Aboveground biomass in smallholder Eucalyptus plantations throughout stand rotation in Madagascar: influence of low starter fertilization and weed competition

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Abstract

Smallholder *Eucalyptus* plantations (EP) in Madagascar Central Highlands (MCH) address substantial fuelwood demand and reduce pressure on natural forests. However, their sustainability is challenged by low soil fertility and inadequate management. While fertilization increases tree growth, high mineral fertilizer costs limit its use by smallholder farmers. Both biomass estimating equation and impact of fertilization on smallholder EP in MCH remain poorly documented. This study aimed to evaluate the impact of low starter mineral fertilization (15 $kg.ha^{-1}$ N, 12 $kg.ha^{-1}$ P, and 17 $kg.ha^{-1}$ K) and weed competition on smallholder *Eucalyptus robusta* growth and aboveground biomass (AGB) while providing allometric equations for AGB estimation. Dendrometric data were collected from six stands aged 2 to 6 years, with fertilized and non-fertilized parts. AGB of 16 trees per stand (8 fertilized, 8 non-fertilized) were destructively measured. AGB of trees were estimated by regression based on tree circumference, height and their combinations. The results indicated circumference as the best single variable predictor ($R^2 > 0.90$) for all tree compartments and stands Fertilization significantly improved global tree survival by 7% and increased height by 3.1 m and circumference by 8.3 cm in 6-year-old stands AGB per hectare globally doubled with fertilization, reaching 55.3 $Mg.ha^{-1}$at 6 yo compared to 29.2 $Mg.ha^{-1}$ in non-fertilized plots. Weed cover and biomass had significant negative linear relationships with AGB and survival rate. This study provides robust allometric equations for biomass estimation and highlights that even low fertilizer application combined with effective weed control can significantly enhance AGB production in smallholder EP.

Keywords: Allometric equations, Biomass estimation, Madagascar Central Highlands, First rotation, *Eucalyptus robusta*

Statement and Declarations

1. Introduction

Forest ecosystems play a crucial role in mitigating climate change through carbon sequestration. Forests store more than 80% of terrestrial aboveground carbon and more than 70% of soil organic carbon (Jandl et al. 2007), making them also essential for offsetting carbon emissions (Cheng et al. 2023). However, deforestation, which refers to converting forests to other land uses (FAO 2022a), peaked globally in the late 20th century (Malhi et al. 2014). Between 1900 and 2020, there was a loss of 420 million hectares of forests (FAO 2020). From 2015 to 2020, deforestation has been estimated at 10 million hectares per year (FAO 2020). Agricultural expansion is the main driver for forest loss worldwide (Malhi et al. 2014; Pendrill et al. 2019; FAO 2022b). Cropland expansion (including large-scale and small-scale farming) is responsible for more than 75% of forest loss in Africa and in Asia and expansion of pasture was the direct cause of 70% of forest loss in South America between 2000 and 2018 (FAO 2022b). However, from 2015 to 2020, afforestation and natural forest expansion have been estimated at about 5 million hectares per year (FAO 2020, 2022a).

Planted forests account for 7% (294 million hectares) of the total forest area (FAO 2020). *Eucalyptus spp*. plantations cover 22.6 million hectares (Zhang and Wang 2021) and are a major source of biomass to supply the pulp and paper industry and to produce charcoal and fuelwood (Booth 2013; Nunes et al. 2020). In 2019, one third of the world's population (about 2.6 billion people) relied on fuelwood to meet their daily energy needs (FAO 2022a). Forest plantations contribute to affordable clean energy (Sustainable Development Goals 7) and reduce pressure on natural forests in Africa, where 63% of households use fuelwood (FAO 2022a).

In Madagascar, 90% of the population depends on biomass for their daily energy needs, with an estimated 18 million m^3 of wood harvested annually (Minten et al. 2013). *Eucalyptus* plantations (EP) fill a significant proportion of the fuelwood demand, including 44% of charcoal's and have an essential socio-economic impact in the country (Verhaegen et al. 2014).

Introduced in Madagascar by the end of 19th century, the fast-growing *Eucalyptus* genus covers 235000 ha among 415000 ha of the total planted forests (Verhaegen et al. 2014). *Eucalyptus robusta Sm* is the most widespread *Eucalyptus* species in Madagascar because of its vigor, even in compact soils, and its resistance to wild fire (Randrianjafy 1999; Verhaegen et al. 2011). However, the sustainability of these EP is threatened by the shortening of the coppice rotation length, from more than 6 years in the 1980's to 2-4 years, due to the increasing demand for fuelwood (Verhaegen et al. 2014).

Several afforestation/reforestation projects have been implemented in Madagascar Central Highlands (MCH) to cope with fuelwood demand and deforestation, and thus facilitate biodiversity conservation actions (Gabathuler et al. 2014; Verhaegen et al. 2014; Bucht 2015; Bouillet et al. 2019; Vieilledent et al. 2020). These afforestation initiatives still have great potential in this vast treeless region, covering 40% of the country's area, but mainly covered by grassland and with less than 4% woodland (Joseph et al. 2021).

Smallholder plantations differ from commercial plantations. Proper management systems and *ad hoc* silvicultural techniques are rarely followed in smallholder plantations, which leads to lowering stand productivity. Maintenance practices like weeding, pruning and thinning which are usual in commercial plantations are often not applied in smallholders' plantations. Most of commercial plantations use hybrids and clones in order to increase plantation's productivity (Laclau et al. 2003; Maciel et al. 2022; Bouillet et al. 2023), while smallholders often use little-improved plant material (Alemayehu and Melka 2022).

Likewise, in Madagascar, the smallholder planted forests that are mainly established on low-fertility soils in MCH (Verhaegen et al. 2011; Mevanarivo et al. 2020) are mostly managed without fertilizer application. Fertilization can enhance tree growth and biomass production (Carrero et al. 2018). Studies have shown the effect on stand production of high amounts of mineral fertilizers in commercial EP. In Brazil, applying a total amount of 160 kg N ha^{-1}, 64 kg

P ha^{-1}, and 210 kg K ha^{-1} at planting and during the first 18 months of age led to mean annual increment of 2-year-old-*Eucalyptus* stand of 42 m^3 ha^{-1} yr^{-1} compared to 26 m^3 ha^{-1} yr^{-1} for the unfertilized control treatment (da Silva et al. 2013). Fertilization also increased *Eucalyptus* fine root specialization to take up N, K and Ca from the soil (Bordron et al. 2019). However, in smallholder EP, fertilization at planting, applied at low amount, and maintenance fertilization is seldom applied (Viera et al. 2016) and their effects on tree growth are poorly documented (Schaller et al. 2003). In Madagascar, the effect of low-doses of starter mineral fertilizers on EP growth in smallholder fields is still unknown, given that mineral fertilizers are expensive (*e.g.* +/- 1 € per kg of NPK 11-22-16) and mainly used for cash crops (Rakotovao et al. 2022).

In Madagascar, weeding is rarely carried out in smallholders 'plantations (Bouillet et al. 2019). Weed competition can lower stand production through competition with tree for water, nutrients and light (Maciel et al. 2022; Corticeiro et al. 2023). The depressive effects of weeds on tree growth depends on parameters such as weeding periodicity, and vegetation cover and composition (Corticeiro et al. 2023). Studies showed that weeding at early phases of tree growth increased significantly the productivity of 12 month-old-*Eucalyptus* plantations in Indonesia (Inail et al. 2021).

In recent decades, efforts to improve the accuracy and facilitate the estimation of forest aboveground biomass (AGB) at various scales using different methods have been a central research topic worldwide (Henry et al. 2011; Clifford et al. 2013; Sun et al. 2024a). AGB accounting for more than 70% of total forest biomass (Cairns et al. 1997; Chen et al. 2018; Sun et al. 2024a), applying robust models for an accurate AGB estimation is therefore crucial as a key indicator of carbon resources and carbon sequestration in terrestrial systems. Forest AGB are commonly estimated by field-destructive sampling and allometric equations, to avoid cutting a whole tree population to determine its biomass (Henry et al. 2011). Allometric equations relate tree biomass to other dendrometric variables, which can be directly measured in the field during forest inventories (Causton 1985). They are generally developed on the basis of circumference at breast height (CBH) and tree height (H) at a local scale (Adinugroho et al. 2023; Sun et al. 2024a). In Madagascar, allometric equations for AGB estimation were mostly developed for natural or naturally regenerated forests (Ramananantoandro et al. 2015; Randriambanona et al. 2019; Randrianasolo et al. 2019) and forest plantation biomasses have been estimated mainly for pine plantations and *Eucalyptus* coppices (Razakavololona 2007; Razafindramanana et al. 2008; Razakamanarivo et al. 2010, 2011, 2012; Baohanta et al. 2012). By contrast, stand growth and AGB of *Eucalyptus* plantations during the first years following afforestation are still poorly documented.

This study aimed to assess the effect of fertilization and age on the growth of smallholder *Eucalyptus robusta* plantations in MCH. The specific objectives are: (i) to establish allometric equations for smallholder EP using field destructive method and (ii) to evaluate the effect of fertilization on tree growth and tree biomass along the first stand rotation. We hypothesized that fertilizer application, even at low rates, will significantly increase AGB in smallholder EP, but that this increase may be inhibited by weed competition.

2. Materials and methods

2.1. Study site

The study was conducted at Ambongamarina, Anjozorobe district, in the North-Eastern part of Analamanga Region in MCH (between 47°55’E and 47°57’E and 18°19’S and 18°21’ S, and at 1207 – 1474 m a.s.l). The study site has a warm temperate climate with dry winter and temperate summer (subtropical highland climate or Cwb according to the Köppen-Geiger classification). Average annual rainfall and temperature were 1230 mm and 20°C respectively. The soils are Orthic Ferralsols according to FAO classification (FAO-UNESCO 1974; FAO 2012) with a pH water of around 5 and clay content around 35% at 0 – 100 cm depth. Spontaneous vegetation is characterized by a pseudo-steppe dominated by *Aristida sp* grasses and *Philippia sp* and *Helichrysum sp* shrubs.

