SHORT COMMUNICATION

Derivation of diameter measurements for buttressed trees, an example from Gabon

Alfred Ngomanda*, Quentin Moundounga Mavouroulou†, Nestor Laurier Engone Obiang*,
Donald Midoko Iponga*, Jacques-François Mavoungou*, Nicaise Lépengué†, Nicolas Picard*,‡[1] and
Bertrand Mbatchi†

* IRET, BP 13354, Libreville, Gabon
† Département de Biologie, Faculté des Sciences de l'Université des Sciences et Technique de Masuku, BP 901, Franceville, Gabon
‡ CIRAD, Campus de Baillarguet, TA C-37D, 34398 Montpellier cedex 5, France
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Many tropical tree species have buttresses at the standard breast height (1.3 m above ground) of diameter measurement, with a presumable role in improving nutrient acquisition or tree anchorage in the ground (Newbery *et al.* 2009, Richter 1984). Measuring the diameter using standard dendrometrical tools such as callipers or graduated tapes, which require that the cross-section of the trunk has a convex shape, is then impossible (Nogueira *et al.* 2006). The recommended method in this case is to measure the diameter above the buttress (DAB), thus possibly leading to biased estimates of the basal area (West 2009), of tree above-ground biomass (Dean & Roxburgh 2006, Dean *et al.* 2003) and of tree growth (Metcalf *et al.* 2009). As an alternative, one can measure the basal area at breast height of buttressed trees, using a method that can deal with the irregular non-convex shape of the cross-section of the stem such as the Picus calliper, photogrammetry or 3D laser scanning (Badia *et al.* 2003, Dean 2003, Newbery *et al.* 2009).

When compared with tree allometry and stem taper, very few dendrometrical studies have been devoted to the size and shape of buttresses. Nogueira *et al.* (2006) compared the conventional diameter of trees (assuming that their cross-section is circular) with the diameter of the circular disc whose area equals the basal area of the tree. Dean *et al.* (2003) and Dean & Roxburgh (2006) measured the three-dimensional shape of buttresses for *Eucalyptus regnans* in temperate Australia, and compared the basal area of the cross-section of the buttressed stem with the area of its convex hull. Newbery *et al.* (2009) also measured the three-dimensional shape of buttresses for *Microberlinia bisulcata* in Cameroon, and established the relationship between buttress height and diameter above buttress. The current study focused on buttress allometry. It aimed at estimating the basal area at breast height of a buttressed tree using tree characteristics that are easier to measure, such as the diameter above buttress or the height of buttresses.

One hundred and two buttressed trees were measured in two sites 34 km apart, Ipassa (0°30′42″N, 12°48′9″E; 50 trees) and Kongou (0°17′27″N, 12°35′21″E; 52 trees), close to the city of Makokou, north-eastern Gabon, central Africa. Both sites are within the Ivindo National Park (UNESCO 1987). Average annual rainfall is 1700 mm, average temperature is 24 °C, and altitude varies around 500 m. The relief consists of an undulating plateau on an ancient crystalline base, interrupted with rivers. Vegetation consists of tropical moist forest, and is dominated by Fabaceae, Cesalpiniaceae and Euphorbiaceae (Doumenge 1990).

Thirty-one species were included in the sample of measured trees, most of them being Fabaceae (Appendix 1, supplementary material). The sizes of the sampled trees were chosen to uniformly cover the widest

[1] Corresponding author. Email: nicolas.picard@cirad.fr
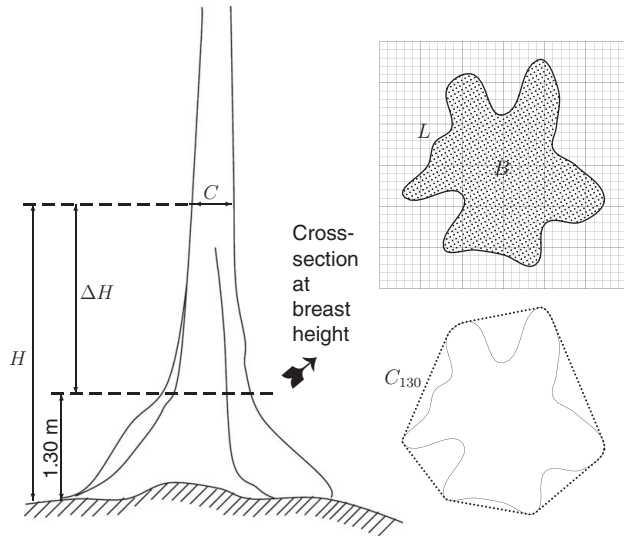
Figure 1. Measurements for a buttressed tree: C is the girth above buttress; H is the height above ground where C was measured; $\Delta H = H - 1.30$ m; C_{130} is the girth at breast height (= length of the dotted line); the basal area at breast height (B) is the number of square cells inside the cross-section (here 316.4 cells) times the unit area of a square cell (= area of the stippled area); L is the perimeter at breast height (= length of the thick black line).

