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Aboveground biomass and growth of smallholder *Eucalyptus robusta* under low starter fertilization and weed competition in Madagascar

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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 estimation 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 *Eucalyptus robusta* growth and aboveground biomass (AGB) while providing allometric equations for AGB estimation. Dendrometric data were collected from four 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 (leaves, branches, trunk) and treatments. Fertilization significantly improved global tree survival by 7% and increased tree height by 3.1 m and circumference by 8.3 cm in 6 yo stands. AGB per hectare doubled with fertilization, reaching 55.3 $Mg.ha^{-1}$ at 6 yo compared to 29.2 $Mg.ha^{-1}$ in non-fertilized plots. Aboveground carbon stock reached 4.6 $MgC.ha^{-1}yr^{-1}$ in fertilized plots. Weed cover and biomass had likely negative linear relationships with tree 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.

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 (FAO, 2022b; Malhi et al., 2014; Pendrill et al., 2019). 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

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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 many developing countries, smallholder tree plantations are expanding rapidly, especially in Southeast Asia (Nawir et al., 2007; Pham et al., 2023; Sandewall et al., 2015) and sub-Saharan Africa (Bailey et al., 2021; Bapfakurera et al., 2024b, 2024a; Elsiddig et al., 2011; Jacovelli, 2014). Tree-based systems currently supply about 70 % of fuelwood needs in Asia and around 20 % in Africa (Bapfakurera et al., 2024a; Sharma et al., 2016). In Rwanda, 80 % of plantation-derived wood volume originates from small-scale plantations, including woodlots and agroforestry systems (Bapfakurera et al., 2024a). The main driver of smallholder plantations expansion, in East Africa, is the increased demand for timber and fuelwood due to population growth (Kimambo et al., 2020).

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 235,000 ha among 415,000 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 deforestations (Bouillet et al., 2019; Bucht, 2015; Gabathuler et al., 2014; Verhaegen et al., 2014; 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 (Bouillet et al., 2023; Laclau et al., 2003; Maciel et al., 2022), while smallholders often use little-improved plant material which contribute to greater variability in stem form (Alemayehu and Melka, 2022).

Likewise, in Madagascar, the smallholder planted forests that are mainly established on low-fertility soils in MCH (Mevanarivo et al., 2020; Verhaegen et al., 2011) 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 (± 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 (Corticeiro et al., 2023; Maciel et al., 2022). 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 EP 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 (Clifford et al., 2013; Henry et al., 2011; 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 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 (Baohanta et al., 2012; Razafindramanana et al., 2008; Razakamanarivo et al., 2012, 2011, 2010; Razakavololona, 2007). 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, 2012; FAO-UNESCO, 1974) 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.

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 (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). The previous land use of these plots is spontaneous herbaceous pseudo-steppe. 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), eight treatments were compared: 2F, 2NF, 4F, 4NF, 5F, 5NF, 6F, 6NF. Tree density recommendation of 1111 trees.ha^{-1} (3 $m \times 3$ 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.

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 and height (H) of each tree in the inner plot (excluding the two border lines) of each selected plot was done at 4, 5 and 6 years, whereas at 2 years only the tree height was measured (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):

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

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 1.1.1.1) (Laclau et al., 2008a). Fresh weight (FW) of each tree compartment was determined directly in the field and sub-samples were oven-dried at 65 °C to obtain dry weight (DW) per compartment and then DW/FW ratios were calculated.

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 LA.