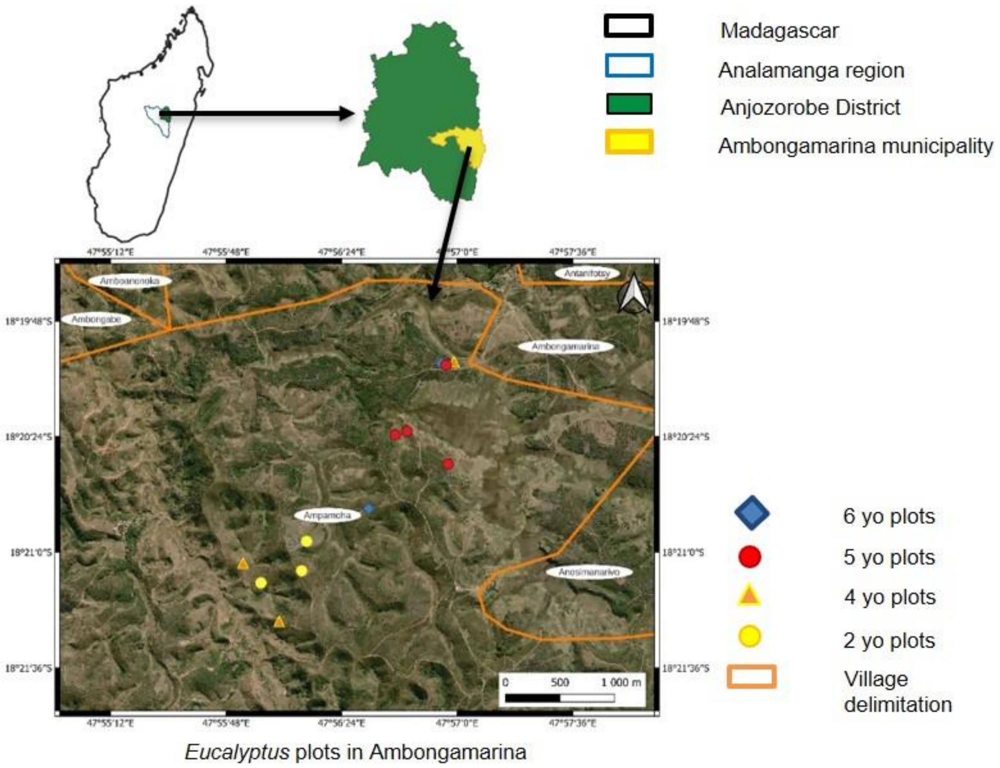

Fig. 1 Map showing the location of smallholder plots selected in this study in Anjozorobe, Madagascar

2.2.Experimental design – studied stands characteristics

Four stands of *E. robusta* managed by smallholder farmers ranging from 2 to 6 years old were selected (**Table 1**). Plots of replicates of selected stands as shown in **Table 1**were within 3 km of each other, all located on the top or upper of the hill, with a slope lower than 30%, representative of afforestation areas (**Fig. 1**). These plantations were in their first stand rotation. Each plot was subdivided into 2 subplots with (F) or without (NF) fertilization at planting time. Mineral fertilization NPK (11-22-16) was applied locally at planting time only (in each tree planting hole) at a rate equivalent to 133 kg.ha^{-1}, equivalent to 15 kg.ha^{-1} N, 12 kg.ha^{-1} P, and 17 kg.ha^{-1} K. From the combination of different modalities of the two studied factors (stand ages and fertilization), we have eight treatments: 2F, 2NF, 4F, 4NF, 5F, 5NF, 6F, 6NF. Tree density recommendation of 1111 trees.ha^{-1} (3 m × 3 m spacing) was seldom followed by smallholder farmers (**Table 1**). The seeds used were collected on unimproved *E. robusta* trees by *Silo National des Graines Forestières* (SNGF), Antananarivo - Madagascar.

Table 1 Stands characteristics. Number of trees and means (with their standard errors) of the tree density per ha, the plot area (ha), equivalent circumference(cm), Basal area (cm^2) and tree height (m) in the eight treatments (4 ages × 2 fertilization: F: fertilized with mineral fertilizers applied at planting 15 kg ha^{-1}N, 12 kg ha^{-1} P and 17 kg ha $^{-1}$K; NF: non-fertilized

Age (years)	Fertilization	Replication	Number of trees	Tree density per ha	Plot area (ha)	Equivalent Cir (cm)	Basal area (cm^2)	Tree height (m)
2	F	3	239	2200 ± 300	0.05 ± 0.02	9.4 ± 0.2	8.1 ± 0.4	1.79 ± 0.04
	NF	3	618	2200 ± 300	0.13 ± 0.07	6.8 ± 0.1	4.4 ± 0.1	1.27 ± 0.02
4	F	2	386	2037 ± 463	0.12 ± 0.10	27.5 ± 0.6	71.5 ± 3.0	7.27 ±0.15
	NF	2	427	2111 ± 389	0.08 ± 0.03	13.4 ± 0.3	17.5 ± 0.8	3.14 ± 0.07
5	F	4	304	1111 ± 0	0.10 ± 0.00	29.1 ± 0.9	85.2 ± 4.8	7.86 ± 0.21
	NF	4	234	1111 ± 0	0.09 ± 0.02	26.9 ± 1.0	75.3 ± 4.9	7.52 ± 0.24
6	F	2	69	1806 ± 694	0.03 ± 0.02	37.9 ± 1.5	126.6 ± 9.0	11.22 ±0.46
	NF	2	321	1805 ± 694	0.17 ± 0.15	29.6 ± 0.8	84.6 ± 4.0	8.10 ± 0.19

2.3. Allometric equations development

2.3.1. Field measurements

AGB measurements by destructive sampling method were carried out in May 2023. A forest inventory of the circumference (Cir) at 1.30 m (at 10 cm for 2 yo trees) and height (H) of each tree in the inner plot (excluding the two border lines) of each selected plot was done, for a total of 2598 trees. Measuring tape (accuracy to 1 mm) was used to measure tree circumferences (Cir). For tree height < 4 m, we used graduate sight (accuracy to 1 cm) and for tree height > 4 m, we used the Haglöf Vertex V 360° (accuracy to 0.1 m). Survival rates of trees (%) in each selected plot were also calculated during forest inventory. From the inventory data, the basal area (BA) of each tree with n stems was calculated as follows (Snowdon et al. 2002):

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

Aboveground biomass was estimated by sampling 8 trees in each treatment, i.e. 64 trees in total. For a given treatment, the sample trees were chosen to be distributed over the range of tree BA (Laclau et al., 2008a; Oliveira et al., 2024; Zewdie et al., 2009). Destructive sampling consisted of weighing the tree's various aerial compartments (trunk, branches, leaves) and measuring the circumference of tree trunk at every meter (every 2 m for trees higher than 10 m and every 0.2 m for trees less than 2 m high). Foliage was collected from 2 to 3 crown sections of the trees (Section 2.3.2.3) (Laclau et al., 2008a). Fresh weight (FW) of each tree component was determined directly in the field and sub-samples were oven-dried at 65°C to obtain dry weight (DW) per component and then DW/FW ratios were calculated.

2.3.2. AGB calculation

Single-variable and multiple-variable allometric models were established for each compartment (trunk, branches, leaves) in each treatment. For tree biomass estimation, power equations of the following form are common (Kuyah et al. 2013; Clifford et al. 2013; Ganamé et al. 2021):

$$y = a.x^b \qquad (2)$$

where y, biomass, is related to a covariate x such as H and/or Cir.

The traditional linear model of Baskerville (1972) was used, so the variables were log-transformed to obtain a linear model while correcting for data heteroscedasticity. The following models were compared for each tree compartment:

$$\mathbf{ln}(\boldsymbol{B}) = \mathbf{ln}(\boldsymbol{b0}) + \boldsymbol{b1} \times \mathbf{ln}(\boldsymbol{Cir}) + \boldsymbol{\varepsilon} \qquad (3)$$

$$\mathbf{ln}(\boldsymbol{B}) = \mathbf{ln}(\boldsymbol{b0}) + \boldsymbol{b1} \times \mathbf{ln}(\boldsymbol{H}) + \boldsymbol{\varepsilon} \qquad (4)$$

$$\mathbf{ln}(\boldsymbol{B}) = \mathbf{ln}(\boldsymbol{b0}) + \boldsymbol{b1} \times \mathbf{ln}(\boldsymbol{Cir} \times \mathbf{H}) + \boldsymbol{\varepsilon} \qquad (5)$$

$$\mathbf{ln}(\boldsymbol{B}) = \mathbf{ln}(\boldsymbol{b0}) + \boldsymbol{b1} \times \mathbf{ln}\left((\boldsymbol{Cir})^2 \times \mathbf{H}\right) + \boldsymbol{\varepsilon} \qquad (6)$$

where B is biomass, b0 and b1 are coefficients of the linear model, Cir is tree circumference and H is tree height.

2.3.2.1. Models' selection criterions

In total, 128 models were established (8 treatments × 4 model forms × (3 compartments + Surface Leaf Area). In order to assess the performance of the models, four statistical parameters were calculated and considered in the following order: (i) the root mean square error (RMSE), which is the average bias between measured and predicted values from the best model among Eq.**(3)**, (4), (5), (6), so the lower the RMSE value, the better the model; (ii) the Akaike Information Criterion (AIC) which is often used as a key statistic component to compare model (Sun et al. 2024b; Adinugroho et al. 2023; Razakamanarivo et al. 2012). The best model has the lowest AIC value; (iii) coefficient of determination (R^2). The higher the R^2, the more significantly the models explain the proportion of variance in ln(AGB); (iv) the mean absolute prediction error (MAPE %), which is calculated from the mean of the residuals expressed in absolute terms and provided as a proportion (%) (Paul et al. 2018).

