REVIEW OF BIOMASS AND VOLUME FUNCTIONS FOR INDIVIDUAL TREES AND SHRUBS IN SOUTHEAST AFRICA

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HOFSTAD, O. 2005. Review of biomass and volume functions for individual trees and shrubs in southeast Africa. Estimation of biomass or volume of trees and shrubs is important in many contexts. Foresters and other natural resource managers in east and southern Africa have been faced with a double challenge in this respect: their forest research institutions have been small and young, and their trees and shrubs are difficult to measure. A number of studies have been made in order to estimate biomass or volume of trees in this part of Africa. This review tries to bring together some of the findings of such studies in order to synthesize a few common principles and to make reliable functions more easily accessible to researchers and resource managers. A general conclusion appears to be that typical miombo trees have larger volumes for equal diameters than species typical in the drier southern woodlands. It is also noted that *Pterocarpus angolensis* takes an intermediary position. Inclusion of height in addition to diameter as independent variable does not increase the coefficient of determination very much. In some cases *dbh* alone gives an R^2 of more than 0.95. This is due to the correlation between diameter and height. In practical inventories of volume or biomass where high precision is not required, economic considerations may, therefore, lead to the conclusion that measurement of height is unnecessary. One study suggests that diameter and crown width is a better pair of independent variables for total biomass of single trees than the traditionally used diameter and height.

Key words: Above-ground woody biomass – individual trees – volume functions – east Africa – southern Africa.

HOFSTAD, O. 2005. Kajian semula fungsi biojisim dan fungsi isi padu untuk pokok individu dan pokok renik individu di tenggara Afrika. Anggaran biojisim atau isi padu pokok dan pokok renik penting dalam banyak konteks. Para rimbawan dan pengurus sumber asli lain di timur dan selatan Afrika menghadapi dua cabaran dari segi ini: institusi penyelidikan perhutanan di sini kecil dan agak baru serta pokok dan pokok reniknya susah disukat. Banyak kajian telah dijalankan untuk menganggar biojisim atau isi padu pokok di bahagian Afrika ini. Kajian semula ini dapat mensintesiskan beberapa prinsip umum dan menjadikan fungsi-fungsi ini dimanfaatkan oleh para penyelidik dan pengurus sumber asli. Kesimpulan yang umum ialah pokok miombo tipikal mempunyai isi padu lebih besar berbanding spesies tipikal berdiameter sama di hutan jarang yang lebih kering di selatan. Taraf *Pterocarpus angolensis* adalah di tengah. Ketinggian dan diameter sebagai pembolehubah tersendiri tidak menaikkan penentu koefisien dengan banyak. Dalam sesetengah kes, *dbh* sahaja memberi R^2 lebih daripada 0.95. Ini kerana wujudnya korelasi antara diameter dengan ketinggian. Dalam inventori isi padu atau biojisim yang praktikal, apabila ketepatan tinggi tidak diperlukan, pertimbangan ekonomi boleh membawa kepada kesimpulan yang ukuran ketinggian tidak perlu. Satu kajian menyarankan yang diameter dan lebar silara ialah pasangan pembolehubah tersendiri yang lebih baik untuk jumlah biojisim pokok individu berbanding pembolehubah tradisional iaitu diameter dan ketinggian.

Introduction

The estimation of biomass or volume of trees and shrubs is important in many contexts in most parts of the world. It may be of interest in purely environmental studies, it may be required in connection with studies of potential supply of both industrial wood and biomass for domestic energy, and it will be an element in all attempts at sustainable management of forests and woodland ecosystems. In order to estimate existing biomass, one option is to start with the mass of individual trees and shrubs and add these for different classes or strata according to the purpose of the analysis. This has been the traditional approach, and shall be reviewed here. Other options involve the measurement of parameters related to stands, vegetation types or even pixels in satellite images in order to estimate the biomass of vegetation in broad categories of land.

One option for estimating the volume of boles is to apply some formula for solids of revolution like a cylinder, a cone, a paraboloid or a neiloid. In lack of empirically based equations, this is a reasonable approach when we are interested in the bole alone. However, when other parts of the tree are of interest, and empirical data are available, statistical estimation of volume tables or functions is preferable.

