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Review

# Below-ground biomass production and allometric relationships of eucalyptus coppice plantation in the central highlands of Madagascar

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ABSTRACT

Short rotations of *Eucalyptus* plantations under coppice regime are extensively managed for wood production in Madagascar. Nevertheless, little is known about their biomass production and partitioning and their potential in terms of carbon sequestration. If above-ground biomass (AGB) can be estimated based on established allometric relations, below-ground (BGB) estimates are much less common. The aim of this work was to develop allometric equations to estimate biomass of these plantations, mainly for the root components. Data from 9 *Eucalyptus robusta* stands (47–87 years of plantation age, 3–5 years of coppice-shoot age) were collected and analyzed. Biomass of 3 sampled trees per stand was determined destructively. Dry weight of AGB components (leaves, branches and stems) were estimated as a function of basal area of all shoots per stump and dry weight for BGB components (mainly stump, coarse root (CR) and medium root (MR)) were estimated as a function of stump circumference. Biomass was then computed using allometric equations from stand inventory data. Stand biomass ranged from 102 to 130 Mg ha$^{-1}$ with more than 77% contained in the BGB components. The highest dry weight was allocated in the stump and in the CR (51% and 42% respectively) for BGB parts and in the stem (69%) for AGB part. Allometric relationships developed herein could be applied to other *Eucalyptus* plantations which present similar stand density and growing conditions; anyhow, more is needed to be investigated in understanding biomass production and partitioning over time for this kind of forest ecosystem.



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# 1. Introduction

Forests comprise the largest carbon pool of all terrestrial ecosystems thanks to the potential of to sequester carbon [1–3]. This important role in regulating carbon cycle is of major concern today in relation to the continuous increase of $CO_2$ in the atmosphere which contributes to global warming [1,4]. In fact, as incited by the Kyoto Protocol in relation with the United Nations Framework on Climate Change, reducing the release of carbon stored in vegetation (i.e. reduce deforestation and forest degradation) or establishing vegetation sinks (i.e. enhance afforestation and reforestation) are among the several methods for reducing the net emissions of $CO_2$ in the atmosphere [5]. The Clean Development Mechanism (CDM) in the Kyoto Protocol will allow afforestation and reforestation projects to be established and financed in the developing countries to assist industrialized countries reach their emission reduction targets. Thus, there is much interest in estimating biomass of forests and tree plantations and this implies a need to explore all biomass components.

As in many countries [6,7], short rotation forestry (SRF, especially under coppice regime) using fast growing exotic species such as Eucalyptus genus is a major forestry practice in the central highland of Madagascar for energy purposes. *Eucalyptus robusta* plantations are well known to the people who are living in the central highland of Madagascar. This practice contributes to alleviate the natural forests' decline which is mainly caused by increasing population and economic pressures [8]. These plantations have been in place since the beginning of the last century [9,10] and are pursued with the increased demand for wood and fuel wood but also for ecological services and future incomes from CDM projects.

In SRF a variety of established methods exists for estimating the biomass in above-ground tree components for not only a direct measure of productivity, but also for nutrient accumulation and distribution. For instance, Senelwa and Sims [11] with *Eucalyptus ovata*, *Eucalyptus saligna*, *Eucalyptus globulus* and *Eucalyptus nitens* in New Zealand, Nordh and Verwijst [12] with *Salix* sp. in Sweden and more recently Zewdie et al. [13] with *E. globulus* in Ethiopia assessed the relationship between above-ground biomass (AGB) production and tree dimensions (height and diameter) to determine a non-destructive sampling equation and demonstrated that a pooled equation could be applicable to a variety of eucalyptus.

Besides, a very limited part of the research was focused in root compartment because, as in any forest ecosystem, biomass of root systems is difficult to measure [14,15]. This is mainly because excavating root systems is a difficult task (measurements are tedious and very time-consuming) but also because there is a lack of adequate method to study the dynamics and functions of this part of the ecosystem [16,17]. Therefore, below-ground biomass (BGB) was generally assessed indirectly by using the Root:Shoot ratio (R:S) which corresponds to the relative biomass allocation between roots and above-ground parts [14]. For SRF, there are few investigations on below-ground biomass measurement such as those conducted by Misra et al. [18] and Wildy and Pate [19] in Australia when studying spatial distribution of below-ground biomass of *E. nitens* and describing the general biology of coppices respectively, and by Bouillet et al. [20], et Saint-André et al. [21] in Congo for their works on spatial distribution of root systems and eucalyptus biomass equations, respectively. But understanding root system is especially important for SRF of eucalyptus because these systems are often based on coppice regeneration, it is then necessary to provide an accurate below-ground biomass. The objective of the present study was therefore: (i) to assess the relationship between BGB production (and also the AGB) and tree dimension (stump circumference or basal area) and (ii) to estimate the biomass production and partitioning in different components of these old *E. robusta* coppices in the central highland of Madagascar.

# 2. Material and methods

## 2.1. Study area

The study was conducted at Sambaina-Manjakandriana, in Malagasy Highlands (47°45′–47°50′ East and 18°50′–18°56′ South and 1350–1750 m elevation). Average annual rainfall and temperature were 1600 mm and 14.5 °C respectively. The geological substratum is composed of granites, and soils are Ferralsols according to the FAO classification [22] with 1:1 clay content of a mean of 55%.