2.3.2.2. Prediction of AGB

The biomass of each aerial compartment for each treatment was estimated using the best models. When back-transforming from logarithmic to the original scale of AGB, a correction factor (CF) is used to remove bias (Paul et al. 2018). In preliminary analysis, we compared the commonly used CF Residual Maximum Likelihood (REML) of Baskerville (1972) and the more appropriate CF for predicting biomass of new trees and shrubs following recommendations from the paper of Clifford et al. (2013), which is the Minimized Mean Square Error (MM) of Shen Zhu (2008). Correction factors REML and MM were finally found to be similar, with a difference of less than one decimal. REML was chosen for simplification as used by numerous authors (Chave et al. 2014; Paul et al. 2018; Adinugroho et al. 2023). This variable is defined as follows:

$$REML = \exp\left(\frac{1}{2}RSE^2\right) \tag{7}$$

$$RSE = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-p} \tag{8}$$

where REML is the correction factor and RSE the Residual Standard Error of the model in Eq.(7). And in the formula of RSE Eq.(8), y_i is the actual observed value, $\hat{y}_i$ is the predicted value by the model, n is the number of observations, p is the number of variables.

From the predicted values of biomass using the best models, individual AGB per tree was calculated as the sum of the estimated biomass for each tree compartment. Total AGB per surface area was calculated by summing individual AGB per tree in each subplot and expressing this value per hectare.

2.3.2.3. Leaf Area Index (LAI) calculation

The Leaf Area Index (LAI) is defined as the ratio of one-sided leaf area in the canopy per ground unit (Watson 1947). LAI is important for assessing forest productivity (Smethurst et al. 2003). During tree felling, the crown was divided into three sections (upper, middle and lower) when crown length > 2 m and two sections (upper and lower) when crown length < 2 m. Twenty-five leaves were collected per section, their weights were recorded, and the leaves were scanned by the scanner of multifunction printer (HP DeskJet 2130) on the day of collection to obtain the leaf area (LA). The leaves were placed on the scanner without overlapping. The scans were produced at a resolution of 300 dpi and saved in '.Jpeg' format. The resulting images were then processed using ImageJ software (Schneider et al. 2012) to calculate leaf area. Afterward, LA of each tree was estimated using the allometric equations (3), (4), (5) and (6), as with AGB. The best models were selected using the same criterions as detailed in 2.3.2.1. LA per plot was calculated as the sum of LA per tree in the plot. LAI is the ratio of LA (m^2) / plot area (m^2).

2.4.Weed cover and biomass measurement

Weed measurements were carried on one plot per treatment so without plot replicate. The weed cover measurement was carried out using transects. Each study plot was considered as one or more squares, depending on the shape of the plots. Transects were defined on the diagonals of these squares using strings. A 3 m tape measure was attached to the string and weed information were recorded in each 10 cm. At each 10 cm point, we recorded the presence or absence of weeds, the name of the species and an estimate of the height of each species.

Weed biomasses were collected by randomly sampling an area of 1 m^2 with 3 replicates on each plot. Each 1m^2 quadrat was cleared and each species present was placed in a separate bag. The fresh weight was determined directly in the field and dry weight was obtained after samples being oven-dried at 65°C.

2.5.Statistical analysis

All statistical analyses were performed with R software version 4.3.1 (R Core Team 2023). The effects of the plantation age and fertilization plus their interaction on the stand growth parameters (tree height, circumference), on the individual tree AGB, the AGB per ha (total, trunk, living branches and leaves), and on the LAI, were tested as fixed factors in mixed linear models. The function 'lme' from package *nlme* (Pinheiro et al. 2023) was used to fit the models. The plot location was included as a random factor. ANOVA test was performed on the mixed linear models and if significant, pairwise comparison by Fisher LSD test were used. Adjusted means were calculated with 'emmeans' function from the package *emmeans* (Lenth R 2024). Default 'adjust' argument in 'emmeans' function was changed to obtain the result of Fisher LSD test. Assignment of differential letters to compare modalities were performed using the 'cld' function from the *multcomp* package (Hothorn et al. 2008). The influence of plantation age and fertilization on survival rates were tested by using ANOVA test and the Fisher LSD test, using function 'LSD.test' of *agricolae* package (de Mendiburu 2023), was performed for means comparison if ANOVA test showed significant differences. Linear regression analyses were carried out between AGB per ha and survival rates as dependent variables and weed cover and biomass as explanatory variables.

3. Results

3.1. Specific allometric equations by destructive method sampling

From the 128 models established, 32 were selected (**Table 2**). These selected models correspond to the best model form for each treatment in each tree compartment and LA (8 treatments × 1 best model form × (3 compartments + Leaf Area). Cir was the best independent predictor, regardless the treatment, with R^2 averaging 0.94 for trunk biomass and for branches biomass and 0.90 for leaves biomass. For aerial biomass estimation, models selected for branches and leaves were based on Cir only Eq. (3), whereas trunk biomass was related to Cir and H Eq.(5). Among the four tested models for trunk biomass estimation, based on the models' selection criterions, the best variable was Cir × H except for the AIC value where $Cir^2 \times H$ had the minimum mean value. With the selected models within the 8 treatments, R^2 varied from 0.96 to 0.99, while AIC varied from -15.47 to 2.44, RMSE varied from 0.03 to 17.89 and MAPE varied from 11 to 44%. For the living branches component, the best explanatory variable was Cir based on models' selection criterions and for all treatments. With Cir only as explanatory variable, the value of R^2 varied from 0.90 to 0.98, the AIC varied from 1.97 to 11.60, the RMSE varied from 0.02 to 6.60 and the MAPE varied from 15.73 to 44.45%. Likewise, for the leaf component, the best explanatory variable for all treatments was also Cir based on all models' selection criterions. For this component, models with Cir achieved R^2 values ranging from 0.82 to 0.96, AIC values ranging from 1.58 to 16.31, RMSE valued ranging from 0.06 to 2.65 and MAPE values ranging from 16.98 to 55.06%.

For LA estimation, the selected models were based on Cir as this variable reached the best performances. For the selected models, the values of R^2 varied from of 0.82 to 0.97, the values of AIC varied from -0.30 to 15.45, the values of RMSE varied from 0.05 to 20.66 and the values of MAPE varied from 15.42 to 54.05%.

Table 2 Selected allometric equations from Eq. (3)(4)(5)(6) showing the best predictor, models' coefficients, correction factor and the four model's selection criterions for each tree compartment and LA

			Equation's coefficients			Correction factor	Selection criterions of models			
Best predictors	**Age * fertilization**	**Number of tree**	**b0**	**b1**	**b2 (exp(b0)**	**REML**	**R^2**	**AIC**	**RMSE**	**MAPE %**
					Trunk biomass					
Cir × H	6F	8	0.52	1.92	1.68	1.03	0.96	2.45	17.90	44.25
	6NF	8	1.35	1.38	3.88	1.01	0.98	-3.91	4.82	19.51
	5F	8	1.30	1.44	3.66	1.02	0.97	1.75	6.27	14.48
	5NF	8	1.24	1.50	3.45	1.01	0.99	-6.94	4.82	16.50
	4F	8	1.36	1.39	3.91	1.00	1.00	-15.47	2.81	11.09
	4NF	8	1.30	1.49	3.68	1.00	0.99	-11.55	0.63	11.76
	2F	8	0.90	1.44	2.45	1.02	0.97	0.52	0.05	14.85
	2NF	8	0.45	1.24	1.56	1.01	0.97	-4.92	0.03	16.06
					Branches biomass					
Cir	6F	8	-10.06	3.23	4.E-05	1.06	0.93	9.19	3.92	43.70
	6NF	8	-7.88	2.84	4.E-04	1.08	0.93	11.25	5.30	38.67
	5F	8	-8.11	2.86	3.E-04	1.07	0.93	10.73	6.60	31.53
	5NF	8	-7.95	2.87	4.E-04	1.04	0.96	5.37	3.46	21.98
	4F	8	-7.18	2.67	8.E-04	1.06	0.92	9.07	4.77	30.89
	4NF	8	-7.74	2.85	4.E-04	1.02	0.98	1.97	0.74	20.12
	2F	8	-8.38	2.77	2.E-04	1.08	0.90	11.60	0.09	44.46
	2NF	8	-7.40	2.33	6.E-04	1.03	0.96	2.90	0.02	15.73
					Leaves biomass					
Cir	6F	8	-9.76	3.03	6.E-05	1.15	0.82	16.31	2.31	46.06
	6NF	8	-4.45	1.74	1.E-02	1.04	0.90	6.24	1.79	27.61
	5F	8	-5.53	2.00	4.E-03	1.07	0.86	10.71	2.22	24.59
	5NF	8	-6.56	2.32	1.E-03	1.02	0.96	1.58	1.19	16.98
	4F	8	-6.51	2.34	1.E-03	1.07	0.89	10.18	2.65	31.40
	4NF	8	-5.84	2.24	3.E-03	1.05	0.93	7.79	1.96	55.06
	2F	8	-7.17	2.61	8.E-04	1.03	0.96	3.80	0.14	30.49
	2NF	8	-5.01	1.63	7.E-03	1.03	0.90	4.02	0.06	20.70
					Leaf area (LA)					
Cir	6F	8	-7.64	2.93	5.E-04	1.14	0.83	15.45	11.66	41.16
	6NF	8	-3.13	1.84	4.E-02	1.04	0.91	6.38	9.43	26.54
	5F	8	-4.99	2.33	7.E-03	1.10	0.86	13.30	20.67	35.21
	5NF	8	-5.49	2.48	4.E-03	1.02	0.97	-0.30	5.70	15.42
	4F	8	-5.42	2.50	4.E-03	1.07	0.89	10.53	18.22	37.89
	4NF	8	-3.97	2.17	2.E-02	1.04	0.94	6.28	10.04	54.05
	2F	8	-5.41	2.64	4.E-03	1.04	0.94	6.69	1.02	33.92
	2NF	8	-3.06	1.59	5.E-02	1.04	0.86	6.89	0.50	27.70

3.2. *Eucalyptus* growth characteristics

Survival rates were significantly influenced by fertilization (p-value < 0.05 using Fisher LSD test) and not by age. Fertilization significantly increased survival rates with mean values of 87% while 80% for non-fertilized trees (**Fig. 2**a).