possible range of sizes. The smallest tree of the sample had a DAB of 26.4 cm while the largest tree had a DAB of 94.5 cm (Appendix 1, supplementary material). Because some species (e.g. *Aucoumea klaineana*) develop buttresses only above a given size, the range of sampled DAB could not be covered for each species.

Five measurements were taken for each tree: (1) the girth at breast height (denoted C_{130}) was measured by a taut tape over the buttresses at a height of 1.30 m above ground (Figure 1, dotted line). (2) The girth above buttress (C) was measured using a graduated flexible tape at the vertical position along the trunk where the trunk cross-section became convex. The DAB is computed from C as C/π. (3) The height above ground where C was measured (H) was measured using a graduated stick. (4) The basal area at breast height (B) was non-destructively measured using a flexible wire. The wire was flattened against the trunk, following the shape of the buttresses at a height of 1.30 m above ground. The wire had to be flexible enough to mould the buttresses, but at the same time rigid enough to keep the shape without distorting it. We used electric wire with a 1-mm diameter. Two pieces of wire were used, one for each half of the trunk. This enabled us to remove the moulded wire from the trunk without distorting it. The two pieces of wire were then put on a wooden board. A grid of 5 × 5-cm square cells was printed on the board. Let N be the number of square cells that were enclosed by the wire. Fractions of cells were counted for those cells that were crossed by the wire. The basal area at breast height was measured as $N \times 25$ cm^2. (5) The perimeter at

breast height (L) was measured as the length of the wire necessary to surround the trunk (Figure 1, thick solid line).

Two additional tree characteristics were computed from the five measured tree characteristics. The equivalent girth at breast height (denoted C_{eq}) was defined as the girth that the tree would have if its trunk had a circular shape, without changing its basal area at breast height. It was computed from B as $C_{eq} = \sqrt{4\pi B}$ and is the quantity that we are interested in measuring, in place of C. Following Dean *et al.* (2003), we defined the fractional basal area deficit (denoted D) as one minus the ratio of the basal area of the tree over the area of the circular disc with the same perimeter L as the tree: $D = 1 - B / (\frac{1}{4\pi}L^2) = 1 - (C_{eq} / L)^2$. Because, for a given area, the shape with the smallest possible perimeter is the circular disc, $0 \leq D < 1$ (with $D = 0$ for a circular disc and $D \to 1$ as buttresses get more irregular). This fractional basal area deficit depends on the shape but is dilation invariant. For example, the fractional basal area deficit of a regular n-sided polygon is $1 - \pi [n \tan(\pi/n)]^{-1}$ irrespective of its side (http://mathworld.wolfram.com; $D \approx 0.40$ for an equilateral triangle, $D \approx 0.21$ for a square, etc.).

Among the seven tree characteristics that were measured, three were considered as easy to measure (namely C_{130}, C and H) and were used as predictors in a model that predicts the quantity of interest (C_{eq}). The girth at breast height C_{130} was significantly correlated with the girth above buttress C (Pearson correlation coefficient: $r = 0.87$, $t = 17.4$, P < 0.001). The height H was not significantly correlated with C ($r = 0.12$, $t = 1.19$, P = 0.24) but was significantly correlated with C_{130} ($r = 0.35$, $t = 3.7$, P < 0.001).