The eucalyptus plantation in this area shows the historical setting of eucalyptus plantations in the whole central highland of Madagascar. These plantations cover 150,000 ha that is to say 46.5% of all plantation forestry in Madagascar and where *E. robusta* is the most widespread species thanks to its aptitude in rough stony soil and bush fire conditions [23]. *E. robusta* shows the natural ability to sprout, so it could be adopted as a coppicing system of renewal as existing in our study area; actually, since their first plantation in 1900, most of all stools have not been renewed. Being planted first along the railway for locomotive fuel wood supply, eucalyptus plantations were used for landed property and mainly for energy purposes from now [8]. Stands have variable areas (from a few hundred of square meter to less than 10 ha) are privately managed and usually harvested at the age of 3–5 years and stumps cut on ground level are left to resprout. No silvicultural treatments are practiced, all stems (shoots) are left after coppicing for natural thinning.

## 2.2. Studied stands characteristics

Nine stands of *E. robusta* (Table 1) were identified and selected to study below-ground (BGB) and above-ground biomass (AGB) production and partitioning in relation to total plantation age which ranged from 47 to 87 years. Plantation age and coppice-shoot age were obtained by means of interviews with elderly and officials local people and of use of aerials photo interpretation. According to the small size of the stands, three plots (10 m × 10 m) were randomly located in each stand. Inventory was made in each plot where all stools (stocking 1) and shoots (stocking 2) density was counted and some variables directly measured: stump circumference of all stools (Cir), circumference at breast height (CBH) and height (H) of all shoots.

**Table 1 – Stand characteristics of the selected *Eucalyptus robusta* plantations in the central highlands of Madagascar ($n = 9$).**

| Plot | Stumps | | | Coppice-shoot | | | |
|---|---|---|---|---|---|---|---|
| | Plantation age (year) | Stocking 1 (stumps.ha$^{-1}$) | Cir (cm) | Coppice age (year) | Stocking 2 (stems.ha$^{-1}$) | CBH (cm) | H (m) |
| 1 | 47 | 2200 | 168.5 (91.8) | 3 | 13200 | 9.1 (4.3) | 4.8 (1.5) |
| 2 | 77 | 3333 | 126.1 (67.5) | 5 | 16967 | 8.7 (6.8) | 4.3 (1.6) |
| 3 | 52 | 2767 | 146.2 (64.9) | 3 | 24800 | 5.8 (3.6) | 3.2 (1.2) |
| 4 | 72 | 3033 | 142.6 (57.2) | 5 | 16500 | 9.9 (6.6) | 5.2 (2.6) |
| 5 | 53 | 2867 | 144.6 (56.8) | 3 | 18167 | 6.5 (4.2) | 3.8 (1.6) |
| 6 | 67 | 3067 | 147.3 (65) | 5 | 15567 | 9.7 (6.7) | 4.7 (2.1) |
| 7 | 72 | 3733 | 124.6 (66.8) | 5 | 17700 | 9.5 (5.8) | 4.8 (1.9) |
| 8 | 67 | 3500 | 130.6 (77) | 3 | 17800 | 7 (3.4) | 3.7 (1.3) |
| 9 | 87 | 3067 | 155.5 (68.7) | 5 | 17033 | 8.2 (5.7) | 4.2 (2.1) |

Values in brackets represented the standard deviation. Plantation age is the date of first eucalyptus plantation, Stocking 1: stump density corresponding to the number of stumps per unit of area, Cir: mean circumference of all stumps in a stand, Coppice age: the date of the last cutting shoots, Stocking 2: shoot density corresponding to the number of shoots per unit of area, CBH: mean circumference at breast height of all shoots in a stand, H: mean height of all shoots in a stand.

### 2.3. *Tree selection*

For each stand, histograms of circumferences have been calculated pooling the data collected on the three sub-plots, then three classes of circumferences were fixed and one tree per class of circumferences was chosen. In order to cover the stand variability, one tree by sub-plot was felled (in total 27 trees). The restricted number of trees to fall down is explained by the difficulty associated to tree uprooting and by the search for a less destructive approach as possible regarding wood production for local communities and environmental damage. All 27 trees were used for below- and above-ground biomass evaluations.

### 2.4. *Below-ground (BGB) biomass measurements*

BGB part of each tree was subdivided into four components: stump, coarse roots (CR), medium roots (MR) and fine roots (FR). Stump was the tree part between above-ground point where the stem was cut and the below-ground points where the roots could be clearly individualized [19,21]. For the actual root system, root diameter was used to classify its subcomponents: diameter $\geq$ 10 mm, 10 mm $<$ diameter $\leq$ 2 mm and diameter $<$ 2 mm for CR, MR and FR respectively. According to the component size, different methods were applied: the first was designed for the larger component (stump, CR and MR) and the second for the smaller (FR).

#### 2.4.1. *First method: stump, CR and MR biomasses*

A sampling unit known as Voronoi polygon was defined for each sampled tree. The Voronoi polygon (Fig. 1) is the polygon of occupancy and the elementary space which is formed by the intersection of the perpendicular lines that pass through the midpoints of the lines connecting the center of the sampled tree to the center of the nearest neighboring trees [16,21]. The whole polygon area was excavated for BGB biomass evaluation where all excavations were done manually to a 1 m depth. This limit was chosen because of the fact that, generally, most of tree root are located in the top 15–60 cm of the soil [24,25]. Stump was separated from individualized roots with the use of a chain saw and CR and MR were sorted manually and sieved to be separated from soil. The excavated root system was weighted and aliquots were sampled for determining dry weight. Moisture samples were oven-dried to a constant weight at 70 °C and weighted.

#### 2.4.2. *Second method: FR biomass*

Root density decreased sharply with depth, with most fine roots in the surface layers 0–25 cm [20]. Reminding that dense mats of shallow fine roots were mostly presented in eucalyptus plantation floor in Malagasy Highlands where fine roots are mixed with plant debris to give a thick (5–10 cm) mat of roots. Thus, FR biomass in soil per stand were evaluated by core sampling (3 replicates, randomly located in the Voronoi polygon) near each sampled tree with metallic cylinder (diameter = 8 cm) to 50 cm depth, assuming that this was the soil layer where FR proliferated [26]. FR were collected from sampled soils by series of washing and sieving. After being oven-dried at 70 °C to a constant weight, FR biomass density was calculated on an area basis.

