

Growth, Biomass and Carbon Stocks in Forest Cover Planted in an Area of Bauxite Mining in Rehabilitation

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ABSTRACT: Forest cover in areas degraded by mining is an alternative way of mitigating CO₂ concentrations in the atmosphere by fixing C in tree biomass. This study evaluated the growth and C stocks of forest cover in an area of bauxite mining with four sources of fertilizer. Height (Ht), diameter at ground level (DGL), and diameter at breast height (DBH) were determined in *Anadenanthera peregrina* (Ap), clonal *Eucalyptus* (Euc), and a mixed plantation of 16 native forest species (Nat) at 6, 18, 36, and 56 months of age. Trunk+bark volume, biomass, and C stock were also determined for these forest covers at 56 months of age. The fertilization treatments were a standard (SF) adopted by the company, SF plus organic fertilizer (OF), chemical fertilizer (CF), and OF+CF. Euc displayed greater values of Ht, DGL, and DBH under OF+CF and OF. Fertilization did not influence the Ht and DBH of Ap, but DGL was higher under OF+CF at 36 months compared to SF. The Ht values of Nat were influenced by fertilization at 18 months, with the lowest values under SF. The fertilization influenced the DGL of Nat at 36 and 56 months, which did not occur with DBH. The pioneer species had higher Ht, DGL, and DGB compared to non-pioneer species, regardless of the type of fertilization studied. Fertilization influenced the Ht and DGL of pioneer species at 18 and 36 months of age and only the Ht of non-pioneer species. The estimates of Euc biomass (255 Mg ha⁻¹) and C stocks (120 Mg ha⁻¹) under OF+OC were four times greater than in Ap and Nat, which showed no difference between themselves or the types of fertilization. The growth and estimates of volume, biomass, and C stocks of the forest cover were comparable to those of unmined areas. Euc had the greatest growth, biomass, and C stocks.

Keywords: Brazilian Atlantic Forest, C sequestration, land reclamation, topsoil revegetation, tree biomass.

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INTRODUCTION

The increased release of CO₂ into the atmosphere through human activity, such as the burning of fossil fuels and changes in land use, has caused major disruptions in the global carbon cycle and it is considered to be one of the causes of possible climate changes. The forest sector is one of the viable alternatives for mitigating the increase in CO₂ concentrations through the fixation of carbon by trees (Melo and Durigan 2006; Locatelli et al., 2015; Widhanarto et al., 2016; Favero et al., 2017).

Forest species have the ability to fix C for long periods and store it in the form of wood (Litton et al., 2007). Its residence time in the ecosystem depends on the age of the plant, the component where the C is allocated, and the intended use of the wood (Diaz-Balteiro and Rodriguez, 2006). Tropical forests have great potential for mitigating CO₂ emissions through the conservation, management, and rehabilitation of degraded environments (Houghton et al., 2015).

Forest rehabilitation coupled with intensive management can be an important tool for storing atmospheric C in degraded tropical environments (Schulze et al., 2000; Campoe et al., 2014; Ferez et al., 2015; Brancalion et al., 2019). Estimating C accumulation over time is a good way to evaluate the success of rehabilitation programs and to indicate the best practices for forest management and conservation (Shimamoto et al., 2014). However, traditional silvicultural techniques applied to plantations of forest restoration in Brazil are limited to low levels of nutrient application and limited control of invasive plants (Souza and Batista, 2004), reducing the success of rehabilitation programs in degraded areas.

The choice of the species to be planted is also very important for the success of the rehabilitation program. The use of tree legumes with the ability to fix N₂ from the atmosphere through symbiosis with N₂-fixing bacteria leads to the belief that these trees can be used to revegetate highly degraded soils and accelerate the rehabilitation process (Chaer et al., 2011). In highly altered soils, such as those occurring in mining areas and where the organic matter content tends to be very low, the introduction of tree species, especially N₂-fixing legumes, tends to significantly increase the levels of C in the soil (Christopher and Lal, 2007).

There are few studies of restoration plantations that include biomass and C modelling, leaving an information gap about the CO₂ sink potential of these forests (Miranda et al., 2011). Therefore, estimating biomass in aerial parts of trees remains an important source of uncertainty of the C balance in tropical regions, partly due to the lack of estimates of aerial biomass and variations between landscapes and types of forest (Houghton et al., 2009).