Estimation of volume tables or functions for individual trees has been one of the first tasks of forest research in many countries since the time of Heinrich Cotta (1763–1844) in Germany. This is a fairly simple task in the boreal (Canada, Russia and Scandinavia) forest zone. Coniferous trees dominating these zones have simple forms, and there are relatively few economically important species. As we move southwards through the semi-boreal (Germany, USA) forest zone and further south, complexity increases. More tree and shrub species become important, and they have forms and shapes that make it more difficult to develop reliable volume or biomass functions. Foresters and other natural resource managers in east and southern Africa, consequently, have been faced with a double challenge in this respect: their forest research institutions have been small and young, and their trees and shrubs are difficult to measure. In spite of this situation, a number of studies have been made in order to estimate biomass or volume of trees in this part of Africa. This review tries to bring together some of the findings of such studies in order to synthesize a few common principles and to make reliable functions more easily accessible to researchers and resource managers.

Dependent variables

Some definitions of central terms are required. First of all, the objects of study—trees and shrubs—need to be defined. Different definitions exist, but the ones given by Little (1979) have been applied here:

- A tree is a perennial woody plant which at maturity is 13 ft ($\hat{=}$ 4 m) or more in height, with a single trunk at least 3 inches (7.62 cm) in diameter, unbranched for at least several feet above the ground, and having a more or less definite crown.

- A shrub is a woody plant that is usually smaller than a tree at maturity and has multiple stems with no clear main trunk. Many species that are usually shrubs occasionally reach the stature of a tree. The difference between a tree and a shrub is often a quantitative difference rather than a qualitative one.

Foresters traditionally have focused on the volume of timber (over or under bark), i.e. the commercially interesting part of a tree–normally the bole, sometimes including large branches. This may still be the most important information about the size of trees, but the scope of most recent studies is wider. As the "creaming" (removal of only the best timber trees of the most valuable species) of pristine forests is coming to an end, smaller and smaller dimension logs are considered commercially valuable. Therefore, the parts of a tree that should be measured and included in the estimated volume approach the total volume of stem and branches. When the supply of fuelwood is considered, this becomes even more evident.

In any case there is a need to decide exactly where the stem and branches end, and where the foliage begins. In many cases the limit is set at a branch diameter of 5 cm. From the point of view of such studies, however, biomass may be a more relevant dependent variable than volume. Therefore, many modern studies aim at estimating above-ground woody biomass. In ecological studies, where organic material in litter and decomposing wood is essential for other organisms in the forest and woodland, the biomass of leaves, bark, stump and roots is also interesting. Relatively few studies including estimates of these parts of trees and shrubs have been done in east and southern Africa. They shall not be reviewed here.

Evidently, there is a close relationship between volume and biomass. This relationship is a direct reflection of specific weight as long as the study focuses on the same parts of the tree or shrub. When more parts of the specimen are included in the estimated biomass than in the volume, the relationship is not equally obvious, but a reasonably good statistical correlation may still be calculated. The estimated volume (stem and large branches) normally represents the major part of total biomass of a tree or shrub. The specific weight of wood (or bark, leaves, etc.) is strongly dependent on water content. Therefore, moisture content must be indicated when giving specific weights for wood of different species. Fresh weights are often given, assuming moisture content of 40–50 percent, and air-dry weights are often given for moisture content between 12 and 18 percent. Basic density is the specific weight of wood without water at all. The specific weight of fresh wood of most tree species in east and southern Africa is in the range of 0.6 to 0.9 (ATIBT, n.d.). It does, of course, matter whether a species is in the upper or lower end of this range.

Independent variables

When ground measurements are made, the diameter of the bole seems to be the most efficient single indicator of volume or mass of trees (Husch *et al.* 1993). Even when several other parameters are measured, the diameter of the bole in most cases contributes significantly to the estimation of volume or mass. Other independent parameters may be height of the tree, diameter of the crown, height of the base of the crown, and some indicator of the form or shape of the tree (Philip 1994). All of these parameters may be measured in different ways.

Diameter of the bole may be measured in different heights from the ground. It has become standard procedure among foresters to measure diameter at breast height *(dbh)*, i.e. 1.3 m above ground. There are two good reasons for this: (i) in most cases this avoids problems related to buttresses and other irregularities in the shape of the stem close to ground, and (ii) it makes measurement easy, thereby reducing inventory costs. If high precision is required, two perpendicular measurements of dbh are made for each tree, and the arithmetic mean is used as estimator. The quadratic mean has also been used for this purpose, but the precision of the estimates is seldom improved significantly by this complication.