### 2.5. *Above-ground (AGB) biomass measurements*

The same 27 sampled trees for BGB measurements were used for AGB measurements. All stems or shoots per selected stool were fallen down and the following compartments were considered according to local people' harvest practice: stems, branches and leaves. For each compartment, all elements of all shoots were gathered, weighted and sampled for oven-dried to determine dry weight matter of the whole compartment.

### 2.6. *Allometric relationships*

Allometric equations are widely used for forest biomass assessment. They link tree biomass to other dendrometric variables which can be directly measured in the field during forest inventories.

#### 2.6.1. *Regression models*

For Eucalyptus forests, relationships between AGB and diameter have already been developed [27]. In SRF under coppice regime, the principles are the same [11,13,21,28], but the

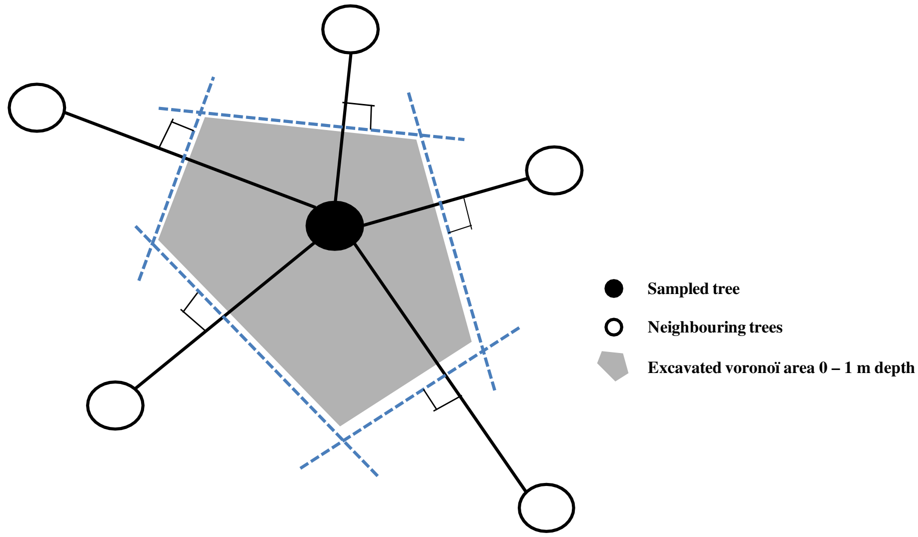


**Fig. 1 – Voronoi polygon for stump, CR and MR extractions.**

difference with conventional forestry is the fact that there are many stems per tree instead of a single stem. In our case, individual tree component model was developed by relating dry weight of each AGB compartment (leaves, branches, stems) with the shoots basal area per tree (BA) [29,30]. The basal area summarizes the number and the size of trees in a stand which corresponds to the area of the cross section of a stem at breast height; it is calculated from circumference measurements. For a stool or tree containing a number of $n$ shoots, its basal area is calculated following the formulas:

$$BA = \sum_{i=1}^{n} (CBH_i)^2/4\pi \quad (1)$$

where $BA$ (in $m^2$ $tree^{-1}$) is the sum of basal area of all shoots of the selected tree, $n$ the number of shoots per stool or tree, CBH (cm) the circumference of each shoot at breast height (1.30 m).

For BGB parts, in the present study, stump circumference (Cir expressed in cm) which was the only visible and measurable variable after coppicing could be used for establishing relationship with larger parts of the BGB components (stump, CR, MR).

As commonly used in forest ecosystems [31], allometric models corresponding to biomass-diameter (or circumference) regressions were used herein to estimate biomass value per tree (Equations (2) and (3)). Variables were log-transformed to avoid heteroscedasticity in the data.

$$\log(AGBi) = \beta_0 + \beta_1 \log(BAi) + \epsilon_i \,;\, \epsilon_i \sim N(0;\sigma^2) \quad (2)$$

$$\log(BGBi) = \beta_0 + \beta_1 \log(Ciri) + \epsilon_i \,;\, \epsilon_i \sim N(0;\sigma^2) \quad (3)$$

#### 2.6.2. *Model selection*

Model performance was assessed on the basis of various indexes. First, the coefficient of determination ($R^2$) of the model was computed. $R^2$ is an indication of the goodness of fit of the model. Besides, in order to highlight the performance of the biomass-circumference model for each tree component, we compared the AIC (Akaike Information Criterion) and the Residual Standard Error (RSE) of each model to the AIC and RSE of a null model.

The RSE was defined as the standard deviation of the residual errors $\epsilon_i$ (with $\epsilon_i = \log(AGB_i) - [\log(AGB_i)]_{estimated}$). The smaller is the RSE, the smaller is the unexplained part in the observed biomass and the better is the model.

The AIC is a penalized estimation of the goodness of fit of the model given the number of parameters

($AIC = -2\log(L) + 2n_{par}$ with L: the model likelihood and $n_{par}$ the number of parameters of the model). The smaller the AIC, the better the model is fitted.

#### 2.6.3. *Model prediction*

Before biomass per tree or per stand calculation, a correction was brought out. Actually, the log-transformation of the data entails a bias in the biomass estimation [31], thus, a multiplicative correction factor ($CF = RSE^2/2$) was applied to the intercept parameter $\beta_0$ when calculating the biomass values.

