 m for 5 years old *Sonneratia* (DBH: 8.9 ± 1.7 cm); and 2.3 ± 0.2 m for 8 years old *Ceriops* (DBH: 5.1 ± 0.2 cm). *R. mucronata* is not only the most dominant mangrove species in Kenya, but also the most exploited species for construction and firewood (Dahdouh-Guebas *et al.*, 2000). The stand density of replanted *Rhizophora* plantation has recently been estimated at 5132 stems ha^{-1}; with a mean canopy height and stem diameter of 8.4 ± 1.1 m (range: 3.0–11.0 m) and 6.2 ± 1.87 cm (range: 2.5–12.4 cm), respectively (Kairo *et al.*, 2008).

MATERIALS AND METHODS

The study used 5 years old plantations of *R. mucronata* and *S. alba*; and 8 years old plantations of *C. tagal* and *A. marina* established at Gazi bay between 1991 and 1994. For the development of biomass equations, trees with stem diameter greater than 5.0 cm inside 10×10 m^2 sample plots were harvested at ground level using handsaws. In total, 86 trees comprising *Rhizophora* (56 trees), *Ceriops* (10), *Avicennia* (10) and *Sonneratia* (10) randomly selected inside the plots were harvested. The diameter of the stems, DBH (measured at 30 cm above the highest prop root in *Rhizophora*) and the heights of all the harvested trees were measured. For trees below 2.0 m in height, for example in the *Ceriops* plantation, stem diameter was taken at a distance of half the height of the tree.

The above-ground part was separated into stem (trunk), branches, leaves, and in the case of *Rhizophora*, into prop roots. The total harvested fresh weight of each component was measured in the field, and representative sub-samples oven-dried to constant weight at 85°C in order to calculate wet–dry weight ratio.

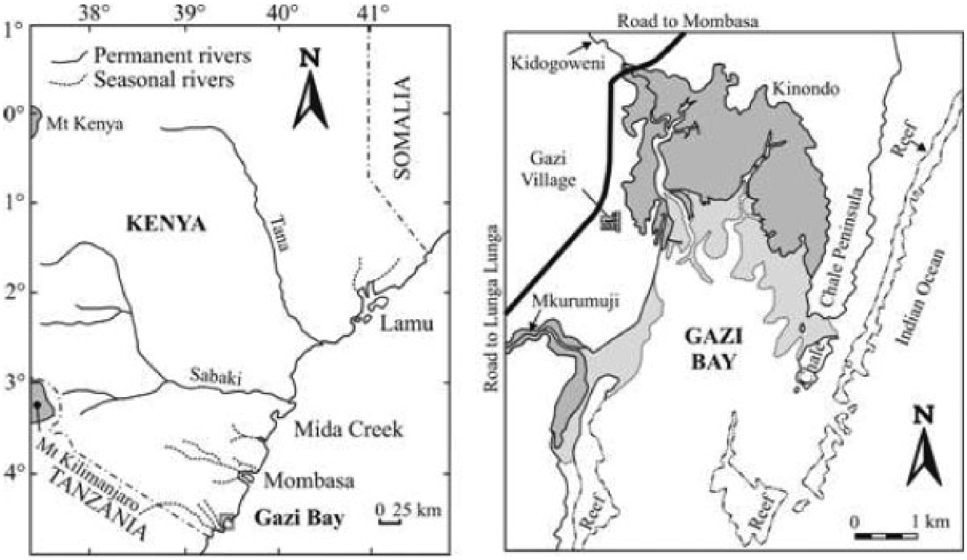

Figure 1. Map of Kenya coast showing the location of the study area (Source: Bosire *et al.*, 2003).