In some studies basal area *(BA)* is used as independent variable. Basal area of an individual tree with a circular cross section of the bole, is equal to $BA = \pi\ (dbh/2)^2$. A reliable correlation between *dbh* and *BA* can be worked out even if the cross-section is not circular.

Tree height is normally measured as the vertical distance between ground at the base of the tree and the highest point of the tree. The same applies to shrubs. To measure this distance is not always easy, particularly in high, dense forest and when trees have rounded or flat crowns. Newer hypsometers reduce this problem, but it is important in the African context that measurement of heights requires the use of instruments of considerably higher cost and complexity than the caliper or tape used for measuring stem diameters. It is much easier to measure crown diameters for shrubs and bushes than for trees, while measuring the diameter of the stem is not relevant for shrubs.

Vegetation types

There is no commonly accepted standard of vegetation classification in east and southern Africa. Two fundamental principles may be followed, i.e. floristic composition or vegetation structure. Different adaptations of both have been applied according to the specific purpose of each study (e.g. White 1983, Timberlake *et al.* 1993). It is, therefore, difficult to be very exact about which forest and woodland types this review tries to cover. In broad terms, however, vegetation in sub-Saharan Africa is determined by temperature and soil water availability. In the wettest conditions in east and southern Africa (montane or coastal forests) we often find closed and evergreen forests. This review does not include species that are common in such ecosystems. Under intermediate conditions, both in terms of temperature and soil water availability, semi-deciduous open forests or woodlands are predominant. Miombo woodland (Campbell 1996) is a widespread vegetation type under such conditions in this part of Africa. Several studies in such vegetation are reviewed here and some of the dominating species are included. Drier and hotter conditions lead to other types of woodland, savanna, shrub- or bushland. A few studies from southern Africa in such vegetation types are included here.

Table 1 Volume of trees in southeastern Africa. Sources are the following studies: B&B = Banks & Burrows (1966), Temu = Temu (1981), M&T = Malimbwi & Temu (1986), M1 = Malimbwi *et al.* (1992), NFS = Norwegian Forest Society (1992), and M2 = Malimbwi *et al.* (2000). n = number of observed trees, R^2 = coefficient of determination, and RMSE = root mean square error of estimate.

Study	Species	dbh	Function*	n	R^2	RMSE
B&B	*Baikiaea plurijuga*	15–70	$V = -0.2421143 + 0.0029874\ (dbh/2)^2$	245	0.95	-
"	*Guibourtia coleosperma*	15–70	$V = -0.2925408 + 0.0033458\ (dbh/2)^2$	75	0.94	-
"	*Pterocarpus angolensis*	15–55	$V = -0.3687583 + 0.0041467\ (dbh/2)^2$	91	0.90	-
Temu	*Brachystegia spiciformis*	5–43	$V = 10^{(-1.2875 + 2.8436 * Log(dbh))}$	-	-	-
		44–65	$V = -271 + 1.401\ dbh^2$	-	-	-
"	*Julbernardia globiflora*	7–65	$V = 369 - 88.2315\ dbh + 6.4175\ dbh^2 - 0.1168\ dbh^3 + 0.0009\ dbh^4$	-	-	-
"	*P. angolensis*	7–65	$V = -170 + 35.8721\ dbh - 2.1968\ dbh^2 + 0.0801\ dbh^3 - 0.0006\ dbh^4$	-	-	-
M&T	*P. angolensis*		$V = 0.092\ dbh^{2.59}$	-	0.97	-
"	*J. globiflora*		$V = -35.85 + 0.76\ dbh^2\ h$	-	0.95	-
			$V = 0.0295\ dbh^{3.015}$	-	0.75	-
M1	Various miombo species	8–43	$V = 0.0001\ dbh^{2.032}\ h^{0.659}$	17	0.95	0.31
NFS	*B. plurijuga*	5–70	$V = 0.0000785\ dbh^{2.598}$	142	0.98	-
"	*P. angolensis*	5–70	$V = 0.0000686\ dbh^{2.678}$	50	0.95	-
"	*Burkea africana*	5–70	$V = 0.0000214\ dbh^{3.030}$	40	0.93	-
"	*Coleospermum mopane*	5–70	$V = 0.0001065\ dbh^{2.471}$	18	0.89	-
M2	*Dalbergia melanoxylon*	7–50	$V_{TOB} = 0.00023\ dbh^{2.231}$	24	0.97	0.23
			$\ln V_{TOB} = -9.887 + 1.824 \ln dbh + 1.155 \ln h$	24	0.99	0.15

*Note: *V* is volume in m^3 (except in Temu where *V* is measured in litres) of one tree, *dbh* is diameter in cm at 1.3 m above ground of the same tree, and *h* is height of the tree in m. Volume of a tree is measured to various limits between bole, branches, and foliage in different studies (see text for details).