As a follow-up on the biomass estimation, the biomass of the components and of the whole BGB and AGB pools was determined using allometric equations on data per sampled tree. Concerning the calculation of the stand biomass per ha, these allometric equations were first applied on inventory data for each plot. The biomass per stand was afterwards obtained by calculating the mean of biomass per ha of the three plots per stand.

### 2.7. *Other statistical analysis*

Correlations between dry weight and dendrometric variables were determined by using the *Pearson's* rank correlation coefficient ($r$). A principal component analysis (PCA) was performed to study relationship between variables that may control BGB and AGB biomass production and partitioning. Coefficient of correlation between those variables was also determined by using $r$.

All model fitting and statistical analysis were performed using XLSTAT 2008 and R software.

## 3. Results

### 3.1. BGB allometric models

First, concerning the model fitting, the biomass-circumference models (Equations (6) to (9) in Table 2) fitted better the data than the null model; they showed smaller RSE and AIC.

Concerning biomass estimation, stump dry biomass varied from 1.6 to 82.2 kg.tree$^{-1}$ (Fig. 2a), CR dry biomass ranged from 2 to 52.6 kg.tree$^{-1}$ (Fig. 2b) and MR dry biomass varied between 0.2 and 8.6 kg.tree$^{-1}$ (Fig. 2c). Consequently, total BGB biomass (FR not included) ranged from 4.5 to 134.4 kg.tree$^{-1}$ (Fig. 2d). Individual tree components in BGB part expressed as a function of the stump circumference had enough high $R^2$ values and, expect for MR, generally accounted for more than 70% of the variance (Table 2).

For these old coppices of *E. robusta* in Malagasy Highlands, the zero-intercept form of the power function of the BGB regression model proved to be the model with the best fit.

### 3.2. AGB allometric models

As for the BGB parts, the biomass-circumference models (Equations (10) to (13) in Table 3) fitted better the data than the null model (see smaller RSE and AIC for the biomass-circumference allometric models than for the null models).

Besides, regarding all shoots that each stool supported, leaf dry biomass ranged from 0.1 to 9.5 kg.tree$^{-1}$ (Fig. 3e), branch dry biomass varied between 0.2 and 7.9 kg.tree$^{-1}$ (Fig. 3f) and stem dry biomass ranged from 0.6 to 38.9 kg.tree$^{-1}$ (Fig. 3g). Total AGB varied then between 1.2 and 51.5 kg.tree$^{-1}$(Fig. 3h).

When expressed as a function of the basal area of all shoots per stool, individual components in AGB part showed high $R^2$ values (Table 3). The relationships accounted generally for more than 84% of the variance expect for the branches component.

### 3.3. Biomass partitioning

FR biomass which were directly assessed by core sampling and reported in Mg ha$^{-1}$ is included with BGB biomass production (Table 4). Overall, BGB biomass ranged from 82.3 to 100.9 Mg ha$^{-1}$. The stump component was the largest part of the BGB production (Fig. 3i); it contained 46.5 ± 3.6 Mg ha$^{-1}$ of biomass. By descending order after the stumps, CR contains 38.2 ± 2.7 Mg ha$^{-1}$; MR and FR were the smallest components with 3.9 ± 0.3 Mg ha$^{-1}$ and 3 ± 2.5 Mg ha$^{-1}$ respectively.

Regarding the AGB part (Fig. 3j), the stem biomass represented the largest production with 19.9 ± 5.9 Mg ha$^{-1}$ against 4.2 ± 1.3 Mg ha$^{-1}$ and 4.8 ± 1.4 Mg ha$^{-1}$ for leaves and branches production respectively. Total AGB biomass varied hence from 19.3 to 39.8 Mg ha$^{-1}$.

### 3.4. Correlation between variables

Concerning the correlations between stand biomass and environmental factors (Table 1 and Fig. 4): (i) there were significant and positive correlations between AGB biomass and coppice age, AGB biomass and shoot dimensions (mean CBH and H) with $r = 0.9$ and 0.8 respectively; (ii) significant and negative correlation were found between stump density (nb. stump.ha$^{-1}$) and stump circumference ($r = -0.9$); shoot density (nb. shoot.ha$^{-1}$) and shoot dimensions (always mean CBH and H; $r = -0.8$), and mean CBH and the number of shoots per stump (Nb shoot/stump in Fig. 4; $r = -0.7$). (iii) Despite a coefficient correlation of 0.5 between BGB biomass and plantation age, this correlation was not significant, as between BGB biomass and all the other variables. Regarding the principal components (PCs), PC#1 showed 53.4% of the variance of our data and was linked to the AGB parts AGB biomass, shoot dimensions and coppice age (Fig. 4i) with $r = 0.9$ for each of them; PC#2 with 22.9% of the variance was linked with the BGB variables (stump circumference and stump density; $r = -0.8$ and 0.8 respectively), and the third PC with its 12.7% (Fig. 4j) represented mainly the BGB biomass ($r = 0.9$).