2.3.2. AGB and LA modelisation

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

$$y = a.x^{b} \quad (2)$$

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, except for the 2-year-old trees, which only considers height (Eq. (4)):

$$\ln(\boldsymbol{B}) = \ln(\boldsymbol{b}0) + \boldsymbol{b1} \times \ln(\boldsymbol{Cir}) + \boldsymbol{\varepsilon} \quad (3)$$

$$\ln(\boldsymbol{B}) = \ln(\boldsymbol{b}0) + \boldsymbol{b1} \times \ln(\boldsymbol{H}) + \boldsymbol{\varepsilon} \quad (4)$$

$$\ln(\boldsymbol{B}) = \ln(\boldsymbol{b}0) + \boldsymbol{b1} \times \ln(\boldsymbol{Cir} \times \mathbf{H}) + \boldsymbol{\varepsilon} \quad (5)$$

$$\ln(\boldsymbol{B}) = \ln(\boldsymbol{b}0) + \boldsymbol{b1} \times \mathbf{ln}\left((\boldsymbol{Cir})^2 \times \mathbf{H}\right) + \boldsymbol{\varepsilon} \quad (6)$$

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

For LAI calculation, 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).

2.3.2.1. Models' selection criterions. In total, 104 models were established (8 treatments × 4 model forms (only 1 model for 2 yo trees) × 4 response variables (3 compartments AGB and Leaf Area). Normality residuals were evaluated using the Shapiro-Wilk test. 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, 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; (iv) the

Table 1
Stands characteristics. Number of trees and means (with their standard error) 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	3	386	2037 ± 463	0.12 ± 0.10	27.5 ± 0.6	71.5 ± 3.0	7.27 ± 0.15
	NF	3	427	2111 ± 389	0.08 ± 0.03	13.4 ± 0.3	17.5 ± 0.8	3.14 ± 0.07
5	F	3	304	1111 ± 0	0.10 ± 0.00	29.1 ± 0.9	85.2 ± 4.8	7.86 ± 0.21
	NF	3	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

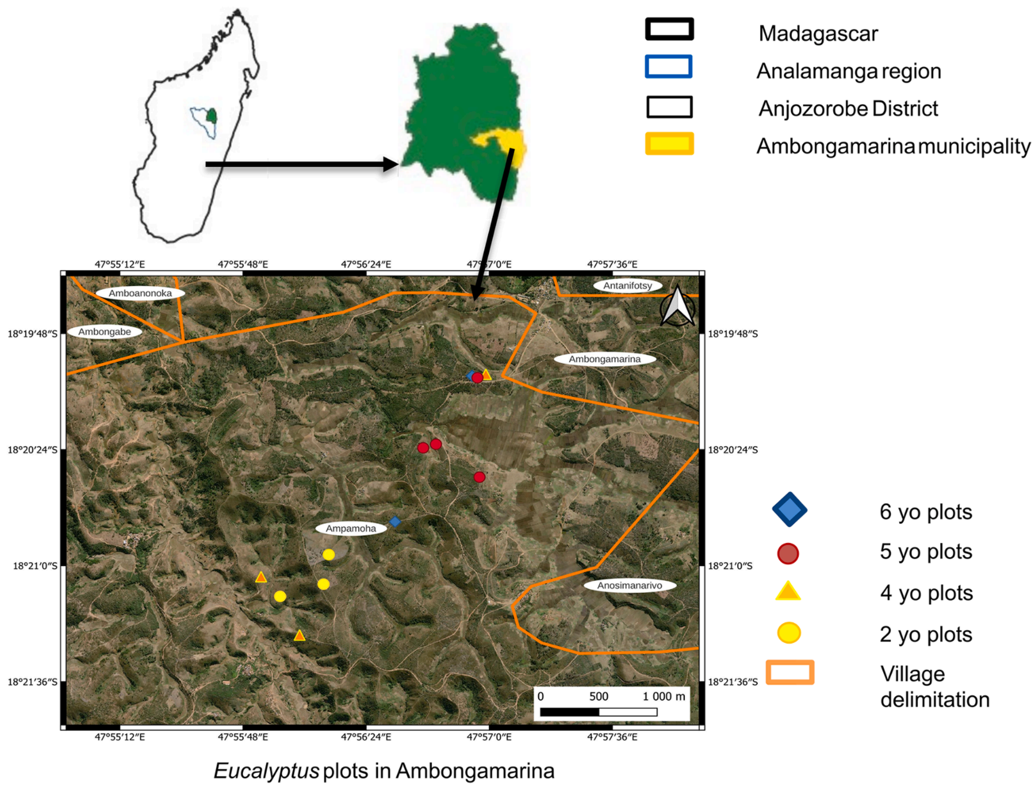

Fig. 1. Map showing the location of smallholder plots selected in this study in Anjozorobe, Madagascar. $n = 3$ for 2, 4 and 5 yo plots and $n = 2$ for 6 yo plots. Map created by Iaviantsoa Ramanandraibe, using data from the Humanitarian Data Exchange (HDX) – https://data.humdata.org.