We fitted all possible combinations of the linear model based on these three predictors with interactions up to the third order (254 models). The full model is: $C_{eq} = a_0 + a_1 C_{130} + a_2 C + a_3 \Delta H + a_4 C_{130}C + a_5 C_{130}\Delta H + a_6 C\Delta H + a_7 C_{130}C\Delta H + \varepsilon$, where $\Delta H = H - 1.30$ m is the height above breast level where C was measured, the a_is ($i = 1, \ldots, 7$) are the coefficients to estimate, and ε is the residual error. Power models (i.e. linear models on log-transformed data) were also tested, but they always provided a worse fit than the corresponding linear models. To account for the heteroscedasticity of residuals, a power model was chosen for the residual variance: $\text{Var}(\varepsilon) \propto C^z$, unless z was close to zero in which case a standard linear model was fitted. The Akaike information criterion (AIC) was used to rank the models. Models were fitted using the nlme routine in the R package. A residual effect of species (with 31 levels), of site (Ipassa or Kongou), and of the fractional basal area deficit D was tested.
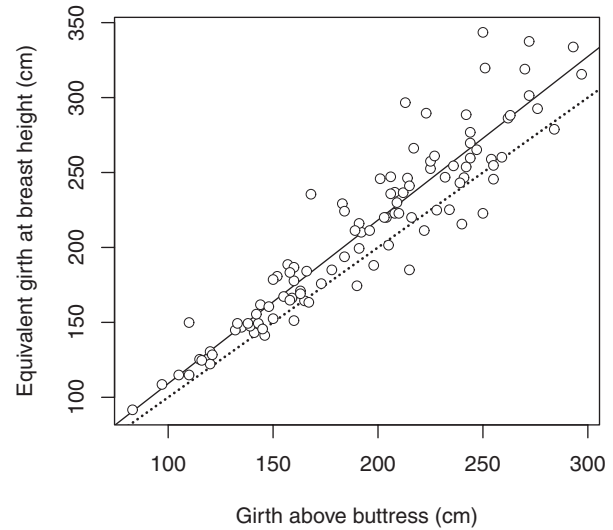
The mean value of the fractional basal area deficit was 0.39 (minimum: 0.09, maximum: 0.79). By comparison, Dean *et al.* (2003) found a maximum of 0.6 for *Eucalyptus regnans* in temperate Australia. When restricting to

Table 1. Fitted models to predict the equivalent girth at breast height C_{eq} from a combination of three predictors: the girth above buttress (C), the girth at breast height (C_{130}), and the height (ΔH) above breast level of measurement of C. Only the models whose coefficients are all significantly different from zero are shown. z is the exponent of the power model used for the residual variance. AIC is the Akaike information criterion (the smaller AIC is, the better the model is). C_{eq}, C and C_{130} are in cm, whereas ΔH is in m.

No.	Model	z	R^2	AIC
1	$C_{eq} = 0.702\,C + 0.292\,C_{130}$	2.07	0.93	864.1
2	$C_{eq} = 1.055\,C - 0.104\,C\Delta H + 0.087\,C_{130}\Delta H$	1.82	0.93	873.8
3	$C_{eq} = 1.015\,C + 0.024\,C_{130}\Delta H$	1.46	0.92	878.4
4	$C_{eq} = 39.9 + 0.567\,C + 0.001185\,CC_{130}$	1.70	0.92	885.0
5	$C_{eq} = 1.034\,C + 0.000096\,CC_{130}\Delta H$	1.34	0.91	885.7
6	$C_{eq} = 14.9 + 0.927\,C + 0.000129\,CC_{130}\Delta H$	1.49	0.92	886.2
7	$C_{eq} = 28.7 + 0.684\,C + 0.000773\,CC_{130} + 0.016\,C_{130}\Delta H$	1.74	0.92	887.3
8	$C_{eq} = 1.021\,C + 0.031\,C\Delta H$	1.40	0.91	887.4
9	$C_{eq} = 18.3 + 0.911\,C - 7.00\,\Delta H + 0.052\,C_{130}\Delta H$	1.69	0.92	888.8
10	$C_{eq} = 1.035\,C + 4.20\,\Delta H$	1.45	0.91	889.4

Figure 2. Equivalent girth at breast height (C_{eq}) versus girth above buttress (C) for 102 buttressed trees measured in North-East Gabon. Solid line is the fitted model $C_{eq} = 1.091\,C$ ($R^2 = 0.90$). Dotted line is the 1:1 line.

species for which at least four individuals were measured (Appendix 1, supplementary material), there was a significant difference of fractional basal area deficit among species (one-way ANOVA: $F_{10,64} = 2.41$, P = 0.02). The species with the most regular trunk shape were *Hymenostegia pellegrinii* ($D = 0.27$ on average) and *Aucoumea klaineana* ($D = 0.28$), whereas the species with the most irregular trunk shape were *Newtonia* sp. ($D = 0.57$) and *Gilletiodendron* sp. ($D = 0.59$). Like Dean *et al.* (2003), we found a significant positive correlation between D and C_{130} ($r = 0.33$, $t = 3.52$, P < 0.001) in the range of our measurements ($103 \le C_{130} \le 465$ cm), indicating that buttresses develop as trees grow.