## 4. Discussions and conclusions

### 4.1. Allometry relationships

In high forest of eucalyptus (another management regime which consists of succession of plantation, harvest and replantation after a long rotation), BGB biomass, or coarse root biomass particularly, is often highly correlated with stem size and biomass [18,32]. Nevertheless, in old coppices of eucalyptus plantations such as in the current study, stump circumference could predict properly BGB biomass. In fact, the

**Table 2 – Model parameters and properties for the allometric model: exp ($\beta_0 + \beta_1$ log (Cir)) of the below-ground tree biomass components.**

| | $\beta'_0$ | $\beta_1$ | df | $R^2$ | RSE | | AIC | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Model | Model null | Model | Model null | |
| Stump | −6.93 | 1.89 | 23 | 0.83 | 0.46 | 1.13 | 35.21 | 78.2 | (6) |
| CR | −3.93 | 1.23 | 21 | 0.69 | 0.46 | 0.83 | 32.34 | 57.77 | (7) |
| MR | −3.17 | 0.64 | 21 | 0.23 | 0.64 | 0.74 | 48.03 | 52.3 | (8) |
| BGB | −4.55 | 1.57 | 23 | 0.77 | 0.46 | 0.97 | 35.52 | 70.62 | (9) |

Dry mass of below-ground components of *Eucalyptus robusta* in the central highlands of Madagascar are expressed in kg.tree$^{-1}$ and related with the stump circumference (Cir) which is expressed in cm. For each model, the estimated value of the intercept $\beta'_0 = (\beta_0 + RSE^2/2)$ included the correction factor ($CF = RSE^2/2$) imposed by the inverse log-transformation of the response variable.

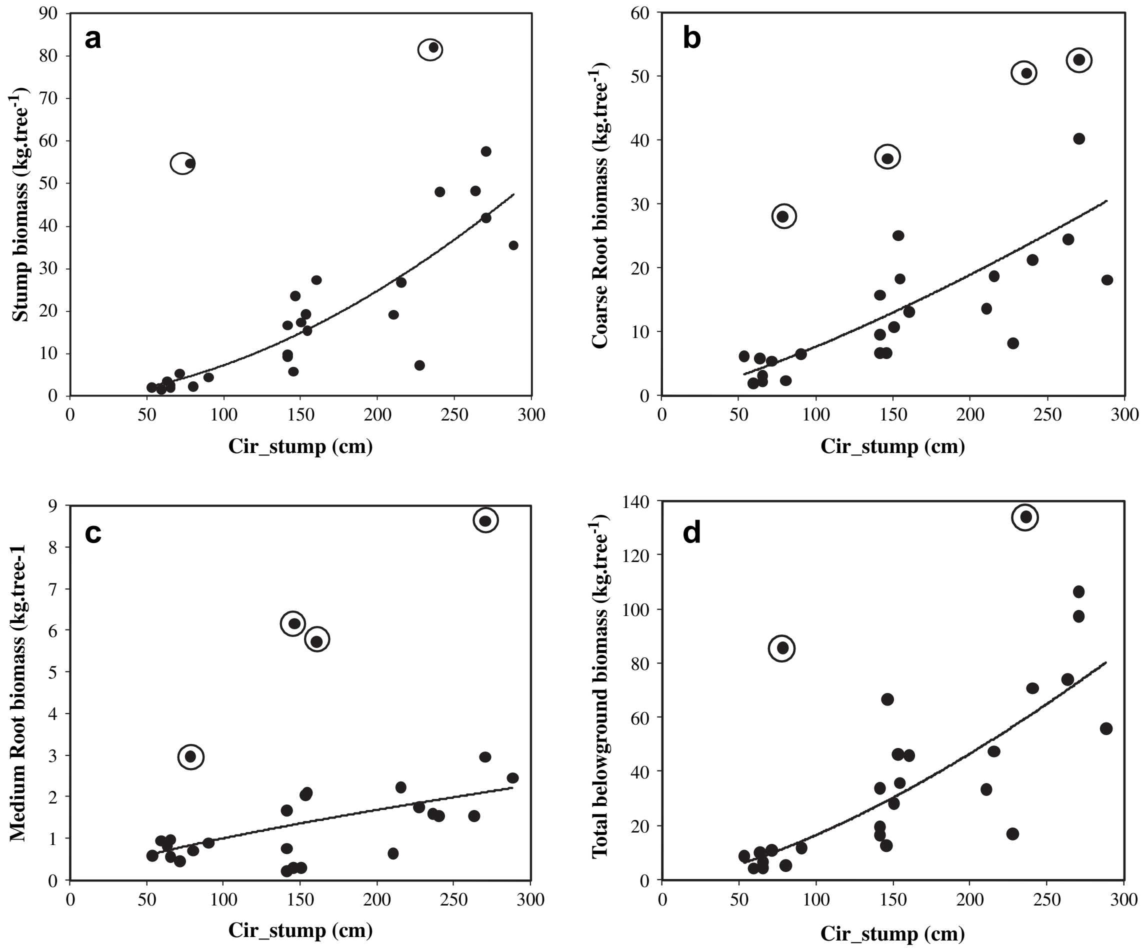


**Fig. 2 – Relationships between stump circumference (cm) and dry weight below-ground biomass components of (a) stumps, (b) coarse roots (CR, with diameter ≥ 10 mm), (c) medium roots (MR, 10 mm > diameter ≥ 2 mm) and (d) total below-ground dry biomass (N = 27). Points surrounded by circle were aberrant values and were not considered when fitting biomass allometric models.**

stump is the only measurable component left after each coppicing event and then it should reflect BGB production. If allometric equation could explain about 87% of overall BGB parts, the explained variance decreased with BGB component size (90% for the stump against only 25% for MR).