Volume of trees

Banks and Burrows (1966) developed preliminary volume functions for the three most important woodland tree species on Kalahari sand in Gwayi, Zimbabwe (Table 1). In these functions *V* is given as m^3 per tree, giving millable plus cordwood volume over bark down to 6 in. diameter. This specification of dependent variable is a reflection of the ample availability of large diameter timber at the time of their study. Parresol (1999) has a thorough discussion of biomass additivity, i.e. how estimates of the biomass of millable and merchantable parts of the bole should be parts of total biomass. This is of some importance when we compare the findings of Banks and Burrows (1966) with estimates of total volume or weight, but the details of this discussion shall not be explored here.

Temu (1981) studied total volume of trees in miombo woodland in central Tanzania (Table 1). The volume functions were selected by the use of residual error and R^2, but these parameters are not reported. Not even the number of sampled trees is mentioned. Malimbwi and Temu (1986) later studied two of these species further (Table 1). In both these studies the dependent variable, *V*, is total volume of the tree (stem and branches) in liters to a top diameter of 5 cm (ob), i.e. the resulting volume figure should be divided by 1000 if we want the volume in m^3. *dbh* is measured in cm, and *h* in meters.

Malimbwi *et al.* (1994) found an allometric model for 17 trees of various miombo species in Tanzania, where V = volume in m^3/tree of all wood (stem and branches down to 1 cm diameter) is the dependent variable, and h = height of tree in m is the independent variable.

The Norwegian Forestry Society (1992) applied functions with *dbh* as the only independent variable to trees in Chobe, Botswana (Table 1). The dependent variable, *V*, in these functions represents total volume of wood down to a diameter of 5 cm, in m^3/tree.

Malimbwi *et al.* (2000) developed volume functions for African blackwood (*Dalbergia melanoxylon*) in southern Tanzania. A total of 24 blackwood trees were measured. The range of the trees was 7 to 50 cm in *dbh* and 6 to 16 m in height. *V* is given in m^3, *dbh* is measured in cm, and *h* in meters. Adding height as predictor improved precision, but led to a more complicated formula (Table 1). Since this species is particularly sought after because of its dark colour and high density, it is not surprising that basic density (oven dry) in these trees was found to be 1.06.

Biomass of trees

Stromgaard (1985) developed two regression models for 271 miombo trees in northern Zambia (Table 2) with biomass (fresh weight in kg/tree) as dependent variable. Diameter (measured in cm), and height (m) are independent variables. The weight of leaves and twigs is included in the biomass measured. Stromgaard (1986) later published an interesting re-interpretation demonstrating the similarities of his two models.

Table 2 Biomass of trees in southeastern Africa. Sources are the following studies: S = Stromgaard (1985), C = Chidumayo (1990), M1 = Malimbwi *et al.* (1992), T = Tietema (1993), and V = Velle (1995). n = number of observed trees, R^2 = coefficient of determination, and RMSE = root mean square error of estimate.

Study	Species	dbh	Function*	n	R^2	RMSE
S	Various miombo species	2–70	$B = 0.3623\ dbh^{1.382}\ h^{0.640}$	271	0.71	-
		2–70	$\ln B = -0.739 + 0.890 \ln dbh + 0.132 \ln dbh^2 + 0.913 \ln h - 0.103 \ln h^2$	271	0.72	-
C	Various miombo species	< 10	$B = 1.6\ dsh - 4$	7	0.94	-
		10–30	$B = 23.34\ dbh - 218.34$	20	-	-
M1	Various miombo species		$B = 0.06\ dbh^{2.012}\ h^{0.7}$	17	0.95	0.31
T	Various woodland species in Botswana	2–36(*dsh*)	$B = 0.1936\ BA^{1.1654}$	512	0.92	-
V	Various woodland species in Uganda		$B = -4.22412 + 0.56\ dbh^2$	1695	0.73	38.00
			$\ln B = -0.89 + 2.053 \ln dbh$	1695	0.81	0.448
			$B = 13.18334 + 0.06259\ dbh^2\ h$	1695	0.75	37.15
			$\ln B = -1.198 + 1.556 \ln dbh + 0.55 \ln h + 0.435 \ln CR$	1695	0.88	0.362