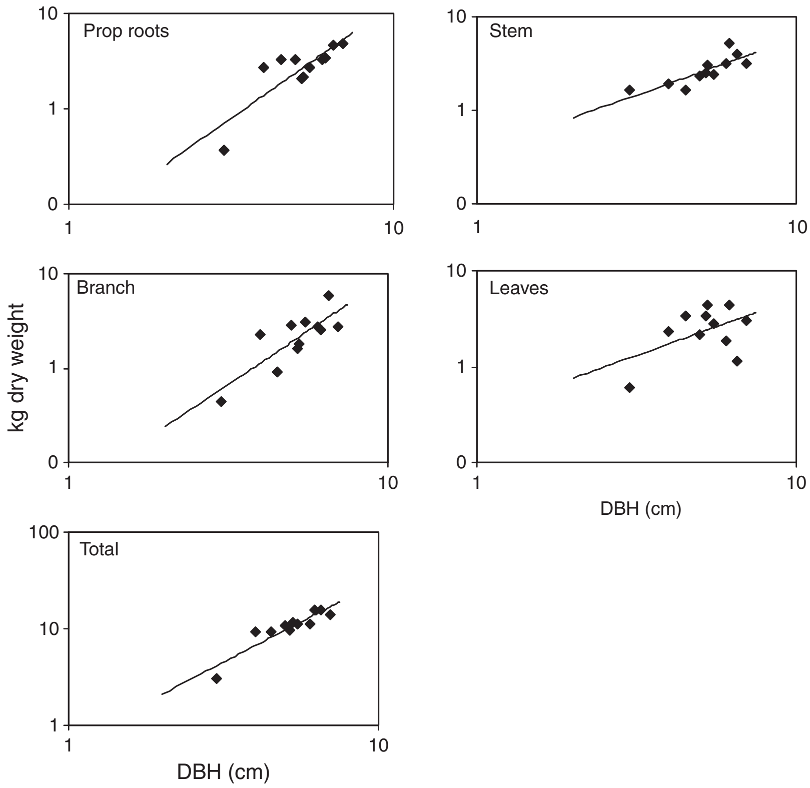

Figure 2. Log–log plots of dry weight against DBH for different components of a 5 years old *Rhizophora mucronata* stand at Gazi bay. The corresponding regression coefficients are given in Table 2.

Each sampled individual tree was then described by its structural parameters and its partitions (above-ground roots, leaves, branches, and trunk) as well as the total biomass values. Simple correlations (Pearson product moment correlation) were sought between tree structural variables and dry weights. The significance of the regression equation was assessed by the coefficient of determination (R^2) and single classification ANOVA, at $P = 0.05$ level. The equations developed were used to establish above-ground biomass values for each tree in the plot. Total plot biomass was obtained from summation of all biomass values of trees in the 14 plots sampled, including eight plots in *Rhizophora* and two plots each in *Ceriops*, *Sonneratia* and *Avicennia* plantations. Biomass values per species were then expressed in dry weight tonnes per hectare (t ha^{-1}).

RESULTS

Allometric equations

Dry weight of the harvested trees was estimated by power functions, and their linear transformation, using *DBH* as the independent variable ($\log y = a + b \log x$, where y = biomass, $x = DBH$ and a and b are regression constants). Figure 2 shows linear relationships obtained when dry weight biomass of different components of *R. mucronata* were plotted against *DBH*. The regression equation used for predicting the total above-ground biomass for *R. mucronata* was: $\log_{10} biomass = -0.1811 + 0.6590 \log DBH$; $R^2 = 0.8347$, $P < 0.05$. In the case of *S. alba*, *C. tagal* and *A. marina* regression values listed in Table 1 were found to be less significant, and the R^2 values were less than 40%. This indicates that plant biomass in these species had no simple relationship with their stem diameters. Consequently, no other forms of equations were tested for *Sonneratia*, *Ceriops* or *Avicennia*.

The best estimate of biomass in *Rhizophora* was obtained when *DBH* was substituted with the square of the diameter multiplied by height ($y = ax^b$ where $y = biomass$ and $x = DBH^2h$). The R^2 values for the total biomass estimate improved slightly ($P > 0.05$) from 0.8347 to 0.8402 (Table 2).