Tree height was significantly influenced by age (p-value < 0.001) and by fertilization (p-value < 0.01). We also reported a significant age × fertilization interaction (p-value < 0.001) (**Fig. 2**b). Fertilized trees height was always significantly higher than non-fertilized trees with mean difference higher at 4 yo (7.3 m for F and 3.1 m for NF) and 6 yo (11.2 m for F and 8.1 m for NF) than at 2 yo (1.8 m for F and 1.3 m for NF) and at 5 yo (7.9 m for F and 7.5 m for NF).

Tree circumference was significantly influenced by age and fertilization (p-value < 0.001). As for tree height, the age × fertilization interaction ($p< 0.001$) was significant for tree circumference (**Fig. 2**c). Tree circumference was always higher for fertilized trees than non-fertilized trees. However, the mean difference between them was higher at 4 yo (27.5 cm for F and 13.4 cm for NF) and 6 yo (37.9 cm for F and 29.6 cm for NF) and lower at 2 yo (9.4 cm for F and 6.8 cm for NF) and 5 yo (29.1 9 cm for F and 26.9 cm for NF).

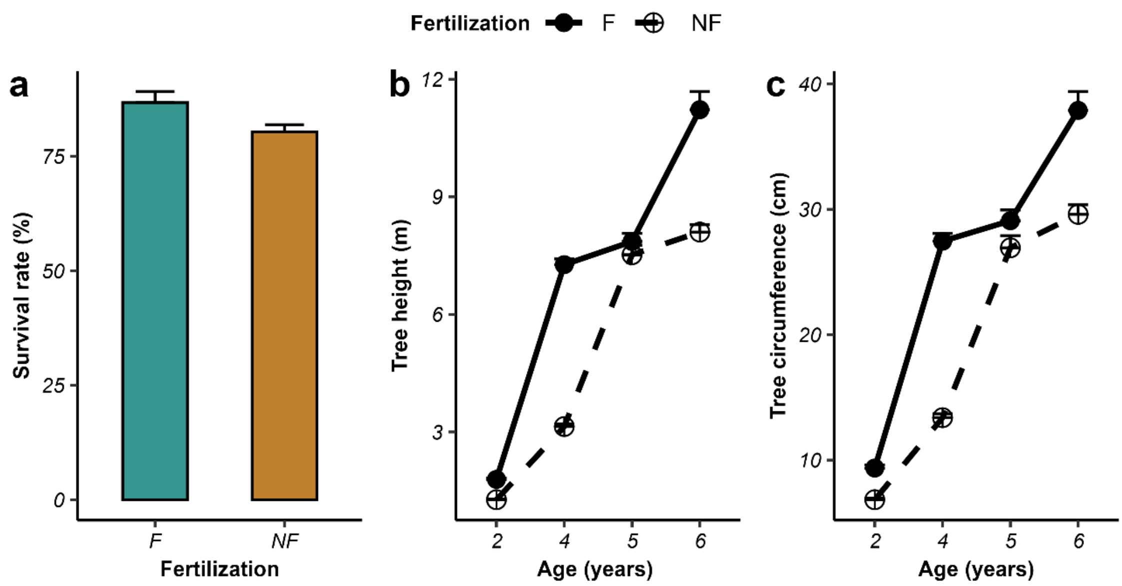

Fig. 2 Effect of low quantity of fertilization applied in smallholder EP on survival rate (a), tree height (b) and tree circumference (c) - * indicates significant difference (p-value < 0.05) regardless of the age in (A) and indicates significant difference (p-value < 0.05) for the same age but with different fertilization in (B) and (C). Standard errors are indicated

3.3.Aboveground biomass

3.3.1. Individual tree AGB

Mean tree AGB calculated for every inventoried tree was significantly (p-value < 0.001) influenced by age not by fertilization although fertilization increased globally AGB per tree by 96%. We reported a significant age × fertilization interaction (p< 0.001) (**Fig. 3**a). The AGB was always significantly greater for fertilized trees than non-fertilized trees except at 2 years after planting. The mean difference of AGB between fertilized and non-fertilized trees was significantly higher at 4 yo (27.20 kg for F and 4.19 kg for NF) and 6 yo (55.90 kg for F and 33.60 kg for NF). The difference was less marked at 2 yo (0.80 kg for F and 0.34 kg for NF) and at 5 yo (33.30 kg for F and 31.30 kg for NF).

3.3.2. Total AGB per surface area

Total AGB production per surface area was significantly influenced by age (p-value < 0.05) and by fertilization (p-value < 0.01). The mean value of AGB significantly increased from 1.2

$Mg.ha^{-1}$ to 41.4 $Mg.ha^{-1}$ between 2 yo and 6 yo plantations, respectively. Fertilization increased total AGB for all age considered (26.3 $Mg.ha^{-1}$ for F plots compared to 12.9 $Mg.ha^{-1}$ for NF plots). The interaction between age and fertilization was not significant due the importance of variance (**Fig. 3**b). Although at 4 yo, total AGB production in fertilized plots were 4 times higher than in non-fertilized plots. At 6 yo, AGB production reached 55.3 $Mg.ha^{-1}$ in fertilized plots and 29.2 $Mg.ha^{-1}$.

3.3.3. Biomass partition in each compartment per surface area

The biomass partition between compartments (%) was not significantly influenced by age nor by fertilization but significantly influenced by compartment and by the interaction of age and compartment (p-value < 0.001). When analyzed per compartment, we reported significant influences of the plantation age (p-values < 0.001) (**Fig. 3**c). Fertilization did not significantly influence the biomass partition except in branches biomass (p-value < 0.001). Non-fertilized trees (29%) had significantly higher percentage of branches than fertilized trees (24%). Except for biomass of trunk (p-value < 0.1), biomass of branches (p-value < 0.001), and leaves (p-value < 0.05) were significantly influenced by the interaction of age and fertilization. For biomass of branches; at 6 yo, the difference was significantly higher between fertilized (18%) and non-fertilized (30%) trees and at 2 yo, where the trend was opposed to 6 yo plantations, with 22% of branches in fertilized trees and 29% in non-fertilized trees. For leaves biomass partition, the interaction of age and fertilization was not significant except at 4 yo where non-fertilized trees had 33% of leaves biomass and 20% for fertilized trees.

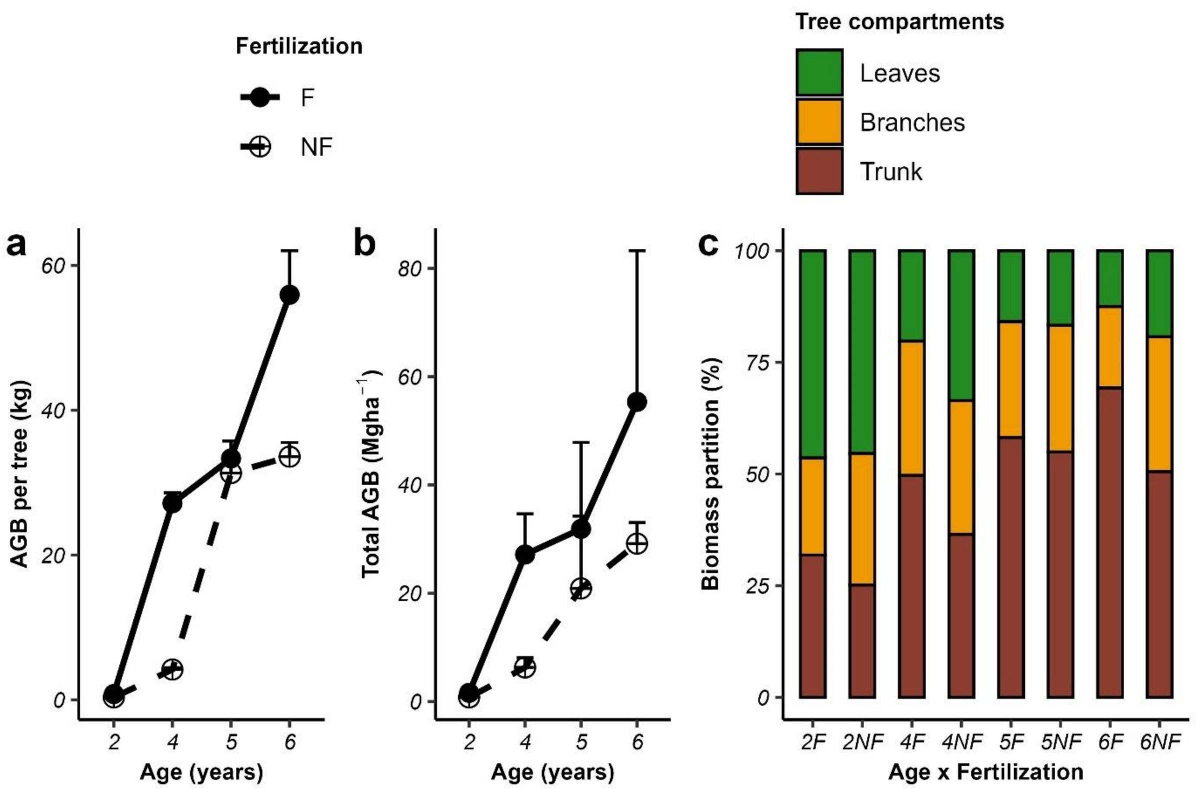

Fig. 3 Effect of low quantity of fertilization along the stands in smallholder EP on AGB per tree (a) and Total AGB per ha (b) -* indicates significant difference (p-value < 0.05) within the same age but with different fertilization; Standard errors are indicated. Variation of biomass partition in each tree compartment for each treatment (Age × Fertilization) (c)

3.4.Leaf Area Index (LAI)

LAI was significantly influenced by plantation age (p-value < 0.05). The mean value of LAI significantly increased from 0.35 to 3.08 from 2 yo to 6 yo, respectively. Fertilization did not significantly affect the value of LAI. However, higher values of LAI were observed for fertilized trees with mean values of 2.21 compared to 1.30 for non-fertilized trees for all plantation ages combined.

3.5.Weed cover and biomass

Weed cover (%) was significantly influenced by age (p-value < 0.05) and not by fertilization (p-value < 0.1). Regardless of the fertilization, the mean value of weed cover significantly decreased along the stand rotation (89% at 2 yo, 75% at 4 yo, 17% at 5 yo and 29% at 6 yo).