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 (Adinugroho et al., 2023; Chave et al., 2014; Paul et al., 2018). 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.

2.4. Weed cover and biomass measurement

Weed measurements were carried in May 2023 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, with sampling locations chosen at random within visually representative areas of 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, 2024). The effects of the plantation age and fertilization plus their interaction on the stand growth parameters (tree height, circumference), on tree AGB, AGB per ha (total, trunk, living branches and leaves), and 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 a 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

Among the 104 models established (Supplementary data), 32 best models were selected corresponding to the best model for each treatment and response variables (8 treatments × 1 best model form × 4 response variables). For 4-, 5-, and 6-year-old trees, Cir was the best independent predictor among the four explanatory variables (Cir, H, Cir × H, and Cir^2 × H), independent of treatment, with R^2 averaging 0.95 for trunk, 0.94 for branch biomass and 0.89 for leaf biomass (Table 2) Models selected for branches and leaves AGB were based on Cir only (Eq. (3)), whereas trunk AGB was related to Cir and H (Eq. (5).

Among the four tested models for trunk ABG of 4-, 5-, and 6-year-old trees, based on the models' selection criterions, the best variable was Cir × H except for the AIC value where Cir^2 × H had the minimum mean value. Within the 6 treatments, models' R^2 varied from 0.96 to 0.99, while AIC varied from −15.47 to 1.75, RMSE varied from 0.63 to 17.90 kg and MAPE varied from 12 to 44 %. For the living branches compartment, 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 0.92 to 0.98, the AIC varied from 1.97 to 11.25, the RMSE varied from 0.74 to 6.60 kg and the MAPE varied from 20.11 to 43.70 %. Likewise, for the leaf biomass, the best explanatory variable for all treatments was also Cir based on all models' selection criterions. For this compartment, 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 1.19 to 2.65 kg 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 5.70 to 20.66 kg and the values of MAPE varied from 15.42 to 54.05 %.

For 2 yo fertilized and non-fertilized trees, models, using only H as the explanatory variable, reached an R^2 between 0.95 and 0.74 for trunk AGB, 0.76 and 0.59 for the living branches AGB, 0.80 and 0.61 for the leaf AGB, and 0.89 and 0.60 for the LA.

3.2. Eucalyptus growth characteristics

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

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. 2b). 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

Table 2
Selected allometric equations from Eqs. (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. The equation form is $\boldsymbol{y = a.x^b}$ where y = biomass, x= best predictor, a = b2 × REML and b = b1.

Best predictors	Age * fertilization	Number of tree	Equation's coefficients			Correction factor	Selection criterions of models			
			b0	b1	b2 (exp(b0))	REML	R^2	AIC	RMSE (kg)	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
H	2F	8	−3.36	2.95	0.03	1.04	0.95	5.73	0.11	29.84
	2NF	8	−3.23	2.79	0.04	1.10	0.74	13.00	0.05	29.46
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
H	2F	8	−3.73	2.77	2.E-04	1.21	0.76	18.78	0.14	68.47
	2NF	8	−3.74	3.22	2.E-04	1.28	0.59	20.76	0.07	50.49
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
H	2F	8	−2.88	2.76	5.E-02	1.07	0.90	10.69	0.24	51.45
	2NF	8	−2.49	2.37	8.E-02	1.13	0.61	15.13	0.11	39.97
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
H	2F	8	−1.07	2.81	0.34	1.08	0.89	11.62	1.62	53.72
	2NF	8	−0.63	2.35	0.53	1.13	0.60	15.29	0.85	46.98