*Note: *B* is biomass in kg of one tree, *BA* is basal area in cm^2, *dsh* is diameter at stump height in cm, and *CR* is width of the crown in m. Mass of a tree is measured to various limits between bole, branches, and foliage in different studies, and mass also depends on water content of wood which varies between studies (see text for details).

Chidumayo (1990) estimated two functions with wood biomass of miombo trees in the Copperbelt of Zambia as dependent variable (Table 2). One function for small trees (*dbh* < 10 cm) uses diameter at stump height (0.3 m) as independent variable. The other function is for larger trees and uses diameter at breast height as independent variable. This function gives unreasonable results for *dbh* > 30 cm.

For biomass Malimbwi *et al.* (1992) found a relationship with diameter and height for the same 17 trees in Tanzania mentioned above, which is quite similar to the first one developed by Stromgaard (Table 2). However, biomass is much higher for large diameters (at given heights) than what follows from Stromgaard's model. Malimbwi *et al.* (1992) also includes functions for biomass of roots.

Tietema (1993a) reported a number of biomass functions for individual trees of different species in Botswana. The combined function for all species is given in Table 2. After comparing this combined function with his own observations for individual species, and a number of other studies, Tietema (1993a) concluded that in a mixed forest in the arid parts of Southern Africa the regression of stem basal area (at ankle height) against weight as given by the combined function can be used for the determination of standing fresh biomass of trees.

Velle (1995) developed biomass functions for a sample of 1695 trees from Uganda. He proposed a general formula for the weight of single woodland trees (trees from humid, high forests in Ugandan are not included):

$$\ln B = a + b \ln D + c \ln H + d \ln CR$$

where B is fresh weight of stem and branches of one tree in kg, D is *dbh* in cm, H is height of the tree in m, and CR is width of the crown in m. For all trees pooled the parameters are given in Table 2. If fewer variables are measured, statistically less significant correlation can be found. Models with diameter and height as independent variables are also given in Table 2. However, Velle (1995) found that for predicting total biomass, *dbh* and crown width are the two most important explanatory variables. If it is important to reduce the number of measurements, measuring those two variables gives better estimates of total biomass than *dbh* and height.

Biomass of shrubs

Tietema (1993b) reported a useful correlation between biomass and size of individual bushes in Botswana. The general form of this relationship is $W = a\ S^b$, where W is the fresh weight in kg and a and b are parameters, $S = H + D_1 + D_2$ in meters, where H is the total height of the bush, D_1 is the first diameter of the crown of the bush, and D_2 is the second diameter of the crown. The two crown diameters are measured along two perpendicular axes. The specific equations for six species of shrubs are given in Table 3.

Visual comparison of models

Estimates of volume of *P. angolensis* trees in Botswana, Tanzania and Zimbabwe may be compared by combining the mentioned function by Banks and Burrow (1966) with that of Temu (1981), Malimbwi and Temu (1986) and a function for the Chobe district (Norwegian Forestry Society 1992) (Figure 1). Banks and Burrows

Table 3 Biomass of shrubs in Botswana. n = number of observed trees, and R^2 = coefficient of determination

Species	Function*	n	R^2
Acacia erubescens	$W = 0.0137\ S^{3.2840}$	38	0.91
A. karroo	$W = 0.0079\ S^{3.1858}$	41	0.91
A. mellifera	$W = 0.0548\ S^{2.5767}$	27	0.90
A. tortillis	$W = 0.0096\ S^{3.3015}$	50	0.90
Dichrostachys cinera	$W = 0.0029\ S^{3.7422}$	33	0.94
Ziziphus mucronata	$W = 0.0130\ S^{2.8625}$	17	0.96