Even though the difference was not significant, weed cover was higher in non-fertilized plots (67%) compared to fertilized plots (38%).

Weed biomass was not significantly influenced by age nor by fertilization. Weed biomass values range from 0.3 to 5.3 $Mg.ha^{-1}$. Regardless of the plantation age, we reported a trend of lower weed biomass on fertilized plots compared to non-fertilized plots with mean values of 1.5 $Mg.ha^{-1}$ and 3 $Mg.ha^{-1}$, respectively. Weed biomass was higher in 2 yo plots with an average value of 4.3 $Mg.ha^{-1}$.

Regression analysis showed a significant negative linear relationship between total AGB and weed cover (p-value < 0.001) and the model explained 91% of the variability of the total AGB (**Fig. 4**a). Similarly, a significant negative linear relationship was found between total AGB and weed biomass (p-value < 0.01) with $R^2 = 0.74$ (**Fig. 4**b).

Survival rates also showed significant negative linear relationships with weed cover (p-value < 0.01) as well as with weed biomass (p-value < 0.05) (**Fig. 4**c and d, respectively).

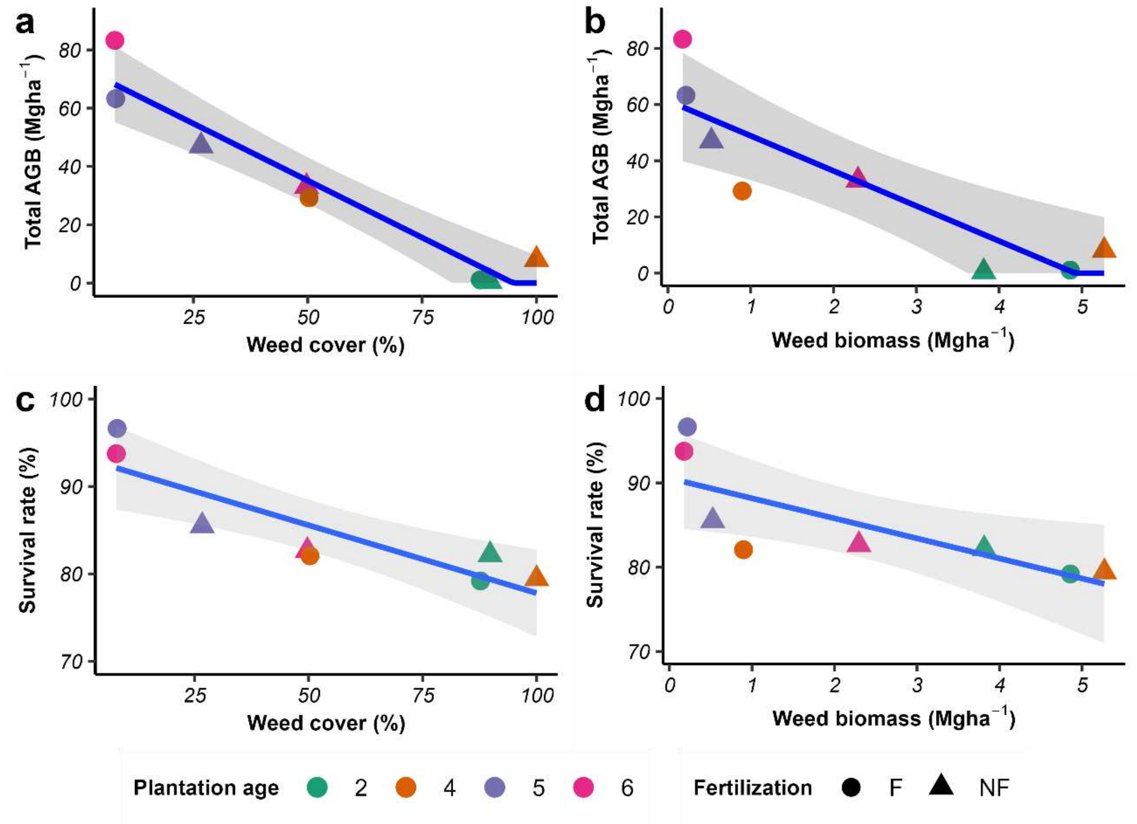

Fig. 4 Linear regression of the Total AGB (Mg ha^{-1}) and Weed cover (%) (a), the total AGB (Mg ha^{-1}) and weed biomass (Mg ha^{-1}) (b), the survival rate (%) and weed cover (%) (c), the survival rate and weed biomass (Mg ha^{-1}) (d), identifying plantation age and fertilization. n = 8

4. Discussion

4.1. Specific allometric equations for smallholders' *Eucalyptus* plantations

In the current study, we developed and evaluated single-variable and multiple-variable allometric equations based on tree height (H) and tree circumference (Cir) for estimating aboveground biomass (AGB) of smallholders' *Eucalyptus robusta* plantations. Cir was the best predictive variable for estimating branches and leaves biomass. However, the combined variables of Cir and H (Cir × H) better fit for trunk biomass estimation. António et al. (2007) found that the combination of tree diameter and tree height improved the biomass prediction for trunk component (stem and bark) while the diameter alone is the best predictor for branch and leaf components. The pipe model theory proposed first by Shinozaki et al.(1964) and tested by previous studies formulated that the sapwood area of trees is proportional to foliage biomass as each unit of foliage requires a unit pipeline of wood to conduct water from roots and to support them physically (Mäkelä 1986; Huang et al. 2023). These agreements are consistent with ours in which the mean value of R^2 of all treatments for trunk biomass estimation was 4% higher using Cir × H compared to Cir alone. Other authors also observed a significant increase in the predictive ability of biomass models in stand total ABG estimation when adding H as an additional explanatory variable in pure *Eucalyptus* plantations (Zewdie et al. 2009; Mukuralinda et al. 2021) as well as associated with crop (Chavan et al. 2024). This better-fit with H as an additional predictor with Cir was also found for other tropical tree species (Chave et al. 2005; Bastien-Henri et al. 2010).

LA was also estimated by allometric equations, and the best models were based on the variable Cir. Previous studies in clonal *Eucalyptus* plantations in Congo found the same result by comparing diameter and height variables but with lower R^2 values, which ranged from 0.41 to 0.79 for different sections of tree crown (Nouvellon et al. 2010).

4.2. *Eucalyptus robusta* growth performance and aboveground biomass production in Madagascar highlands smallholder plantations

Our data clearly showed pretty good growth of *Eucalyptus robusta* as smallholder plantations in Madagascar conditions (Lebot and Ranaivoson 1994; Razafimahatratra et al. 2016). Lebot and Ranaivoson (1994) found that *E. robusta* was the most productive species with *E. grandis* and the most widespread and cultivated species at the smallholder level in Madagascar. Our results were consistent with those of Razafimahatratra et al. (2016) in Antsirinala (18° 55′ S, 48° 10′ E), Madagascar, with similar site characteristics (900 m a.s.l., 1,300 mm of annual rainfall, 19°C of mean annual temperature, 3m × 3m tree spacing). At 4 yo and 6.5 yo, *E. robusta* mean heights at Antsirinala were 8.4 m and 10.6 m, respectively, with corresponding mean circumferences of 29.2 cm and 33.9 cm, respectively. These values differed little from our results for fertilized trees whose growth was just under at 4 yo (7.2 m in height and 27.5 cm in circumference) and just over at 6 yo (11.2 m in height and 37.9 cm in circumference). Moreover, slightly higher amount of fertilization was used in Antsirinala, with 200 g of NPKZn (8-16-24-2) + 50 g of urea per tree applied at planting (Razafimahatratra et al. 2016), compared to 120g NPK 11-22-16 per tree in our experiment. This higher amount of fertilization increased the early tree growth with mean tree height of 2.7 m at 20 months of age compared to 1.8 m for the 2-year-fertilized trees in our study.

However, the growth of *Eucalyptus* trees in smallholder's stands is much lower than that in commercial plantations (**Table 3**). For instance, in *Eucalyptus* hybrid clonal plantations in South China, eucalypts were 17 m high at 4.5 yo with mean CBH of 42 cm which are 2,2 and 1.4 times more than the values in our study (Yang et al., 2023). In Brazil, *Eucalyptus grandis* tree height reached 9.5 m at 2 yo (Eufrade Junior et al. 2016) and 24 m at 6 yo (Bouillet et al. 2013) which 5 and 2 times more than the values of our smallholder plantations. Differences in tree growth observed within commercial plantations can be explained by the differences in ecological conditions, silvicultural practices and plant material (Bouillet et al. 2013; Binkley et al. 2017). Consistently, the large differences between commercial and the smallholder plantations in our study underline the importance of fertilization and the seeds quality in *Eucalyptus* plantations.

These differences in tree growth parameters resulted in AGB accumulation lower in smallholder stands than in commercial plantations (Kuyah et al. 2013). In our experiment, fertilized trees produced total AGB of 1.60 Mg.ha^{-1} and 53.7 Mg.ha^{-1} at 2 and 6 yo, respectively. These values are 12 and 1.4 times, respectively, lower than in commercial plantations in Congo at the same age which are also different from our study in a climatic context with a significantly higher mean temperature (see **Table 3**) (Laclau et al. 2000). Moreover, in our study, 50% of the total aerial biomass was accumulated in the trunk, only at 4 yo for fertilized trees, and at age 5 for non-fertilized trees. As a comparison, by age 4, 80% of total AGB was accumulated in wood proportion in commercial *Eucalyptus* plantations in Congo (Laclau et al. 2000). In addition, a greater proportion of aboveground than belowground biomass allocation was found in sites with higher fertility than in sites with lower fertility (Epron et al. 2015). The growth of the living biomass predominated in commercial plantations up to 2-3 yo. After 3 years happened the tree stage of heartwood formation and maximal wood production and the optimal logging age is at 7 yo (Laclau et al. 2000). The improvement of growth by fertilization at planting were more pronounced with significantly larger dose (Laclau et al. 2000).

The mean LAI in the current study tends to stabilize at 4 yo in the fertilized plots, reaching approximately 3. At 6 yo, at 1805 trees ha^{-1}, mean LAI values were similar to those of pure clonal *Eucalyptus* plantation in Brazil with 1111 $tree.ha^{-1}$ at 4.3 yo (Oliveira et al. 2024). Mean LAI values were found to increase with tree density (Smethurst et al. 2003; Laclau et al. 2008b; Oliveira et al. 2024).