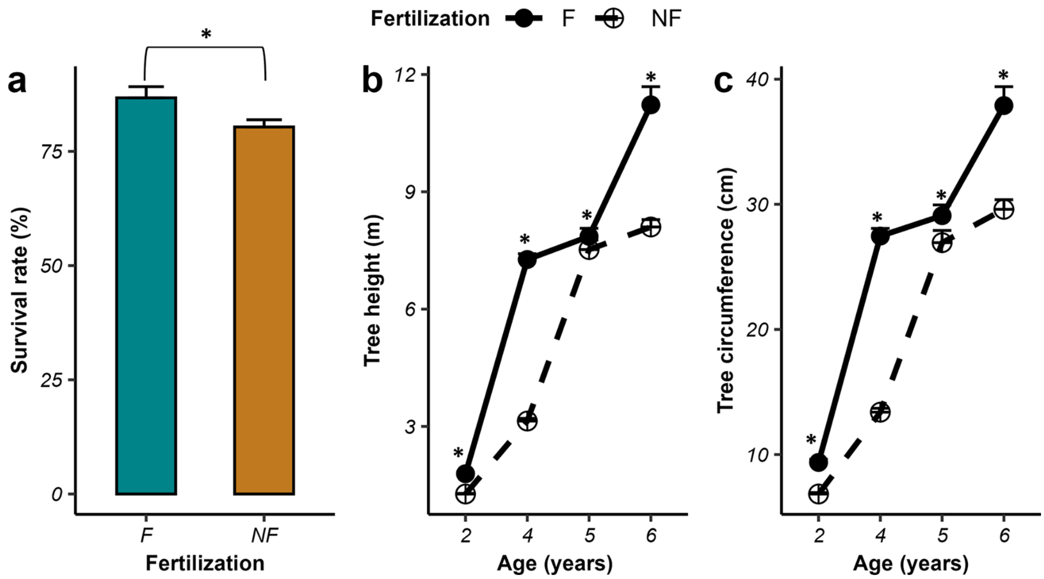

Fig. 2. Effect of low quantity of fertilization applied in smallholder EP on survival rate (a), tree height (b) and tree circumference (c); Standard errors (SE) are indicated according to the number of trees for each treatment, as shown in Table 1.

(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. 2c). 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 cm for F and 26.9 cm for NF).

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 but not by fertilization, although fertilization increased globally AGB per tree by 95 %. We reported a significant age × fertilization interaction ($p < 0.001$) (Fig. 3a). 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 (26.90 kg for F and 4.25 kg for NF) and 6 yo (55.90 kg for F and