Soils on Fe and Al ore deposits are naturally highly weathered and the ore extraction activity is expected to cause even more drastic changes in their properties. These conditions lead to the need for strategies that favor their rehabilitation, such as fertilization and planting of forest species, which allow the restoration of the ecological function of the degraded landscape and greater C sequestration. Thus, the aim of this study was to evaluate the growth of three types of forest cover, planted in a bauxite mining area, amended with four sources of fertilizer, and to estimate the biomass and C stocks of tree trunks along 56 months.

MATERIALS AND METHODS

Characterization of the study area and experimental design

The study was carried out on a rural property located in São Sebastião da Vargem Alegre, Minas Gerais, Brazil (21° 1' 58" S and 42° 35' 8" W), at an altitude of 780 m a.s.l., in an

area of bauxite extraction by Companhia Brasileira de Alumínio - Votorantim Metais. The predominant climate is Cwa (Köppen Classification System), with hot and rainy summers and a well-defined dry season. The average annual precipitation and temperature are 1,287 mm and 20.3 °C, respectively (Inmet, 2016). The soils were classified as *Latossolo Vermelho Amarelo distrófico típico* (Santos et al., 2013), which corresponds to an Oxisol (Soil Survey Staff, 2014). After mining, the surface layer (0.00-0.20 m) of the soil (stored \cong one year) was returned to the area during topographic reconfiguration, followed by decompaction with a subsoiler at a depth of 0.60 m.

The experiment was installed in March 2011 using a randomized block design with split plots and three replicates. The plots (40 × 18 m) comprised the following forest cover: *Anadenanthera peregrina* (L.) Speg (Ap); clonal *Eucalyptus* (a hybrid from a cross between *Eucalyptus urophylla* and *Eucalyptus grandis* - clone AEC144[®]) (Euc) and a mixed plantation (Nat) consisting of 16 native forest species from the region, *A. peregrina* - Ap, *Ficus insipida* Willd - Fi, *Inga edulis* Mart. - Ie, *Piptadenia gonoacantha* (Mart.) JF Macbr. - Pg, *Enterolobium contortisiliquum* (Vell.) Morong.- Ec, *Ceiba speciosa* (A. St.-Hil.) Ravenna Cs, *Sapindus saponaria* L. - Ss, and *Pera glabrata* (Schott) Poepp. Ex Baill.- Pgl; forest species considered as pioneers, and the non-pioneer species *Trichilia* sp - Tsp, *Cupania oblongifolia* Mart. - Co, *Apuleia leiocarpa* (Vogel) JF Macbr. - Al, *Handroanthus chrysotrichus* (Mart. Ex A. DC.) Mattos - Hc, *Hymenaea courbaril* var. *stilbocarpa* (Hayne) YT Lee and Langenh - Hcs, *Lecythis* sp - Ls, *Paubrasilia echinata* Lam. - Pe, and *Annona squamosa* L.) - As. These native species were planted in Quincunx (4 pioneers, with one climax in the center) at a spacing of 2.0 × 1.5 m, using seedlings produced from seeds collected in fragments of Atlantic Forest (Woodland). For Euc and Ap, the adopted spacing was 3 × 2 m.

The subplots (10 × 18 m) included the standard fertilization used by the company (SF) in their rehabilitation activities of mined areas, with the propositions under study, which considered the SF and organic fertilization (OF), chemical fertilization (CF), and a combination of OF+CF. Six months before planting the trees, SF composed of 2.0 t ha⁻¹ dolomitic limestone and 30.0 t ha⁻¹ poultry litter (fresh, with an average of 30 % moisture) was applied over the whole area; the OF was composed of SF and 30 t ha⁻¹ poultry litter, and the CF included the application of a further 3 t ha⁻¹ dolomitic limestone and 0.75 t ha⁻¹ Bayovar natural reactive phosphate for Euc and Ap, and 1.5 t ha⁻¹ for Nat. The application of OF+CF was a combination of the two supplementary applications (OF and CF). Part of the dose of poultry litter and limestone was applied to the planting hole and part between the rows, in this case, incorporated into the 0.00-0.15 m layer 30 days before planting, so that all plants received the same dose of fertilizer. The treatments with Euc and Ap received 22 % of the dose of poultry litter in the planting hole and 78 % between the rows, while the treatment with Nat received 44 % in the planting hole and 56 % between the rows. Similarly, the application of the limestone was carried out so that 25 % of the total dose was applied to the holes and 75 % between the rows for Euc and Ap; for Nat, 50 % was applied to the planting hole and the remainder (50 %) between the rows. The reactive natural phosphate was applied to the bottom of the planting holes.