In regard to the AGB part, allometric equations developed here were closed to those used for classical AGB biomass assessment [11,13,33]. Instead of establishing allometric relationship between each shoot diameter or circumference and the dry weight of its component; it was the whole biomass of the considered component for a tree which was directly related with the basal area of all shoots per tree. Actually, diameter or CBH of all shoots per tree was highly variable and the basal area (expressed from CBH; see *formulas* (1)) seemed

**Table 3 – Model parameters and properties for the allometric model: exp ($\beta_0 + \beta_1$ log (BA)) of the above-ground tree biomass components.**

| | $\beta_0$ | $\beta_1$ | df | $R^2$ | RSE | | AIC | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Model | Model null | Model | Model null | |
| Leaves | 6.78 | 1.2 | 23 | 0.84 | 0.42 | 1.03 | 30.33 | 75.53 | (10) |
| Branches | 5.56 | 0.95 | 22 | 0.63 | 0.57 | 0.94 | 44.44 | 66.28 | (11) |
| Stems | 7.44 | 1.05 | 21 | 0.88 | 0.31 | 0.89 | 14.64 | 61.24 | (12) |
| AGB | 7.87 | 1.05 | 21 | 0.92 | 0.24 | 0.88 | 3.89 | 60.14 | (13) |

Dry biomass of above-ground components of *Eucalyptus robusta* in the central highlands of Madagascar are expressed in kg.tree$^{-1}$ and related with the basal area of shoots per stool expressed in m$^2$.tree$^{-1}$. For each model, the estimated value of the intercept $\beta'_0 = (\beta_0 + RSE^2/2)$ included the correction factor (CF = RSE$^2$/2) imposed by the inverse log-transformation of the response variable.

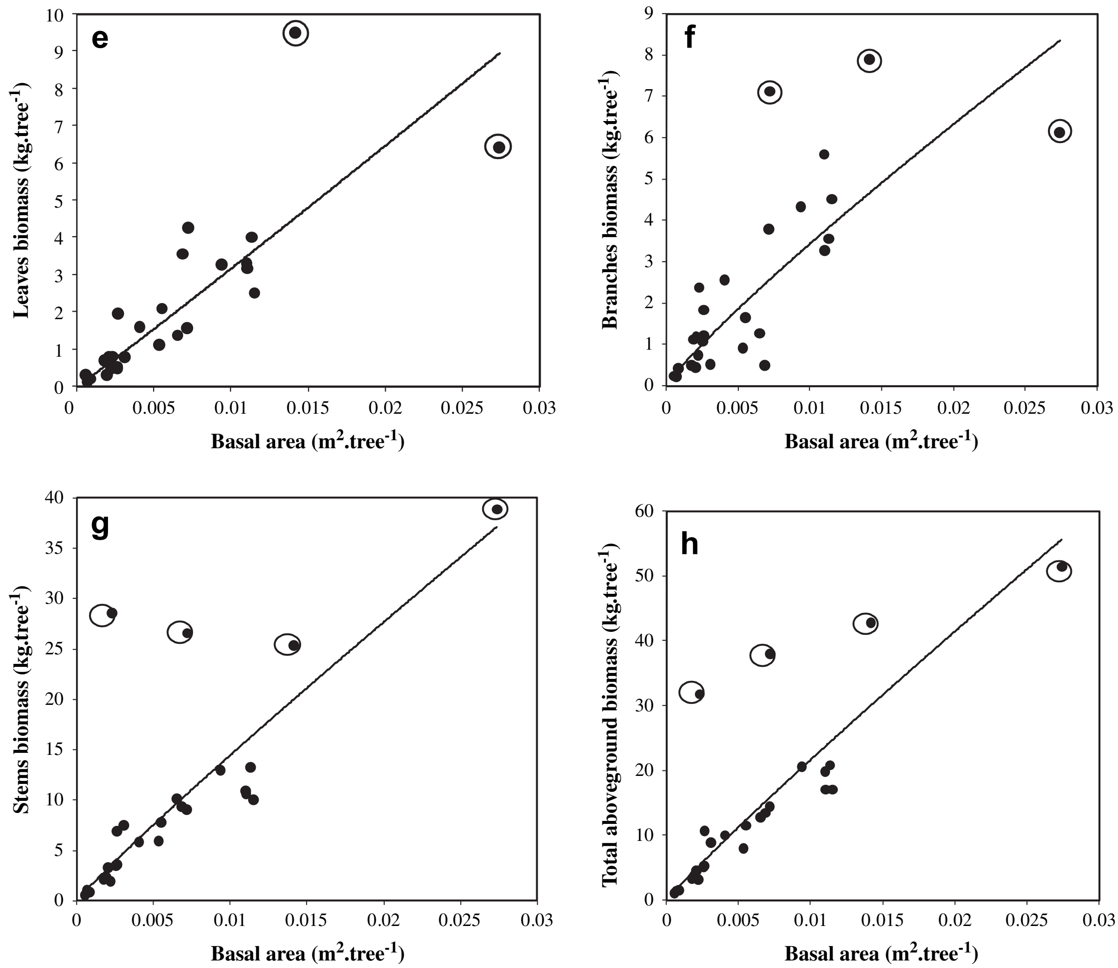


**Fig. 3 – Relationships between shoots basal area ( $g$ in $m^2$.tree$^{-1}$) and dry weight above-ground biomass components of (e) leaves, (f) branches, (g) stems and (h) total above-ground dry biomass ($N = 27$). Points surrounded by circle were aberrant values and were not considered when fitting biomass allometric models.**

to be the best predictor for AGB biomass. The use of CBH alone (expressing the basal area) for AGB biomass estimation is common to many studies that showed that diameter at breast height (DBH) is one of the universally used predictors, because it shows a high correlation with all tree biomass components and easy to obtain accurately [27,28,34]. But many studies demonstrated too that tree diameter (or circumference), tree height and a combination of these variables could be also used as predictor variables for AGB biomass estimation [13,35]. Yet, field work for obtaining reliable height to develop more