Standing biomass

Biomass values for the different components of the four mangrove stands and their structural characteristics are presented in Table 3 and Figure 3. In *Sonneratia* and *Ceriops*, branch biomass represented the highest proportion of the total above ground dry weight, 48.20% and 43.62%, respectively. In *Avicennia* and *Rhizophora* trees, stems (52.19%) and prop roots (30.28%) accounted for the greatest percentage of the biomass (Figure 3). Mean total above-ground biomass for trees with $DBH > 5.0$ cm amounted to 20.25 t dry matter ha^{-1} for *Rhizophora*, 11.7 t dry matter ha^{-1} for *Avicennia*, 6.7 t dry matter ha^{-1} for *Sonneratia* and 3.7 t dry matter ha^{-1} for *Ceriops* (Table 3).

DISCUSSION AND CONCLUSIONS

In this study, biomass of different components of *R. mucronata* was best estimated by power curves, and their linear transformation, using *DBH* as the independent variables. The best estimate of total above ground biomass ($R^2 > 0.84$) was

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Table 1. Allometric regressions of above-ground biomass on DBH for four mangrove species

Species	Plant component	*a*	*b*	R^2	S.E.	Significance level
R. mucronata	Branch	−1.3116	2.2731	0.6546	0.42	**
(5 years old) $n = 56$	Leaves	−0.4811	1.1982	0.2338	0.37	ns
	Stem	−0.4465	1.2206	0.6579	0.33	**
	Prop root	−1.3010	2.4044	0.7026	0.37	***
	Total	−0.1811	0.6590	0.8347	1.05	***
A. marina	Branch	0.3703	0.2708	0.0284	0.44	ns
(8 years old) $n = 10$	Leaves	−0.0719	0.1887	0.0048	0.21	ns
	Stem	−0.5781	1.5175	0.3647	0.98	ns
	Total	0.2540	0.9140	0.3135	1.34	ns
C. tagal	Branch	−0.3627	0.7372	0.0036	0.24	ns
(8 years old) $n = 10$	Leaves	0.1862	−0.3740	0.0016	0.10	ns
	Stem	−2.1549	3.0864	0.0658	0.15	ns
	Total	−0.3209	1.2036	0.0125	0.45	ns
S. alba	Branch	0.0083	0.4910	0.0559	0.46	ns
(5 years old) $n = 10$	Leaves	0.1616	−0.3179	0.0107	0.16	ns
	Stem	0.4256	−0.0245	0.0004	0.21	ns
	Total	0.6715	0.1473	0.0118	0.58	ns

a and *b* are constants in the equation $\log biomass = a + b \log DBH$. R^2 is the correlation coefficient, S.E. is the standard error of the biomass estimate and *n* is the sample size. *Biomass* in kg and *DBH* in cm. The significance level (*t*-test) is given as, *: $P < 0.05$; **: $P < 0.01$; ***: $P < 0.001$; ns = not significant.

Table 2. Allometric relations of above-ground biomass for 5 years old *Rhizophora mucronata* based on different independent variables (see also Figure 2)

Independent variable (*x*)	Dependent variable (*y*)	*a*	*b*	R^2	Significant level
DBH	Prop Roots	−1.3010	2.4044	0.7026	***
	Branch	−1.3116	2.2731	0.6546	**
	Stems	−0.4465	1.2206	0.6579	**
	Leaves	−0.4811	1.1982	0.2338	ns
	Total	−0.1811	0.6590	0.8347	***
h	Prop Roots	−0.9905	2.3918	0.3142	ns
	Branch	−0.9897	2.2131	0.2804	ns
	Stems	−0.5567	1.6710	0.5573	**
	Leaves	−1.0899	2.4937	0.4578	*
	Total	−0.1722	2.0124	0.5486	**
$DBH \times h$	Prop Roots	−1.4413	1.4267	0.6043	**
	Branch	−1.4330	1.3398	0.5556	**
	Stems	−0.6275	0.8088	0.7056	***
	Leaves	−0.8639	0.9518	0.3605	*
	Total	−0.3630	1.0554	0.8155	***
DBH^2h	Prop Roots	−1.4295	0.9154	0.6553	**
	Branch	−1.4260	0.8620	0.6057	**
	Stems	−0.5761	0.4968	0.7012	***
	Leaves	−0.7289	0.5476	0.3143	ns
	Total	−0.3198	0.6601	0.8402	***