In addition to the fertilization carried out at planting, the areas also received two doses of top-dressing, the first, one month after setting up the experiment, consisting of 10 kg ha⁻¹ of N, 22 kg ha⁻¹ of P, and 8 kg ha⁻¹ of K when planting the Euc and Ap, and 20 kg ha⁻¹ of N, 44 kg ha⁻¹ of P, and 16 kg ha⁻¹ of K when planting the multiple native species, enriched with micronutrients (1.7 kg ha⁻¹ of B, 0.8 kg ha⁻¹ of Zn, 0.8 kg ha⁻¹ of Cu) for the Euc and Ap, and double this dose for the native species, placed (in shallow holes) 0.20 m to the side of the plants. The second fertilization was carried out 10 months after starting the treatments, applying 67 kg ha⁻¹ of N, 17 kg ha⁻¹ of P, and 67 kg ha⁻¹ of K to the Euc and Ap, and 134 kg ha⁻¹ of N, 34 kg ha⁻¹ of P, and 134 kg ha⁻¹ of K to the Nat, in 0.05-m-deep grooves, in the upper part of the canopy projection area.

It should be noted that only treatments with CF and OF+CF received the top-dressing, since this was carried out using chemical fertilizer only.

Tree growth in height and diameter and allometric equations

Total tree height (Ht) and circumference at ground level (CGL) and/or at breast height, 1.3 m from the ground (CBH), were measured at 6, 18, 36, and 56 months for each tree in the experiment. To determine the height, a graduated pole was used in Nat and Ap, and a hypsometer (Forest Vertex IV) in Euc. For CGL and CBH, a metric tape was used, with the data subsequently converted into diameter at ground level (DGL) and diameter at breast height (DBH).

Three trees of each species were selected for rigorous cubing (non-destructive method) at 56 months of age after separation into diametric class at a range of 2 cm. To do this, the trunk circumference was measured with a tape in height intervals of 0, 0.30, 0.70, 1.00, 1.30, and 2.30 m. Starting at a height of 2.30 m, measurements were taken at 1-meter intervals using a Wheeler Pentaprism (Wheeler, 1962), which allows diametrical values to be obtained at different trunk heights up to the diameter limit of the device, which is 6.5 cm. The volume of each section was obtained by the successive application of Smalian's formula: $V = [(AS_1 + AS_2)/2] \times L$, in which: V is the section volume with bark (m^3), AS_1 and AS_2 are the sectional areas obtained at the ends of each section (m^2), and L is the length of the section (m). In the case of diameters smaller than 6.5 cm, the rest of the tree was considered as a cone. Dendrometry data allowed the allometric equations to be adjusted based on the Schumacher and Hall (1933) and Spurr (1952) models for each species planted. The best model was chosen based on parameter consistency, coefficient of determination (R^2) and residual standard error (S_{yx}).

Estimates of the biomass of the evaluated trees (B) were obtained by multiplying the volume of each tree (trunk+bark) (V) by the wood basic density, individually for each species (Zanne *et al.*, 2009). Carbon stocks in the tree biomass were estimated considering the volume of each species multiplied by the conversion factor 0.47, that is, it was considered that 47 % of the biomass is composed of C, according to IPCC (2006).

The results of height (Ht), diameter at ground level (DGL), diameter at breast height (DBH), volume, biomass, and C stock were subjected to analysis of variance (ANOVA) in a split-plot scheme, in which the forest covers composed the treatments in the plots and the types of fertilization represented the subplots, in a randomized block design with three replicates. Regardless of the significance of the ANOVA F-test, the interaction between forest cover and types of fertilization was further analyzed in order to evaluate the effect of the types of fertilization within each forest cover and the effect of the forest cover within each type of fertilization, both by Tukey test at $p < 0.10$. In this case, the mean square and the respective number of residual degrees of freedom, according to Satterthwaite, were used in combination. The species were compared by the results of increments in height (Ht) and diameter at ground level (DGL), using the means and the respective standard errors of the mean.

All analyses were performed using the Statistica 7.0 and R (R Core Team, 2013) statistical software.