**Table 4 – Biomass production (Mg ha$^{-1}$) for the selected stands of *Eucalyptus robusta* in the central highlands of Madagascar ($N = 9$).**

| Plot | Age | Leaves | Branches | Shoot | AGB | Stump | CR | MR | BGB |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 47 | 3.8 (0.4) | 4.2 (0.6) | 14.5 (1.9) | 21.8 (2.9) | 50.1 (12.6) | 32.6 (9.1) | 3.0 (0.9) | 91.7 (24.3) |
| 2 | 77 | 6.5 (2.4) | 6.6 (1.6) | 23.4 (6.9) | 35.2 (10.4) | 43.5 (6.2) | 34.1 (6.1) | 3.8 (0.7) | 87.5 (14.3) |
| 3 | 52 | 3.0 (0.9) | 3.7 (0.8) | 12.3 (3.2) | 18.5 (4.8) | 45.0 (6.0) | 33.8 (1.7) | 3.5 (0.5) | 89.0 (7.4) |
| 4 | 72 | 7.0 (1.3) | 7.3 (1.0) | 25.9 (4.0) | 39.0 (6.0) | 45.9 (0.5) | 35.7 (1.4) | 3.8 (0.3) | 92.5 (2.2) |
| 5 | 53 | 2.8 (1.3) | 3.6 (1.3) | 11.7 (4.8) | 17.6 (7.2) | 44.2 (6.3) | 34.2 (3.7) | 3.6 (0.4) | 88.6 (10.7) |
| 6 | 67 | 6.4 (1.3) | 6.8 (0.9) | 23.9 (3.8) | 36.0 (5.7) | 50.4 (6.6) | 37.7 (5.5) | 3.9 (0.7) | 99.4 (13.6) |
| 7 | 72 | 6.3 (1.7) | 6.9 (1.2) | 23.9 (5.0) | 36.0 (7.6) | 47.7 (9.7) | 37.6 (3.8) | 4.2 (0.5) | 96.3 (13.7) |
| 8 | 67 | 2.7 (0.6) | 3.5 (0.3) | 11.4 (1.6) | 17.2 (2.5) | 50.8 (15.2) | 37.7 (4.5) | 4.1 (0.4) | 99.2 (20.4) |
| 9 | 87 | 4.8 (2.1) | 5.4 (2.0) | 18.6 (7.4) | 27.9 (11.2) | 56.0 (11.1) | 40.4 (6.7) | 4.0 (0.6) | 108.4 (19.8) |

Values in bold are the mean of biomass production for each component in each stand; components are: leaves, branches and shoots for ABG part and stump, coarse roots (CR), medium roots (MR) for the BLG part. Values in brackets represented the standard deviation, and **Age** corresponds to the date of first eucalyptus plantation.

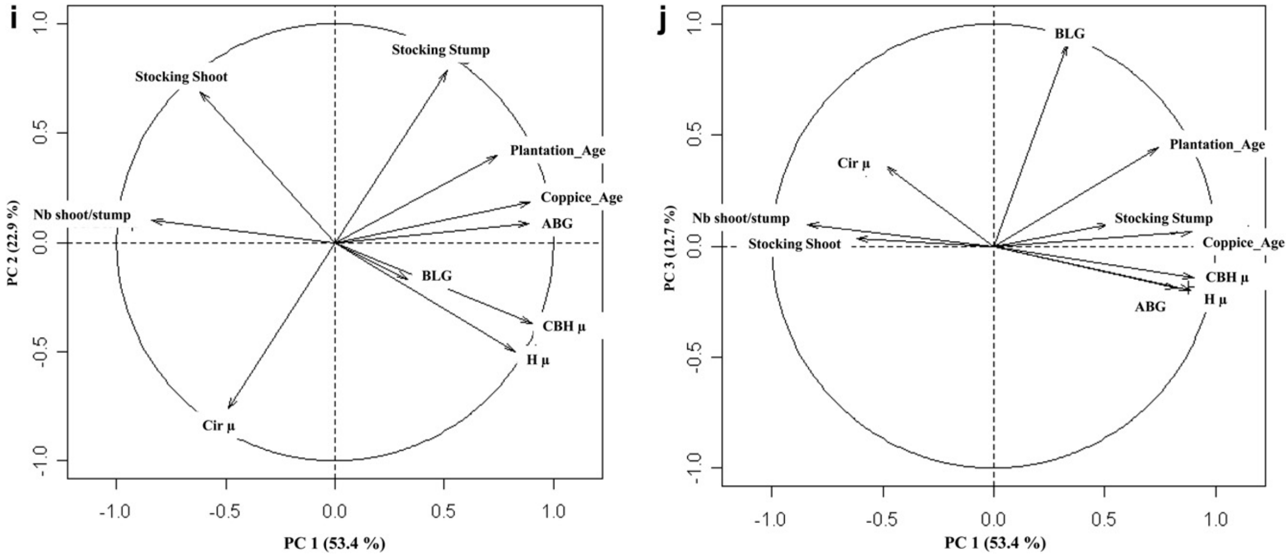


**Fig. 4 – Projections of the measured and calculated variables in the principal component spaces: (i) for the space (1, 2) and (j) for the space (1, 3). Abbreviations of variables are given in Table 1.**

accurate allometric models are time-consuming. We agree then with their conclusion which stipulated that developing regression models based only in stem diameters (and basal area), for practical purposes allowed a minimized inventory cost to estimate AGB while still being sufficiently accurate.

### 4.2. Biomass production and partitioning

First, about AGB biomass per tree (and AGB tree component partitioning), values ranged among those from other studies. For instance: (i) Senelwa and Sims [11] in New Zealand found that total AGB varied from 0.6 to 102 kg tree$^{-1}$ for coppices of eucalyptus of 3–5 years, (ii) Antonio et al. [27] in Portugal from 0.2 to 254.1 kg.tree$^{-1}$for coppices of *E. globulus* between 2.5 and 13 years old (duration of plantation not precised) and (iii) Zewdie et al. [13] reported 0.5–123.4 kg.stem$^{-1}$ for greater stools of *E. globulus* in Ethiopia. AGB productions per unit of area were within the range reported by other authors [13,36,37].