Survival rate is an important parameter for AGB evaluation at the smallholder level. Our data showed that survival rates values ranged from 70 to 100%, to be compared from 84% to 100 % in *Eucalyptus* commercial plantations in Brazil (Bouillet et al. 2013). These figures are largely higher than the average survival rates of 60% for the forest plantations established in the central highlands of Madagascar (Gabathuler et al. 2014).

Table 3 Eucalyptus growth in commercial plantations in different sites. Climatic conditions and species are displayed with H (Height), CBH (Circumference at Breast at Height), DBH (Diameter at Breast Height), AGB (Aboveground Biomass) and/or production

Study	**Site localization**	**Mean annual rainfall and temperature**	**Species**	***Eucalyptus* growth and aboveground biomass/production**
Laclau et al. (2000)	Congo	1200 mm and 25°C	Hybrid *E.PF1* (one of the most productive clones)	H: 11 m at 2.1 yo and 22.7 m at 5.2 yo CBH: 31.9 cm at 2.1 yo and 48.7 cm at 5.2 yo

				AGB: 20 $Mg.ha^{-1}$ at 2.1 yo and 62 $Mg.ha^{-1}$ at 5.2 yo
Yang et al. (2023)	Guangzhou, Southern China	1922 mm and 22°C	*E.urophylla* × *E.grandis* clones	H: 17 m at 4.5 yo CBH: 42 cm at 4.5 yo
Eufrade et al. (2016)	Botocatu city, São Paulo, Brazil	1428 mm and 20°C	*E.urophylla* × *E.grandis* clones	H: 9.5 m at 2 yo DBH: 7 cm at 2 yo
Bouillet et al. (2013)	Itatinga station, São Paulo, Brazil	1390 mm and 19°C	*E. grandis*	H: 24 m at 6 yo CBH: 42 cm at 6 yo Stemwood production of 20.5 $Mg.ha^{-1}year^{-1}$

4.3. Weeding is key to smallholder *Eucalyptus* plantations success

Except at planting, weed control was neglected in our study as in most smallholder plantations (Bekele 2013; Alemayehu and Melka 2022) . Survival rates and total AGB showed significant negative relationship with weed cover and biomass. In Chile, Vargas et.al (2018) tested, in a high (2103 mm yr^{-1}) rainfall site, various intensities of weed control, depending on cleared surface area around each tree in *E. globulus* plantations. Increasing the intensity of weed control was shown to increase survival rates. At 9 years after planting, survival rates were + 69 % higher in plots with total weed control than in not weeded control plot. Competition for light between weeds and trees could explain this finding with the high amount weed biomass reducing greatly light availability for the young trees. Likewise, various studies showed significant effect of weed control on tree growth and *Eucalyptus* stand production (Vargas et al. 2018; Carrero et al. 2018; Inail et al. 2021; Corticeiro et al. 2023). In Portugal in *E. globulus Labill., 1800* plantations, weeding led to significant higher tree height increment between age 1.5 and 5.5 yo (Corticeiro et al. 2023). Inail et al. (2021) showed a significant increase in tree height, tree diameter, and volume of *E. pellita* with early weed control up to 1 year, until canopy closure.

In Venezuela, Carrero et.al (2018) showed important gains of productivity in *Eucalyptus* plantations from weed control which allowed a gain of 1.7 Mg ha^{-1} yr^{-1} in stem biomass.

4.4. Importance of starter fertilization

Our experiment showed the importance to apply fertilization at planting in smallholder plantations. Such starter fertilization enhanced aboveground growth and biomass. The potential productivity of commercial *Eucalyptus* plantations is very high, as found across 36 sites from Brazil to Uruguay and 18 clones, with stemwood production averaging 22 Mg ha^{-1} yr^{-1} at 6 years of age (Binkley et al. 2017). Various studies showed that *Eucalyptus* commercial plantations require much higher amounts of fertilizers than the smallholder plantations in Madagascar (Laclau et al. 2008a; Bordron et al. 2019). Nutrient requirements (N, P, K, Ca, Mg) and accumulation in *Eucalyptus* tree biomass increased sharply during the first two years (Laclau et al. 2003). Applying fertilization at planting improves tree nutrient uptake and reduces cations loss in *Eucalyptus* plantations by increasing root mass, length and area density (Bordron et al. 2019). The risk of loss of fertilizers in *Eucalyptus* plantations through deep drainage is low (Laclau et al. 2010), all the more so as *Eucalyptus* trees have the capacity to take up nutrients early and at long distance, both horizontally and in depth (Bouillet et al. 2013).

Planted forests in MCH are established in low-fertility soils (Verhaegen et al. 2011). Soil total nitrogen and potassium are particularly low, mainly on the slopes (Rasoarinaivo et al. 2024). Due to the high cost of mineral fertilizers and scarcity of organic fertilizers, smallholders tend to prioritize them for staple and cash crops over tree plantations (Rakotovao et al. 2017, 2022; Raminoarison et al. 2024). However, taking account the marked effect of low starter fertilization on tree growth and stand production, as shown in this study, various projects on smallholder *Eucalyptus* plantations in Madagascar should be helped to cover the costs of NPK fertilizers. Application of low dose of fertilizer at planting was also encouraged in Tanzania on smallholder plantations of *Pinus patula Schiede ex Schltdl.* et *Cham* and *E. grandis W.Hill ex Maiden* (Mwambusi et al. 2021).

After stand harvesting, maintenance of forest residue in commercial *Eucalyptus* plantations was also shown to maintain soil organic carbon and increase of wood productivity during the second rotation compared to plots where forest residue were removed (Epron et al. 2015; Rocha et al. 2018). Therefore, forest residue maintenance may be also recommended to improve the fertility of soils and the production of following stand rotations of smallholder plantations.

5. Conclusion

Accurate biomass estimates are essential for forest managers to estimate biomass production and carbon stocks. The allometric equations established in this study can be used by researchers and managers of smallholder *Eucalyptus* plantations in Madagascar. The use of Cir and H is required to have the best estimates of total AGB, so it is recommended to record both parameters in forest inventory. However, getting reliable height data can be time consuming and reliable measurement tools can be expensive (*e.g.* Haglöf Vertex 5 instrument). On the other hand, Cir explained more than 90% of the total variation in each tree compartment. Cir was found to be a strong indicator of AGB. For more practical purposes requiring less precision of AGB production, Cir alone is sufficient. Remote sensing techniques can also provide a solution to the complexity of data collection and for monitoring tree growth (Guimarães et al. 2020; Leite et al. 2020). A study of photogrammetric processing for planted forests in the MCH is currently in preparation.

Weeding is critical for stand production. Weed control must be applied, at least until the canopy closure. We also showed that applying low amount of fertilizers at planting increased markedly tree growth and stand production of smallholder *Eucalyptus* plantations on low-fertility soils in Madagascar. The stands can then be harvested for the first time after 6-7 years, with shoots very likely more vigorous than those emitted by trees grown without fertilization. However, given the cost of fertilizers, mechanisms to help smallholders purchase fertilizers need to be put in place, as is already the case for some reforestation projects in Madagascar.

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Data availability All data is included in the manuscripts in the form of figures and tables.

Declarations

Conflicts of interest The authors have no relevant financial or non-financial interests to disclose.

References

Adinugroho WC, Krisnawati H, Imanuddin R, et al (2023) Developing biomass allometric equations for small trees in mixed-species forests of tropical rainforest ecozone. Trees, Forests and People 13:100425. https://doi.org/10.1016/j.tfp.2023.100425

Alemayehu A, Melka Y (2022) Small scale eucalyptus cultivation and its socioeconomic impacts in Ethiopia: A review of practices and conditions. Trees, Forests and People 8:100269. https://doi.org/10.1016/j.tfp.2022.100269

António N, Tomé M, Tomé J, et al (2007) Effect of tree, stand, and site variables on the allometry of *Eucalyptus globulus* tree biomass. Can J For Res 37:895–906. https://doi.org/10.1139/X06-276

Baohanta R, Thioulouse J, Ramanankierana H, et al (2012) Restoring native forest ecosystems after exotic tree plantation in Madagascar: Combination of the local ectotrophic species

Leptolena bojeriana and Uapaca bojeri mitigates the negative influence of the exotic species Eucalyptus camaldulensis and Pinus patula. Biological Invasions 14:2407–2421. https://doi.org/10.1007/s10530-012-0238-5

Baskerville GL (1972) Use of Logarithmic Regression in the Estimation of Plant Biomass. Can J For Res 2:49–53. https://doi.org/10.1139/x72-009

Bastien-Henri S, Park A, Ashton M, Messier C (2010) Biomass distribution among tropical tree species grown under differing regional climates. Forest Ecology and Management 260:403–410. https://doi.org/10.1016/j.foreco.2010.04.035

Bekele M (2013) Forest plantations and woodlots in Ethiopia. African Forest Forum Working Paper Series 1:

Binkley D, Campoe OC, Alvares C, et al (2017) The interactions of climate, spacing and genetics on clonal *Eucalyptus* plantations across Brazil and Uruguay. Forest Ecology and Management 405:271–283. https://doi.org/10.1016/j.foreco.2017.09.050

Booth TH (2013) Eucalypt plantations and climate change. Forest Ecology and Management 301:28–34. https://doi.org/10.1016/j.foreco.2012.04.004

Bordron B, Robin A, Oliveira IR, et al (2019) Fertilization increases the functional specialization of fine roots in deep soil layers for young Eucalyptus grandis trees. Forest Ecology and Management 431:6–16. https://doi.org/10.1016/j.foreco.2018.03.018

Bouillet J-P, Bordron B, Laclau J-P, et al (2023) Early and long-distance uptake by Eucalyptus grandis of N, K and Ca tracers injected down to a depth of 7 m. Forest Ecology and Management 550:121507. https://doi.org/10.1016/j.foreco.2023.121507