RESULTS

Plantation growth

The *Anadenanthera peregrina* (Ap) trees showed no difference for Ht when submitted to the different fertilizers at the four ages under study ($p > 0.10$) (Figure 1a). However, differences were seen in DGL at 36 months, when the trees submitted to OF+CF (8.34 cm)

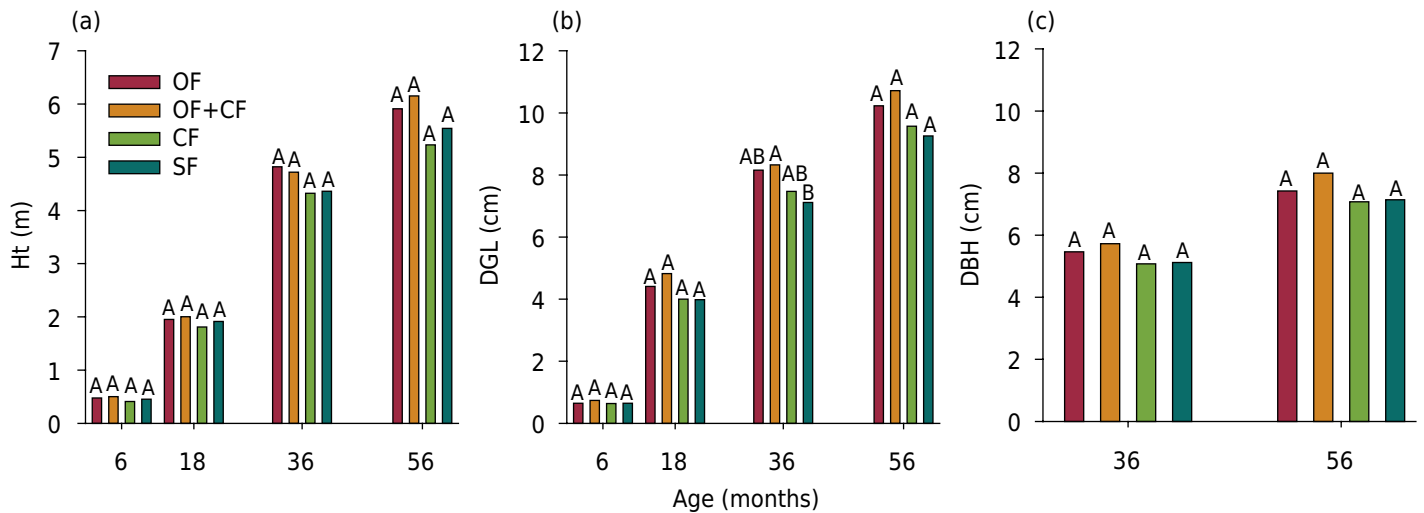


Figure 1. Growth in height, Ht (a); trunk diameter at ground level (DGL; b), trunk diameter at breast height (DBH; c) in *A. peregrine* at 6, 18, 36, and 56 months of age, submitted to organic (OF), combined organic and chemical (OF+CF), chemical (CF), and standard (SF) fertilizers, planted in an area of bauxite mining. Uppercase letters compare fertilization treatments within the same age and, when equal, indicate no differences between them by the Tukey's test at 10 % probability level.

showed higher values than trees under SF (7.13 cm) ($p < 0.10$) (Figure 1b). The growth of Ap trees in diameter at breast height (DBH, cm) was not influenced by fertilization treatments at 36 and 56 months of age (Figure 1c).

The smallest increment of Ht in Ap occurred from 36 to 56 months of age in all fertilization treatments studied (SF: $1.18 \text{ m} \pm 0.29$; OF: $1.09 \text{ m} \pm 0.31$; OF+CF: $1.44 \text{ m} \pm 0.64$; CF: $0.91 \text{ m} \pm 0.19$). In SF, the greatest increment was observed from 18 to 36 months of age ($2.45 \text{ m} \pm 0.24$) compared to those from 6 to 18 months ($1.46 \text{ m} \pm 0.10$) and from 36 to 56 months ($1.18 \text{ m} \pm 0.29$). For the other fertilization treatments, no difference was observed between the increments of height for 6 to 18 and 18 to 36 months. For DGL, the largest increase was seen from 6 to 18 (SF: $3.34 \text{ cm} \pm 0.23$; OF: $3.76 \text{ cm} \pm 0.46$; OF+CF: $4.08 \text{ cm} \pm 0.15$; CF: $3.36 \text{ cm} \pm 0.20$), and from 36 to 56 months (SF: $3.13 \text{ cm} \pm 0.03$; OF: $3.74 \text{ cm} \pm 0.38$; OF+CF: $3.51 \text{ cm} \pm 0.22$; CF: $3.47 \text{ cm} \pm 0.27$), regardless of the applied fertilization, representing on average 36 and 35 % compared to the total growth, respectively.