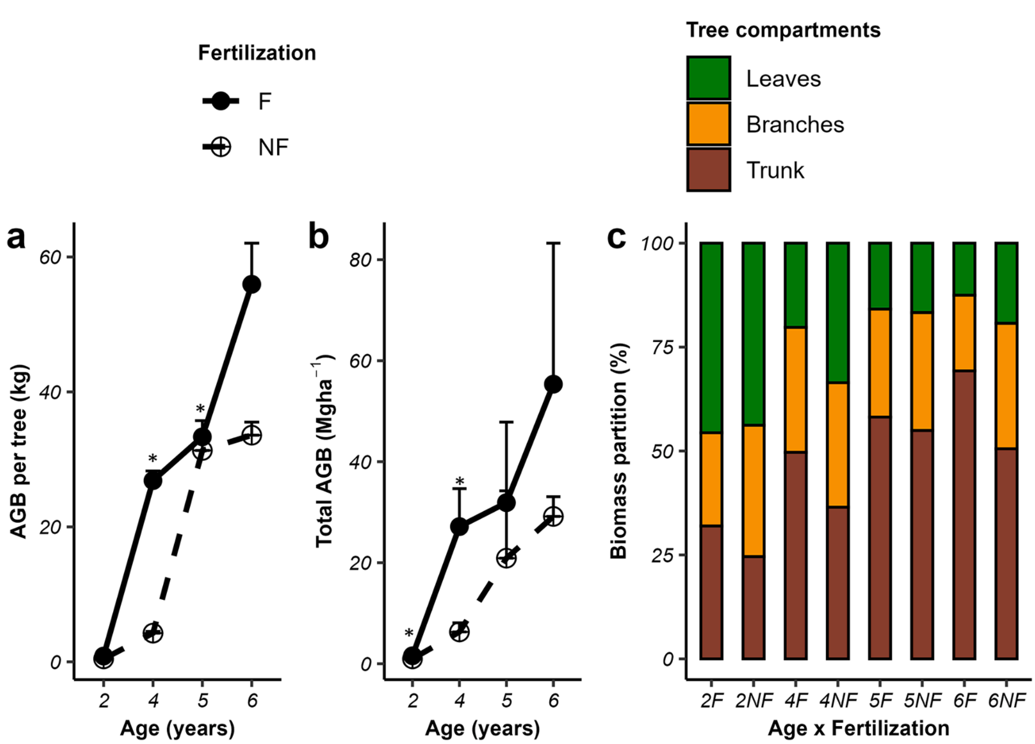

Fig. 3. Effect of low quantity of fertilization along the stands in smallholder EP on AGB per tree (a) and Total AGB per ha (b Standard errors (SE) are indicated according to the number of trees for each treatment in (a), and according to the number of plot replications for each treatment in (b), as shown in Table 1. Variation of biomass partition in each tree compartment for each treatment (Age × Fertilization) (c).

33.60 kg for NF). The difference was less marked at 2 yo (0.86 kg for F and 0.44 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 1.3 Mg.ha^{-1} to 42.3 Mg.ha^{-1} between 2 and 6 yo, respectively. Fertilization increased total AGB for all ages considered (26.6 Mg.ha^{-1} for F plots compared to 13.0 Mg.ha^{-1} for NF plots). The interaction between age and fertilization was not significant due the high AGB variability (Fig. 3b). 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} in non-fertilized plots.

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 type and by the interaction of age and compartment (p-value < 0.001). When analyzed per compartment, we reported significant effects of the plantation age (p-values < 0.001) (Fig. 3c). Fertilization did not significantly influence the biomass partition except for branches biomass (p-value < 0.001). Non-fertilized trees (29 %) had significantly higher percentage of branches than fertilized trees (24 %). Except for the biomass of trunk (p-value < 0.1), the biomass of branches (p-value < 0.001), and leaves (p-value < 0.05) were significantly influenced by the interaction of age and fertilization. At 6 yo, the percentage of branches biomass was significantly higher between fertilized (18 %) and non-fertilized (30 %) trees. At 2 yo, the trend was opposed to 6 yo, with 22 % of branches in fertilized trees and 32 % in non-fertilized trees. The interaction of age and fertilization did not affect significantly the leaves biomass partition, except at 4 yo where non-fertilized trees had 33 % of leaves biomass and 20 % for fertilized trees.

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 0.36 to 3.12 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 1.31 for non-fertilized trees for all plantation ages taken into account.

3.5. Weed cover and biomass

Weed cover (%) was influenced by age but not by fertilization. Regardless of the fertilization, the mean value of weed cover 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 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 likely negative linear relationship between total AGB and weed cover and the model explained 91 % of the variability of the total AGB (Fig. 4a). Similarly, a negative linear relationship was found between total AGB and weed biomass with $R^2 = 0.74$ (Fig. 4b).

Survival rates also showed negative linear relationships with weed cover as well as with weed biomass (Fig. 4c and d, respectively).