*Note: W is fresh weight in kg of one shrub/bush, $S = H + D_1 + D_2$ in meters, where H is the total height of the bush, D_1 is the first diameter of the crown of the bush, and D_2 is the second diameter of the crown.
Source: Tietema (1993b)

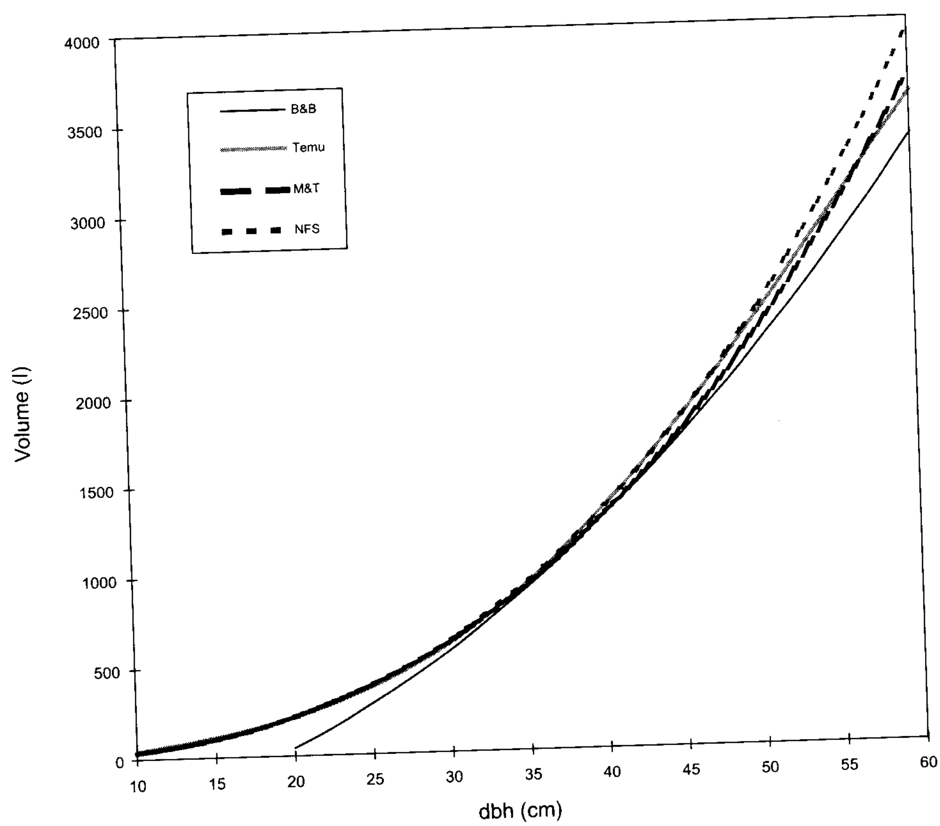

Figure 1 Volume functions for *Pterocarpus angolensis* developed in Botswana, Tanzania and Zimbabwe
B&B: Banks & Burrows (1966) Temu: Temu (1981)
M&T: Malimbwi & Temu (1986) NFS: Norwegian Forest Society (1992)

(1966) estimated millable and cord volume. It is, therefore, reasonable that their function gives smaller volumes than the other curves giving total volume. It is more surprising that their function gives almost the same volumes as the others for trees of 35<*dbh*<45 cm. In general the four functions compare quite well, though.

Similarly, different functions for *Brachystegia spiciformis* and *Julbernardia globiflora* in miombo woodland can be compared with those for *Coleospermum mopane* and *Baikiaea plurijuga* which are dominating tree species in more southerly woodland types (Figure 2). Although there are some differences in the functions, e.g. the difference between total and millable volume of the NFS and B&B functions for *B. plurijuga*, and the volume and weight of *C. mopane* in the NFS and Tietema studies, a general conclusion appears to be that typical miombo trees have larger volumes for equal diameters than species typical in the drier southern woodlands. Comparing with Figure 1 we also note that *P. angolensis* takes an intermediary position.