a and *b* are constants in the equation $\log y = a + b \log x$. R^2 is the correlation coefficient. *Biomass* in kg. height *h* in m and *DBH* in cm. Sample size is 56 trees. The significance level (*t*-test) is given as: $^*P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$; ns = not significant.

Table 3. Above-ground biomass and biomass partitioning in four planted mangrove species. Number in parenthesis indicates the percentage of total biomass

Species	Branch biomass (kg dry wt)	Leaf biomass (kg dry wt)	Trunk biomass (kg dry wt)	Prop root biomass (kg dry wt)	Estimated stand biomass (t ha^{-1})
Rhizophora mucronata (5 years old) $n = 56$	149.6 ± 2.7 (24.62%)	128.8 ± 1.4 (21.19%)	145.3 ± 1.0 (23.91%)	184.0 ± 1.0 (30.28%)	20.25
Avicennia marina (8 years old) $n = 10$	42.2 ± 1.4 (36.00%)	13.8 ± 0.7 (11.82%)	61.1 ± 3.1 (52.19%)	—	11.7
Sonneratia alba (5 years old) $n = 10$	32.3 ± 1.5 (48.20%)	8.7 ± 0.5 (13.00%)	26.0 ± 0.7 (38.79%)	—	6.7
Ceriops tagal (8 years old) $n = 10$	16.0 ± 0.8 (43.62%)	8.8 ± 0.3 (24.07%)	11.8 ± 0.5 (32.31%)	—	3.7