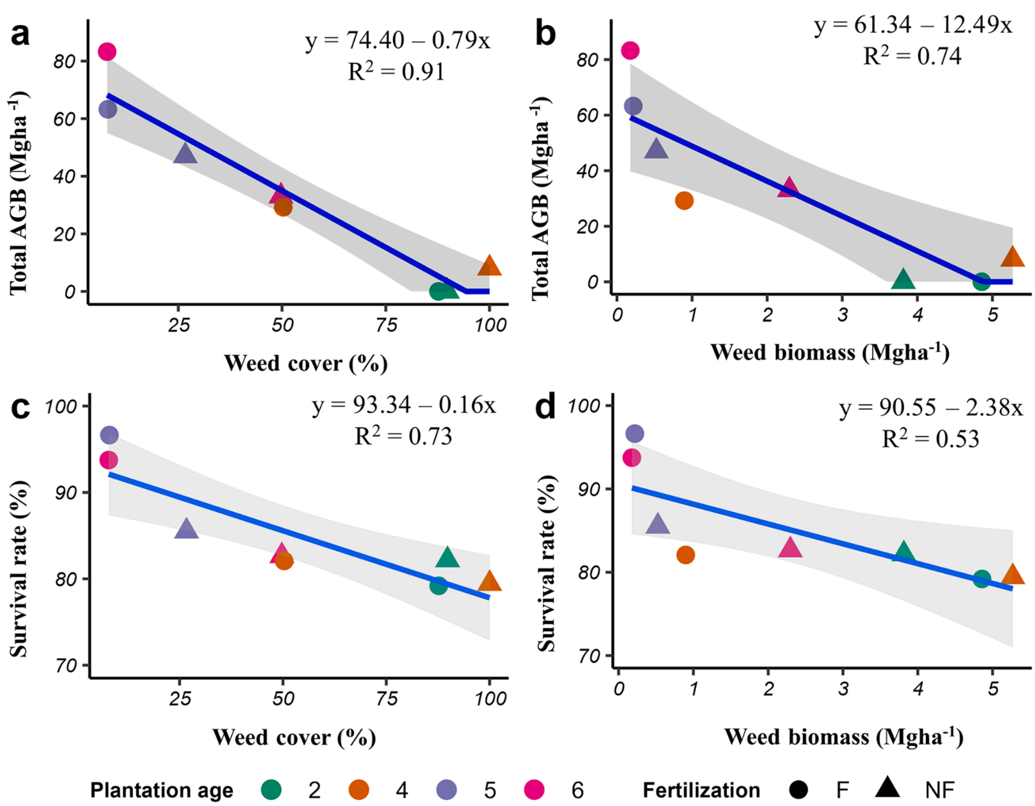

Fig. 4. Linear regression of the Total AGB (Mg ha^{-1}) and Weed cover (%) (a), the total AGB (Mg ha^{-1}) and weed biomass (Mg ha^{-1}) (b), the survival rate (%) and weed cover (%) (c), the survival rate and weed biomass (Mg ha^{-1}) (d), identifying plantation age and fertilization. $n = 8$.

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 compartment (stem and bark) while the diameter alone is the best predictor for branch and leaf compartments. The pipe model theory proposed by Shinozaki et al. (1964) and tested by further 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 (Huang et al., 2023; Mäkelä, 1986). Our findings met this theory, as 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 (Bastien-Henri et al., 2010; Chave et al., 2005).

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).

Furthermore, while these equations were calibrated in Madagascar, they remain scarce for *Eucalyptus* grown under smallholder conditions. This highlights the originality and broader relevance of this study for smallholder plantations, considered as a core landscape restoration pathway (Kimambo et al., 2020).

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

Our data clearly showed good growth of *E. 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., 1300 mm of annual rainfall, 19 °C of mean annual temperature, 3 *m* × 3 m 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 120 g 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 intensively managed 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 Cir of 42 cm which are 2,2 and 1.4 times more than the values in our study (Yang et al., 2023). In Brazil, *E. 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 found in our plantations. Differences in tree growth observed within commercial plantations can be explained by the differences in ecological conditions, silvicultural practices and plant material (Binkley et al., 2017; Bouillet et al., 2013). 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.