Bouillet J-P, Laclau J-P, Gonçalves JLDM, et al (2013) Eucalyptus and Acacia tree growth over entire rotation in single- and mixed-species plantations across five sites in Brazil and Congo. Forest Ecology and Management 301:89–101. https://doi.org/10.1016/j.foreco.2012.09.019

Bouillet J-P, Rasamindisa A, Rakotondraoelina H, Razafimahatratra S (2019) Capitalisation des réalisations et acquis du projet ARINA. Aménagement et Reboisements Intégrés dans le district d’Anjozorobe en bois-énergie. CIRAD

Bucht K (2015) Plantation projects in Madagascar: approaches, objectives and reflections for fuelwood production. Tropical Resources 34:62–71

Cairns MA, Brown S, Helmer EH, Baumgardner GA (1997) Root biomass allocation in the world’s upland forests. Oecologia 111:1–11. https://doi.org/10.1007/s004420050201

Carrero O, Stape JL, Allen L, et al (2018) Productivity gains from weed control and fertilization of short-rotation *Eucalyptus* plantations in the Venezuelan Western Llanos. Forest Ecology and Management 430:566–575. https://doi.org/10.1016/j.foreco.2018.07.050

Causton DR (1985) Biometrical, structural and physiological relationships among tree parts. Attributes of trees as crop plants / edited by MGR Cannell and JE Jackson

Chavan SB, Dhillon RS, Sirohi C, et al (2024) Optimizing planting geometries in eucalyptus-based food production systems for enhanced yield and carbon sequestration. Front Sustain Food Syst 8:. https://doi.org/10.3389/fsufs.2024.1386035

Chave J, Andalo C, Brown S, et al (2005) Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145:87–99. https://doi.org/10.1007/s00442-005-0100-x

Chave J, Réjou-Méchain M, Búrquez A, et al (2014) Improved allometric models to estimate the aboveground biomass of tropical trees. Global Change Biology 20:3177–3190. https://doi.org/10.1111/gcb.12629

Chen L, Ren C, Zhang B, et al (2018) Estimation of Forest Above-Ground Biomass by Geographically Weighted Regression and Machine Learning with Sentinel Imagery. Forests 9:582. https://doi.org/10.3390/f9100582

Cheng J, Huang C, Gan X, et al (2023) Can forest carbon sequestration offset industrial CO2 emissions? A case study of Hubei Province, China. Journal of Cleaner Production 426:139147. https://doi.org/10.1016/j.jclepro.2023.139147

Clifford D, Cressie N, England JR, et al (2013) Correction factors for unbiased, efficient estimation and prediction of biomass from log–log allometric models. Forest Ecology and Management 310:375–381. https://doi.org/10.1016/j.foreco.2013.08.041

Corticeiro S, Maia P, Gonçalves C, et al (2023) How Weed Control Affects Eucalyptus globulus Labill. Productivity: Results from Two Long-Term Trials. Forests 14:1958. https://doi.org/10.3390/f14101958

da Silva PH, Poggiani F, Libardi PL, Gonçalves AN (2013) Fertilizer management of eucalypt plantations on sandy soil in Brazil: Initial growth and nutrient cycling. Forest Ecology and Management 301:67–78. https://doi.org/10.1016/j.foreco.2012.10.033

de Mendiburu F (2023) agricolae: Statistical Procedures for Agricultural Research

Epron D, Mouanda C, Mareschal L, Koutika L-S (2015) Impacts of organic residue management on the soil C dynamics in a tropical eucalypt plantation on a nutrient-poor sandy soil after three rotations. Soil Biology and Biochemistry 85:183–189. https://doi.org/10.1016/j.soilbio.2015.03.010

Eufrade Junior HJ, Melo RX de, Sartori MMP, et al (2016) Sustainable use of eucalypt biomass grown on short rotation coppice for bioenergy. Biomass and Bioenergy 90:15–21. https://doi.org/10.1016/j.biombioe.2016.03.037

FAO (2022a) The State of the World's Forests 2022. FAO

FAO (2020) Global Forest Resources Assessment 2020. FAO

FAO (2022b) FRA 2020 Remote Sensing Survey. FAO

FAO (2012) Base harmonisée mondiale de données sur les sols version 1.2 | Portail d'information sur les sols | Organisation des Nations Unies pour l'alimentation et l'agriculture. https://www.fao.org/soils-portal/soil-survey/cartes-historiques-et-basesde-donnees-des-sols/base-harmonisee-mondiale-de-donnees-sur-les-sols-version-12/fr/. Accessed 26 Apr 2023

FAO-UNESCO (1974) FAO/UNESCO Soil Map of the World | FAO SOILS PORTAL | Food and Agriculture Organization of the United Nations. https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/. Accessed 26 Apr 2023

Gabathuler E, Rabevohitra MVR, Rakotondranaly N, Bachmann F (2014) Reboisements paysans sur les Hautes Terres c-entrales de Madagascar

Ganamé M, Bayen P, Ouédraogo I, et al (2021) Allometric models for improving aboveground biomass estimates in West African savanna ecosystems. Trees, Forests and People 4:100077. https://doi.org/10.1016/j.tfp.2021.100077

Guimarães N, Pádua L, Marques P, et al (2020) Forestry Remote Sensing from Unmanned Aerial Vehicles: A Review Focusing on the Data, Processing and Potentialities. Remote Sensing 12:1046. https://doi.org/10.3390/rs12061046

Henry M, Picard N, Trotta C, et al (2011) Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations. Silva Fenn 45:477–569. https://doi.org/10.14214/sf.38

Hothorn T, Bretz F, Westfall P (2008) Simultaneous Inference in General Parametric Models. Biometrical Journal 50:346–363

Huang C, Zhang Y, Chen L, et al (2023) Pipe Model Can Accurately Estimate Crown Biomass of Larch (Larix olgensis) Plantation Forest in Northeast China. Forests 14:400. https://doi.org/10.3390/f14020400

Inail MA, Hardiyanto EB, Mendham DS, Thaher E (2021) Growth Response to Weed Control and Fertilisation in Mid-Rotation Plantations of Eucalyptus pellita in South Sumatra, Indonesia. Forests 12:1653. https://doi.org/10.3390/f12121653

Jandl R, Lindner M, Vesterdal L, et al (2007) How strongly can forest management influence soil carbon sequestration? Geoderma 137:253–268. https://doi.org/10.1016/j.geoderma.2006.09.003

Joseph GS, Rakotoarivelo AR, Seymour CL (2021) How expansive were Malagasy Central Highland forests, ericoids, woodlands and grasslands? A multidisciplinary approach to a conservation conundrum | Elsevier Enhanced Reader. https://doi.org/10.1016/j.biocon.2021.109282

Kuyah S, Dietz J, Muthuri C, et al (2013) Allometry and partitioning of above- and below-ground biomass in farmed eucalyptus species dominant in Western Kenyan agricultural landscapes. Biomass and Bioenergy 55:276–284. https://doi.org/10.1016/j.biombioe.2013.02.011

Laclau, Almeida JCR, Goncalves JLM, et al (2008a) Influence of nitrogen and potassium fertilization on leaf lifespan and allocation of above-ground growth in Eucalyptus plantations. Tree Physiology 29:111–124. https://doi.org/10.1093/treephys/tpn010

Laclau, Bouillet J-P, Gonçalves JLM, et al (2008b) Mixed-species plantations of Acacia mangium and Eucalyptus grandis in Brazil: 1. Growth dynamics and aboveground net primary production. Forest Ecology and Management 255:3905–3917. https://doi.org/10.1016/j.foreco.2007.10.049

Laclau J-P, Bouillet J-P, Ranger J (2000) Dynamics of biomass and nutrient accumulation in a clonal plantation of Eucalyptus in Congo. Forest Ecology and Management 128:181–196. https://doi.org/10.1016/S0378-1127(99)00146-2

Laclau J-P, Deleporte P, Ranger J, et al (2003) Nutrient Dynamics throughout the Rotation of Eucalyptus Clonal Stands in Congo. Annals of Botany 91:879–892. https://doi.org/10.1093/aob/mcg093

Laclau J-P, Ranger J, de Moraes Gonçalves JL, et al (2010) Biogeochemical cycles of nutrients in tropical *Eucalyptus* plantations. Forest Ecology and Management 259:1771–1785. https://doi.org/10.1016/j.foreco.2009.06.010

Lebot V, Ranaivoson L (1994) Eucalyptus genetic improvement in Madagascar. Forest Ecology and Management 63:135–152. https://doi.org/10.1016/0378-1127(94)90107-4

Leite R, Silva C, Mohan M, et al (2020) Individual Tree Attribute Estimation and Uniformity Assessment in Fast-Growing Eucalyptus spp. Forest Plantations Using Lidar and Linear Mixed-Effects Models. Remote Sensing 12:3599. https://doi.org/10.3390/rs12213599

Lenth R (2024) emmeans: Estimated Marginal Means, aka Least-Squares Means

Maciel JC, Duque TS, Ferreira EA, et al (2022) Growth, Nutrient Accumulation, and Nutritional Efficiency of a Clonal Eucalyptus Hybrid in Competition with Grasses. Forests 13:1157. https://doi.org/10.3390/f13081157

Mäkelä A (1986) Implications of the pipe model theory on dry matter partitioning and height growth in trees. Journal of Theoretical Biology 123:103–120. https://doi.org/10.1016/S0022-5193(86)80238-7

Malhi Y, Gardner TA, Goldsmith GR, et al (2014) Tropical Forests in the Anthropocene. Annual Review of Environment and Resources 39:125–159. https://doi.org/10.1146/annurev-environ-030713-155141

Mevanarivo ZE, Ramananantoandro T, Tomazello Filho M, et al (2020) Variability in the physico-chemical properties of wood from Eucalyptus robusta depending on ecological growing conditions and forestry practices: The case of smallholdings in the Highlands of Madagascar. Maderas Ciencia y tecnología 22:425–438. https://doi.org/10.4067/S0718-221X2020005000401

Minten B, Sander K, Stifel D (2013) Forest management and economic rents: Evidence from the charcoal trade in Madagascar. Energy for Sustainable Development 17:106–115. https://doi.org/10.1016/j.esd.2012.08.004