For BGB, studies in eucalyptus plantations (5–6 years after planting, corresponding to one cycle) in Portugal and in Cameroon [14,21,38] reported 13.8–26.8 Mg ha$^{-1}$. These BGB biomasses are very small compared to BGB estimated in our study (75–94 Mg ha$^{-1}$) probably due to the difference of system management (multiple stems versus single stem of high forest), the duration of plantation (from 47 to 87 years herein, corresponding to more than nine cycles) and soil fertility and physical constraints. In fact, in coppicing species such as eucalyptus, there is an underground lignotuber which contains a large store of potential bud-forming sites capable of producing several individual shoots [19]. After each cutting cycle, this part of the tree is recovered by cambium for emerging new shoots and constitutes the stump. Stump is the

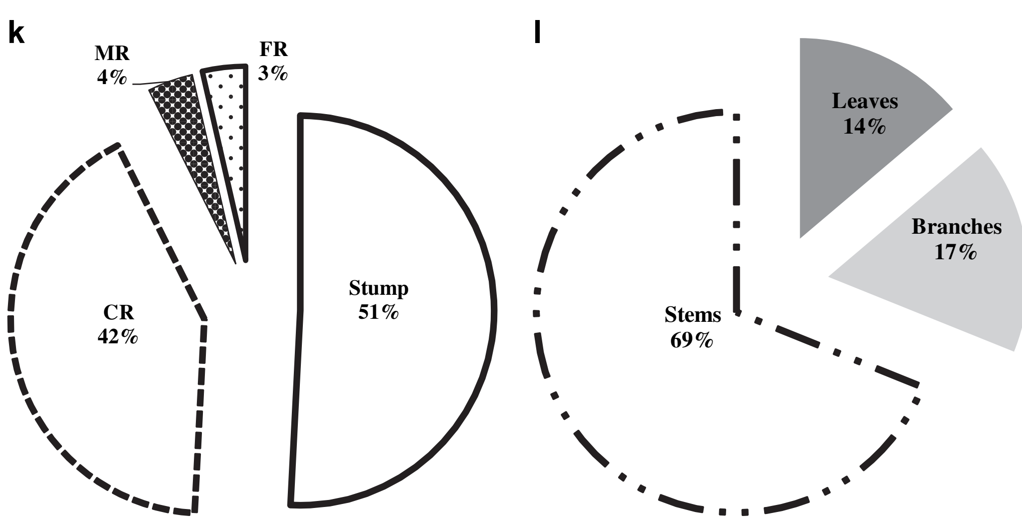


**Fig. 5 – Biomass partitioning in below (k) and above-ground (l) parts for the stands of *E. robusta* in the central highlands of Madagascar ($N = 9$).**

woody base of the trees as left after coppicing and they included a large part of the root system [21] before CR biomass (Fig. 5k and Fig. 5l) [18]. Besides, FR biomass represented only a small part of this root system, which is similar with the result reported by Giardiaa and Ryan [39].

In terms of biomass partitioning between AGB and BGB part, the Root:Shoot (R:S) ratios found in our study ranged from 2.2 to 5. These values were inverse of those in regarding all types of biomes to study root biomass allocation in the world'ys upland forests which varied from 0.05 to 0.7 with tendency values of 0.2–0.3 [14,29,40]. If R:S ratio shows that the lower root mass, the lower the ratio and higher aerial biomass production [24] that is usually exist in conventional forest regime, R:S found in our study (with old coppices) do not rather reflect this natural allocation of biomass where the proportion of BGB is higher in younger tree [18,32]. Actually, when AGB part is removed every cutting cycle, the BGB part left in the stand could continuously increases and stores nutrient reserve for new resprouting. We agree then with the statement that BGB had to be estimated directly in Eucalyptus coppice plantations, rather than by using R:S ratio [14].

### 4.3. *Biomass production over time*

An attempt of studying relations between duration of plantation and tree compartments (AGB and BGB) was performed. Results showed that there should be no significant (at $\alpha = 0.05$) relationships between plantation age and AGB ( *p-value* = 0.07) in the one hand and with BGB ( *p-value* = 0.08) in the other hand. These findings fitted and emphasized the PCA results (Fig. 4).

Actually, in short rotation forestry, coppice-shoot age was found to be a significant factor influencing allometric relationships [13,21,28,41]. But for BGB part, considering the data herein, only plantation age could not explain biomass production over time. In fact, PCA results showed that BGB was independent from AGB as it was found in other studies [42]. Actually, Fig. 4 shows that BGB, AGB and plantation age are not correlated. Thus, other variables that may influence BGB and AGB production should be considered or combined to well characterize BGB dynamic such as distribution of stump circumference, spacing between stumps and site characteristics (mainly, soil characteristics and climate).

## 5. Conclusions

As a conclusion, this work demonstrated that BGB biomass could be accurately estimated using allometric relations including stem circumference as an explicative variable. For ecosystems such as old coppices of *E. robusta* in the Central Highlands of Madagascar, the BGB part was pointed out to constitute major components for biomass accumulation. Actually, BGB biomass contributed greatly (more than 77%) in the 102–130 Mg ha$^{-1}$ of the whole biomass density. This important contribution of the BGB part has to be explored in developing Clean Development Mechanism (CDM) projects, because, added to wood energy supplies, incomes which can be generated from carbon sequestration activities could be profitable for rural people. Nevertheless, more investigation is needed to well understand biomass production over time and the question of ecosystem sustainability. Other factors (mainly soil characteristics and climatic variables) have to be considered.

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