Table 3
Eucalyptus growth in this study and in commercial plantations in various sites. Climatic conditions and species are displayed with H (Height), Cir (Circumference), 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
Present study	Madagascar	1230 mm 20 °C	*E. robusta* (non-improved seeds)	• H: 1.8 m (2 yo); 1.2 m (6 yo) (fertilized trees) • Cir: 9 cm (2 yo); 38 cm (6 yo) (fertilized trees) • AGB: 1.6 Mg. ha^{-1} (2 yo); 55.3 Mg.ha^{-1} (6 yo) (fertilized trees)
Laclau et al. (2000)	Congo	1200 mm 25 °C	Hybrid *E.PF1* (one of the most productive clones)	• H: 11 m (2.1 yo); 22.7 m (5.2 yo) • Cir: 31.9 cm (2.1 yo); 48.7 cm (5.2 yo) • AGB: 20 Mg.ha^{-1} (2.1 yo); 62 Mg. ha^{-1} (5.2 yo)
Yang et al. (2023)	Guangzhou, Southern China	1922 mm 22 °C	*E.urophylla* × *E.grandis* clones	• H: 17 m (4.5 yo) • Cir: 42 cm (4.5 yo)
Eufrade et al. (2016)	Botocatu city, São Paulo, Brazil	1428 mm 20 °C	*E.urophylla* × *E.grandis* clones	• H: 9.5 m (2 yo) • DBH: 7 cm (2 yo)
Bouillet et al. (2013)	Itatinga station, São Paulo, Brazil	1390 mm 19 °C	*E. grandis*	• H: 24 m (6 yo) • Cir: 42 cm (6 yo) • Stemwood production of 20.5 Mg.$ha^{-1}$$year^{-1}$

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 1.6 Mg.ha^{-1} and 55.3 Mg.ha^{-1} at 2 and 6 yo, respectively (Table 3). 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, 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 trunk 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 than lower fertility (Epron et al., 2013). The growth of the living biomass predominated in commercial plantations up to 2–3 yo. The maximal mean annual wood production and optimal logging age is around 7 yo, with optimal stand production when the *ad hoc* amount of fertilizer is applied at planting (Laclau et al., 2000).

By using default trees carbon fraction (0.50) (IPCC, 2006), fertilized smallholder plantations stocked 27.6 MgC.ha^{-1} in aboveground compartments after 6 years of plantation which is equivalent to 4.6 MgC. ha^{-1}yr^{-1}.

The mean LAI in our study tended 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* plantations 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 (Laclau et al., 2008b; Oliveira et al., 2024; Smethurst et al., 2003).

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).

4.3. Weeding is key to smallholder Eucalyptus plantations success

Our assessment of weed cover and biomass is subject to methodological limitations, as measurements were conducted within each treatment of a single plot, despite the presence of pseudo-replicates within each plot. Although differences were not tested, high trends were observed. Except at planting, weed control was not carried out in our study as in most smallholder plantations (Alemayehu and Melka, 2022; Bekele, 2013). Survival rates and total AGB are very likely to be negatively correlated 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 compared to unweeded control plot (Vargas et al., 2018). Competition for light and water between weeds and trees could partly explain this finding with the high amount weed biomass reducing greatly light availability for the young trees and likely intensified water stress during the dry season (Vargas et al., 2018; Whitehead and Beadle, 2004). Likewise, various studies showed significant effect of weed control on tree growth and *Eucalyptus* stand production (Carrero et al., 2018; Corticeiro et al., 2023; Inail et al., 2021; Vargas et al., 2018). In Portugal in *E. globulus* 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, diameter, and volume of *E. pellita* with early weed control up to 1 year, until canopy closure. In Venezuela, Carrero et.al (2018) showed that weed control led to an average gain of 1.7 Mg ha^{-1} yr^{-1} in stem biomass of *E. spp*. in 2 to 6 yo trees.

4.4. Importance of starter fertilization

We showed the importance to apply fertilization at planting in smallholder *Eucalyptus* plantations. Such starter fertilization enhanced aboveground tree 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 (Bordron et al., 2019; Laclau et al., 2008a). 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., 2023).