Mukuralinda A, Kuyah S, Ruzibiza M, et al (2021) Allometric equations, wood density and partitioning of aboveground biomass in the arboretum of Ruhande, Rwanda. Trees, Forests and People 3:100050. https://doi.org/10.1016/j.tfp.2020.100050

Mwambusi JN, Kapp G, Chamshama SAO (2021) The Silviculture of Woodlots of Smallholder Forest Producers in Mufindi District, Tanzania: Knowledge and Treatments. Tanzania Journal of Forestry and Nature Conservation 90:40–61

Nouvellon Y, Laclau J-P, Epron D, et al (2010) Within-stand and seasonal variations of specific leaf area in a clonal Eucalyptus plantation in the Republic of Congo. Forest Ecology and Management 259:1796–1807. https://doi.org/10.1016/j.foreco.2009.05.023

Nunes LJR, Meireles CIR, Pinto Gomes CJ, Almeida Ribeiro NMC (2020) Forest Contribution to Climate Change Mitigation: Management Oriented to Carbon Capture and Storage. Climate 8:21. https://doi.org/10.3390/cli8020021

Oliveira IR, Bouillet JP, Guillemot J, et al (2024) Changes in light use efficiency explains why diversity effect on biomass production is lower at high planting density in mixed-species plantations of Eucalyptus grandis and Acacia mangium. Forest Ecology and Management 554:121663. https://doi.org/10.1016/j.foreco.2023.121663

Paul KI, Radtke PJ, Roxburgh SH, et al (2018) Validation of allometric biomass models: How to have confidence in the application of existing models. Forest Ecology and Management 412:70–79. https://doi.org/10.1016/j.foreco.2018.01.016

Pendrill F, Persson UM, Godar J, et al (2019) Agricultural and forestry trade drives large share of tropical deforestation emissions. Global Environmental Change 56:1–10. https://doi.org/10.1016/j.gloenvcha.2019.03.002

Pinheiro J, Bates D, R Core Team (2023) _nlme: Linear and Nonlinear Mixed Effects Models_

R Core Team (2023) R: A Language and Environment for Statistical Computing

Rakotovao NH, Rasoarinaivo AR, Razafimbelo T, et al (2022) Organic inputs in agroforestry systems improve soil organic carbon storage in Itasy, Madagascar. Regional Environmental Change 22:13. https://doi.org/10.1007/s10113-021-01863-2

Rakotovao NH, Razafimbelo TM, Rakotosamimanana S, et al (2017) Carbon footprint of smallholder farms in Central Madagascar: The integration of agroecological practices. Journal of Cleaner Production 140:1165–1175. https://doi.org/10.1016/j.jclepro.2016.10.045

Ramananantoandro T, Rafidimanantsoa HP, Ramanakoto MF (2015) Forest aboveground biomass estimates in a tropical rainforest in Madagascar: new insights from the use of wood specific gravity data. J For Res 26:47–55. https://doi.org/10.1007/s11676-015-0029-9

Raminoarison M, Jaillard B, Razafimbelo T, et al (2024) Optimizing soil and plant functions: combinatory design of fertilizing resources assemblage for rainfed rice in Madagascar. Experimental Agriculture 60:e18. https://doi.org/10.1017/S0014479724000103

Randriambanona H, Randriamalala JR, Carrière SM (2019) Native forest regeneration and vegetation dynamics in non-native Pinus patula tree plantations in Madagascar. Forest Ecology and Management 446:20–28. https://doi.org/10.1016/j.foreco.2019.05.019

Randrianasolo ZH, Razafimahatratra AR, Razafinarivo RNG, et al (2019) Which allometric models are the most appropriate for estimating aboveground biomass in secondary forests of Madagascar with *Ravenala madagascariensis*? Scientific African 6:e00147. https://doi.org/10.1016/j.sciaf.2019.e00147

Randrianjafy H (1999) Les plantations d'eucalyptus à Madagascar : Superficie, rôle et importance des massifs

Rasoarinaivo AR, Bordron B, Rabemiafara OJ, et al (2024) Topographie : un facteur clé de la fertilité des sols de reboisements à Madagascar. Biotechnology, Agronomy, Society and Environment (submitted):

Razafimahatratra AR, Ramananantoandro T, Razafimaharo V, Chaix G (2016) Provenance and progeny performances and genotype × environment interactions of Eucalyptus robusta grown in Madagascar. Tree Genetics & Genomes 12:38. https://doi.org/10.1007/s11295-016-0999-6

Razafindramanana N, Serpantié G, Carrière SM, et al (2008) Afforestation et stockage du carbone dans le sol et la végétation : cas de la lisière ouest du corridor forestier de Fianarantsoa (Madagascar). 4

Razakamanarivo RH, Grinand C, Razafindrakoto MA, et al (2011) Mapping organic carbon stocks in eucalyptus plantations of the central highlands of Madagascar: A multiple regression approach. Geoderma 162:335–346. https://doi.org/10.1016/j.geoderma.2011.03.006

Razakamanarivo RH, Razafindrakoto M-A, Albrecht A (2010) Fonction puits de carbone des taillis d'eucalyptus à Madagascar. Bois et Forêts des Tropiques 305:5. https://doi.org/10.19182/bft2010.305.a20438

Razakamanarivo RH, Razakavololona A, Razafindrakoto M-A, et al (2012) Below-ground biomass production and allometric relationships of eucalyptus coppice plantation in the central highlands of Madagascar. Biomass and Bioenergy 45:1–10. https://doi.org/10.1016/j.biombioe.2011.01.020

Razakavololona A (2007) Evaluation du stock de carbone dans les différents compartiments de la biomasse végétale et dans le sol sur une chronoséquence de plantation d'Eucalyptus sur les Hautes Terres de Madagascar. Cas de Sambaina- Manjakandriana. Mémoire en vue de l'obtention du Diplôme d'Etudes Approfondies (DEA) Option Eaux et Forêts, Université Antananarivo - ESSA - Département des Eaux et Forêts

Rocha JHT, Gonçalves JLDM, Brandani CB, et al (2018) Forest residue removal decreases soil quality and affects wood productivity even with high rates of fertilizer application. Forest Ecology and Management 430:188–195. https://doi.org/10.1016/j.foreco.2018.08.010

Schaller M, Schroth G, Beer J, Jiménez F (2003) Species and site characteristics that permit the association of fast-growing trees with crops: the case of *Eucalyptus deglupta* as coffee shade in Costa Rica. Forest Ecology and Management 175:205–215. https://doi.org/10.1016/S0378-1127(02)00079-8

Schneider CA, Rasband WS, Eliceiri KW (2012) NIH Image to ImageJ: 25 years of image analysis. Nat Methods 9:671–675. https://doi.org/10.1038/nmeth.2089

Shen H, Zhu Z (2008) Efficient mean estimation in log-normal linear models. Journal of Statistical Planning and Inference 138:552–567. https://doi.org/10.1016/j.jspi.2006.10.016

Shinozaki K, Yoda K, Hozumi K, Kira T (1964) A Quantitative Analysis of Plant Form-the Pipe Model Theory: I.basic Analyses. 日本生態学会誌 14:97–105. https://doi.org/10.18960/seitai.14.3_97

Smethurst P, Baillie C, Cherry M, Holz G (2003) Fertilizer effects on LAI and growth of four Eucalyptus nitens plantations. Forest Ecology and Management 176:531–542. https://doi.org/10.1016/S0378-1127(02)00226-8

Snowdon, Raison, Keith, et al (2002) Protocol for Sampling Tree and Stand Biomass. Australian Greenhouse Office

Sun X, Wang Q, Song G (2024a) Revisiting generic allometric equations for estimating forest aboveground biomass in Japan: Importance of incorporating plant functional types and origins. Biomass and Bioenergy 180:107025. https://doi.org/10.1016/j.biombioe.2023.107025

Sun X, Wang Q, Song G (2024b) Revisiting generic allometric equations for estimating forest aboveground biomass in Japan: Importance of incorporating plant functional types and origins. Biomass and Bioenergy 180:107025. https://doi.org/10.1016/j.biombioe.2023.107025

Vargas F, Rubilar R, Gonzalez-Benecke CA, et al (2018) Long-term response to area of competition control in Eucalyptus globulus plantations. New Forests 49:383–398. https://doi.org/10.1007/s11056-017-9625-1

Verhaegen D, Randrianjafy H, Montagne P, et al (2011) Historique de l'introduction du genre Eucalyptus à Madagascar. Bois for trop 309:17. https://doi.org/10.19182/bft2011.309.a20462

Verhaegen D, Randrianjafy H, Rakotondraoelina H, et al (2014) Eucalyptus robusta pour une production durable de bois énergie à Madagascar : bilan des connaissances et perspectives. Bois for trop 320:15. https://doi.org/10.19182/bft2014.320.a20541

Vieilledent G, Nourtier M, Grinand C, et al (2020) It's not just poverty: unregulated global market and bad governance explain unceasing deforestation in Western Madagascar. 2020.07.30.229104

Viera M, Ruíz Fernández F, Rodríguez-Soalleiro R (2016) Nutritional Prescriptions for Eucalyptus Plantations: Lessons Learned from Spain. Forests 7:84. https://doi.org/10.3390/f7040084

Watson DJ (1947) Comparative Physiological Studies on the Growth of Field Crops: I. Variation in Net Assimilation Rate and Leaf Area between Species and Varieties, and within and between Years. Annals of Botany 11:41–76

Yang L, Lin Y, Kong J, et al (2023) Effects of fertilization and dry-season irrigation on the timber production and carbon storage in subtropical Eucalyptus plantations. Industrial Crops and Products 192:116143. https://doi.org/10.1016/j.indcrop.2022.116143

Zewdie M, Olsson M, Verwijst T (2009) Above-ground biomass production and allometric relations of Eucalyptus globulus Labill. coppice plantations along a chronosequence in the central highlands of Ethiopia. Biomass and Bioenergy 33:421–428. https://doi.org/10.1016/j.biombioe.2008.08.007

Zhang Y, Wang X (2021) Geographical spatial distribution and productivity dynamic change of eucalyptus plantations in China. Scientific Reports 11:19764. https://doi.org/10.1038/s41598-021-97089-7