Among the 254 possible models, 71 had all their coefficients significantly different from zero. The intercept was most of the time not significantly different from zero, which is consistent with the fact that C_{eq} must be zero when all tree characteristics are zero. The ten models with the lowest AIC are listed in Table 1 by increasing order of AIC. The best model is the one that predicts C_{eq} from C and C_{130}. Because C and C_{130} are strongly positively correlated, their effects on C_{eq} are largely confounded, with C capturing the main variation of C_{eq}. Since C and C_{130} are quite easy to measure and ΔH does not add to the predictive power of these two variables, this model is designed to be the most useful. No residual effect of species was found for this model (ANOVA of weighted residuals: $F_{30,71} = 1.13$, P = 0.33). No residual effect of site was found either ($F_{1,100} = 0.83$, P = 0.36). However, adding D as an extra predictor significantly improved the model ($t = -3.78$, P < 0.001). The correlation between residuals and D was negative: all other things being equal, the

equivalent girth at breast height increases as the trunk shape becomes circular, which is self-consistent.

If C_{130} is not available, the best model is the one that predicts C_{eq} from C and $C \times \Delta H$, and is ranked as the eighth model (Table 1). ΔH most often occurs as a multiplying factor of C or C_{130} (or of both of them) which is consistent with a constant linear taper curve of the stem. Considering that the coefficient associated to C in model 8 is close to one, model 8 can be interpreted as a Taylor first-order expansion at 1.30 m of the exponential taper equation (Metcalf *et al.* 2009): $C = C_{eq} \exp(-\alpha(H - 1.30))$, where the tapering coefficient $\alpha > 0$ corresponds to the coefficient associated to $C\Delta H$ in model 8. The value found here ($\alpha = 0.031$) is in the range of α values found by Metcalf *et al.* (2009) for five tropical species ($0.0149 \le \alpha \le 0.1190$).

If C is the only variable that has been measured, the best model is: $C_{eq} = 1.091\,C$ (Figure 2). This model is ranked 17th among the 71 models (AIC = 894.9, $R^2 = 0.90$). When C_{130} is the only available variable, the best model is: $C_{eq} = 17.94 + 0.726\,C_{130}$. This model is ranked 38th among the 71 models (AIC = 949.1, $R^2 = 0.83$).

Because the equivalent diameter at breast height is on average 9.1% greater than the diameter above buttress (Figure 2), and because buttressed trees are often the largest trees with the largest contribution to basal area or above-ground biomass, using the former in place of the latter can have practical implications when estimating structural stand attributes. For instance, using the Chave *et al.* (2005) allometric equation for moist forest stands, the mean above-ground dry biomass of the sampled trees was 5.75 Mg when using C as a predictor, and 7.06 Mg when using C_{eq} as a predictor (18.5% increase).

Nevertheless, the issue of estimating the biomass of large buttressed trees cannot be solved by simply replacing C with C_{eq}. First, large trees are prone to hollows that detract from the cross-sectional area (Dean *et al.* 2003, Nogueira *et al.* 2006). Second, using C or C_{eq} to predict biomass will depend on how trees were measured to derive the biomass equations. Because biomass data sets most often mix buttressed trees that are measured above the buttresses and non-buttressed trees that are measured at breast height (Chave *et al.* 2005), the uncertainty on the height of measurement is included in the prediction error of the biomass equation. Reducing this uncertainty would require clear documentation of the measurement and appropriate allometric relationships (Sillett *et al.* 2010).

Another pending question is whether buttresses correspond to a distortion of the shape of the stem without any change in basal area, or whether they induce a change of basal area as compared with a cylindrical tree with the same DAB. Considering that buttresses have a mechanical role (Newbery *et al.* 2009, Richter 1984) but no specific role in sap transportation, it can be expected that the tapering of basal area will be the same with or without a buttress. Indeed, buttresses are often accompanied by a downward tapering of the central stem (i.e. a decreasing central radius), towards ground level (Newbery *et al.* 2009, Pallardy 2008, p. 12), or even sometimes a reversed taper in equivalent girth as shown by the points below the 1:1 line in Figure 2.

ACKNOWLEDGEMENTS

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APPENDIX

Appendix is available as supplementary material on-line at http://journals.cambridge.org/tro