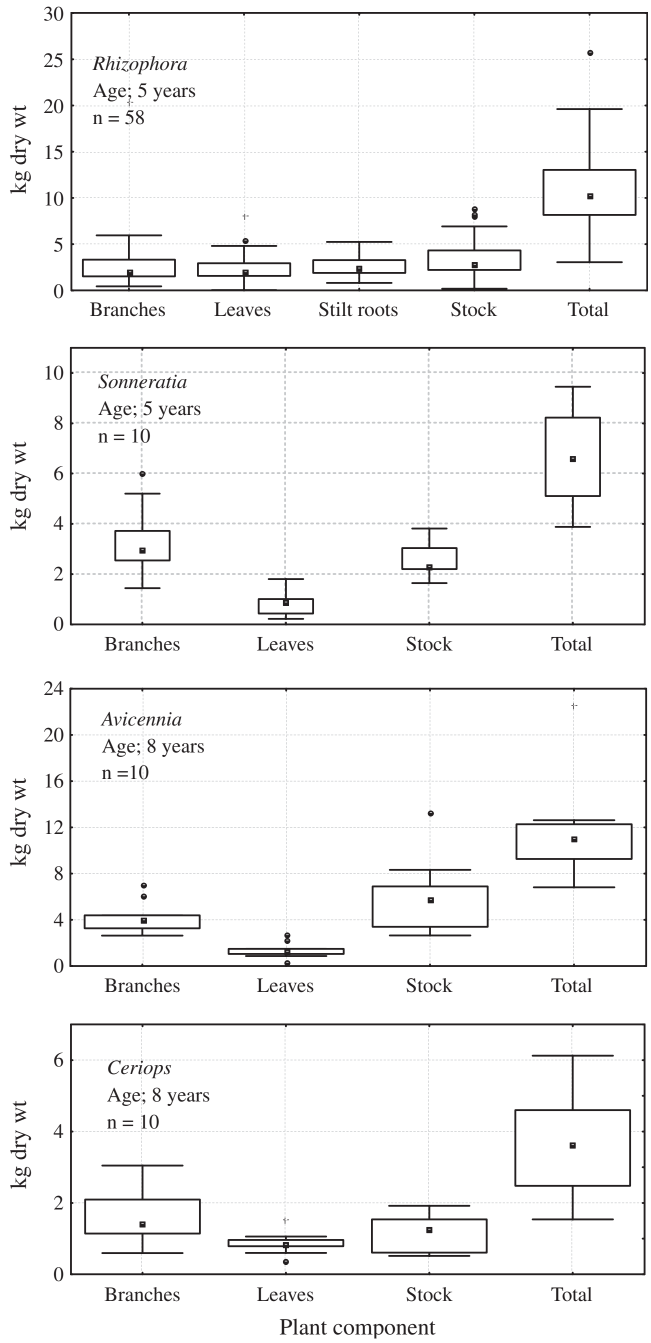

Figure 3. Distribution of above-ground biomass amongst different plant components for mangrove plantation of different species.

obtained using a combination of tree height and diameter at breast height (DBH^2h) as the independent variables (Table 2). There was no close relationship between height (and/or stem diameter) and biomass of *S. alba*, *C. tagal* or *A. marina* ($R^2 < 0.32$; Table 2), and none of the regression models suggested by previous workers (cited above) was successful.

Results discussed in this paper indicate that regression models developed for estimating biomass of natural mangrove stands in Asia and Pacific could not be applied directly without modification for mangrove plantations in Kenya. Regression models vary between species (Clough, 1992). Even within the same species, regression models will vary at different localities, depending on site-specific factors such as tree density, location on the ground, whether it is a monoculture or mixed forest, and management practices (Christensen, 1978; Woodroffe, 1985).

In production forestry, the stem yields most of the commercially useful timber. The proportion of stem biomass to total above-ground biomass was highest in *Avicennia*, whereas *Rhizophora* had significantly lower fraction of stem biomass to the total above-ground biomass (Table 3). Although differences in growth rate between species may be the main criterion for selecting species for production forest in a particular area, the results shown in Table 3 provide information that might be useful in selecting the species for production forestry, depending on whether the product of interest is building poles, firewood or even a protective function. In fast growing species such as *A. marina* and *S. alba*, (Kairo *et al.*, 2001), planned thinning and pruning would help meet the subsistence demand of small wood requirement, particularly firewood and building.

The reliability and limitations of allometric relationships for estimating tree biomass, and their application in forestry have been reviewed by Whittaker and Marks (1975) and Causten (1985). In the present study, sampling was done in a relatively dense even-aged mangrove plantation. Tree harvesting was restricted to trees whose stem diameter (*DBH*) was greater than or equal to 5.0 cm. On a few occasions, the tallest tree in a stand that could be harvested for building, but with diameter less than 5.0 cm, was used. This may account for the relatively low correlation coefficients (R^2) obtained in the study (Table 2) also derived from the multicollinearity of individual sampling points. Multicollinearity causes no special problems when inferences on Y are made within the region of sample observations (Neter *et al.*, 1988). The regression equations derived in this study for the replanted mangrove plantations may not be appropriate for open natural plantations, where horizontal expansion of the crown of individual trees is less restricted by the crown of their neighbours. The effects of tree population density on the allometric relationship between stem biomass and *DBH* are not clear (Clough and Scott, 1989), but it seems likely to be less affected by stand structure than those for the branches and leaves. Furthermore, prospective users of the allometric relations derived should be careful when extrapolating the relationship to trees outside the range of *DBH* used to obtain the relationship. A wise procedure will be to survey several trees in a plot and check whether they conform to the allometric relationship for the species.

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