It should be noted that in many of the referred studies it is shown that the inclusion of height in addition to diameter as independent variable does not increase R^2 more than from about 70 to 80 percent. In some cases *dbh* alone gives an R^2 of more than 0.95. This is partly due to the correlation between diameter and height, and partly caused by the irregular shapes of broadleaved trees growing in fairly open forests. In practical inventories of volume or biomass where high

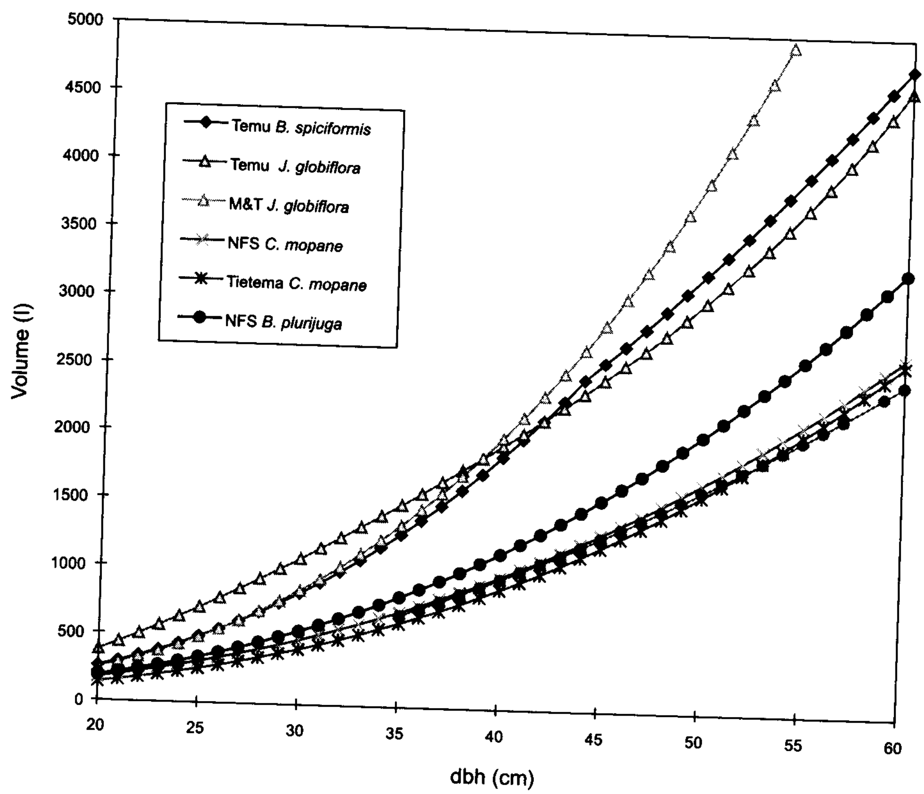

Figure 2 Volume or mass of *Brachystegia spiciformis*, *Julbernardia globiflora*, *Coleospermum mopane* and *Baikiaea plurijuga* according to different studies

precision is not required, economic considerations may therefore lead to the conclusion that measurement of height is unnecessary. Velle's (1995) observation that the measurement of crown width, in addition to diameter, may contribute significantly to better estimates of total biomass could be useful in the design of efficient inventories in the future.

Conclusions

It is not easy to recommend one, or a few, functions to be used to estimate tree volume or biomass of trees and shrubs in eastern and southern parts of Africa. Partly, one must relate the functions to the ecosystems from which data were originally collected. Wetter ecosystems tend to produce larger trees. However, for ecosystems where several functions have been developed, one should be able to select the function with better fit. The volume function for *Baikiaea plurijuga* developed by NFS is based on a fairly large sample and has a $R^2 = 0.98$. In typical miombo found in both Tanzania and Zambia one might use Mwalimbi *et al.*'s (1992) volume function in spite of their sample being rather small. The alternative is some of the available functions for dominating miombo species like *Brachystegia spiciformis* and *Julbernardia globiflora*, but the statistical fitness of these functions is not well described in the reviewed studies.

For biomass of a combination of miombo trees, Stromgaard's logarithmic function seems to be the best available in spite of the fairly low R^2. The function is based on a large sample. Both Tietema and Velle have made thoroughly estimated biomass functions for many individual species and groups of several species in drier Botswana and wetter Uganda respectively. There are no better biomass functions for trees available for these ecosystems at present. Unfortunately, only one study has been found for estimation of biomass of shrubs. Shrubs are more important in arid ecosystems. It is therefore logical that Tietema's study was made in Botswana. While waiting for similar studies in less arid environments, one can only hope that shrubs have similar relationships between size and weight also when growing in other parts of southeastern Africa. However, the functions must be used with caution outside the area where sampling took place, of course.

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