Planted forests in MCH are established on low-fertility soils (Verhaegen et al., 2011). The dominant Ferralsols exhibit severe edaphic limitations, characterized by low nutrient status, high phosphorus sorption resulting in poor phosphorus availability (Andriamananjara et al., 2019), low organic matter and carbon content, and reduced biological activity (Raminoarison et al., 2024; Razafimbelo et al., 2022). Total nitrogen and potassium levels are particularly deficient, especially on slopes (Rasoarinaivo et al., 2025). 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., 2022, 2017; 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. At 6 yo, fertilized plots produced AGB of 55.3 Mg ha^{-1} (49.4 Mg ha^{-1} in trunk and branch biomass) vs 29.2 Mg ha^{-1} for non-fertilized plot (23.8 Mg ha^{-1} in trunk and branch biomass). Using the mean basic wood density of 0.5 g cm^{-3} for *E. robusta*, as reported by Ramilison et.al. (2024) in a neighboring area, this trunk and branch biomass corresponds to 98.9 and 47.5 m^3 ha^{-1} of merchantable wood volume for fertilized and non-fertilized plots, respectively. At the prevailing market value of 100,000 MGA m^{-3}, the wood volume translates into a gross revenue of about 9886,000 MGA ha^{-1} for fertilized plots vs 4752,000 MGA ha^{-1} for non-fertilized plots. After accounting for fertilizer costs of 638,400 MGA ha^{-1} (based on an average price of 4800 MGA kg^{-1} of NPK from the national distributor), the net revenue of fertilized plot is about 9247,600 MGA ha^{-1} with a net economic benefit of applying low-dose starter fertilization of around 4500,000 MGA ha^{-1} over six years. This amount corresponds to more than 18 times the statutory minimum monthly agricultural wage in Madagascar (242,000 MGA month^{-1}; Decree n° 2023–563). 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 soil fertility and production of following stand rotations of smallholder plantations.

5. Conclusion

Accurate biomass estimates are of great importance to estimate trees and stand production and carbon stocks. The allometric equations established here could be used by researchers and managers of smallholder *Eucalyptus* plantations. As the use of Cir and H is required to get the best estimates of total AGB, it is then 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, that was found to be a strong indicator of AGB explained more than 90 % of the total variation of biomass of each tree compartment. For more practical purposes, the only Cir can be sufficient to estimate AGB production. Remote sensing techniques can also provide a solution to the complexity of data collection and to monitoring tree growth (Guimarães et al., 2020; Leite et al., 2020). Thus, a study of photogrammetric processing for planted forests in the MCH is currently ongoing.

Weeding is critical for *Eucalyptus* stand production. Weed control must be carried out, at least until 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. Given the primordial role of smallholder plantations in providing household energy in Madagascar and across sub-Saharan African countries, support mechanisms to help smallholders purchase fertilizers need to be put in place, as is already the case for some reforestation projects in Madagascar.

CRediT authorship contribution statement

Iaviantsoa Ramanandraibe: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bruno Bordron:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Funding acquisition, Conceptualization. **Fenitra Razafindrakoto:** Methodology, Investigation, Formal analysis, Data curation. **Julien Sarron:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Daniel Epron:** Writing – review & editing, Validation. **Angelina Rasoarinaivo:** Writing – review & editing. **Tantely Maminiaina Razafimbelo:** Supervision, Methodology, Funding acquisition, Conceptualization. **Jean-Pierre Bouillet:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

We certify, on behalf of all the authors, that:

- The work as submitted has not been published or accepted for publication, nor is being considered for publication elsewhere, either in whole or substantial part.

- The work is original and all necessary acknowledgements have been made

- All authors and relevant institutions have read the submitted version of the manuscript and approve its submission.

- All persons entitled to authorship have been so included.

The work conforms to the legal requirements of Madagascar, and to accepted international ethical standards.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2025.101006.

Data availability

Data will be made available on request.

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