At an age of six months, the Euc submitted to OF and OF+CF showed greater Ht ($p < 0.10$) (1.96 and 1.94, respectively) compared to the trees under SF (1.24 m) and CF (1.51 m). At 18 months of age, the trees submitted to fertilization with OF+CF (9.86 m) had the largest growth in Ht (m) ($p < 0.10$) compared to SF (9.39 m). After 36 months of planting, Euc trees submitted to OF+CF (19.80 m) and OF (19.49 m) had higher Ht than those under SF (18.63 m) ($p < 0.10$). At 56 months, only OF+CF (22.74 m) led to higher Ht ($p < 0.10$) than SF (21.33 m).

The diameter at ground level (DGL) was influenced for each age under study (Figure 2b). At an age of six months, the trees submitted to OF (3.51 cm) and OF+CF (3.45 cm) were similar ($p > 0.10$) and differed from those under SF (2.58 cm) and CF (2.92 cm) ($p < 0.10$). At 18 and 36 months, the DGL of plants submitted to OF+CF (12.03 cm and 17.38 respectively) and to OF (11.56 cm and 16.85 cm, respectively) were similar ($p > 0.10$). However, only the DGL of trees under OF+CF was greater ($p < 0.10$) than those of the trees under SF (10.64 and 15.87 cm, respectively) and CF (10.88 cm and 15.85, respectively). At 56 months, the trees under OF (20.32 cm) and OF+CF (20.71 cm) were larger ($p < 0.10$) than those under SF (18.80 cm) and CF (18.80 cm). The DBH (cm) (Figure 2c) was influenced by the fertilization treatments only at 36 months of age ($p < 0.10$), when the value found under OF+CF (14.64 cm) was higher than those under SF (13.37 cm) and CF (13.24 cm)

The greatest increment of Ht for Euc was observed from 18 to 36 months in all fertilization treatments studied (SF: 9.24 m ± 0.50; OF: 9.70 m ± 0.77; OF+CF: 9.94 m ± 0.33; CF: 9.19 m ± 0.39), while the smallest increment was found from 36 to 56 months of age (SF: 2.70 m ± 0.58; OF: 2.88 m ± 0.49; OF+CF: 2.95 m ± 0.15; CF: 2.83 m ± 0.21), representing on average 43 and 13 % in comparison to the total growth, respectively. For the growth in DGL, the greatest increment (42 %) occurred from 6 to 18 months (SF: 8.05 cm ± 0.07; OF: 8.05 cm ± 0.38; OF+CF: 8.58 cm ± 0.67; CF: 7.95 cm ± 0.67), whereas the smallest increment (16 %) occurred from 36 to 56 months (SF: 2.93 cm ± 0.23; OF: 3.47 cm ± 0.52; OF+CF: 3.33 cm ± 0.23; CF: 3.96 cm ± 0.29), regardless of the fertilization treatments studied.

No effects were seen from the different fertilizers on growth in Ht in Nat at 6, 36, and 56 months of age (Figure 3a). However, at 18 months, trees submitted to SF (1.77 m) had the lowest values ($p < 0.10$) of Ht compared to the other fertilization treatments.

The DGL of Nat was influenced by the fertilizer at 36 and 56 months (Figure 3b). At 36 months, trees submitted to SF (8.00 cm) had lower values of DGL (cm) ($p < 0.10$) compared to the other fertilization treatments. At 56 months, trees submitted to CF (11.61 cm) had higher DGL ($p < 0.10$) than those under SF (9.88 cm). The other treatments did not differ from one another ($p > 0.10$). The DBH (cm) was not influenced by the fertilizer for any the ages under study (Figure 3c).

The largest increase in Ht occurred between 18 and 36 months (SF: 2.26 m ± 0.10; OF: 2.37 m ± 0.13; OF+CF: 2.29 m ± 0.21; CF: 2.51 m ± 0.02), with an average of 45 % in comparison to the total. The same behavior was also observed for DGL, with the largest increments in DGL obtained from 18 to 36 months of age (SF: 3.73 m ± 0.42; OF: 4.35 m ± 0.14; OF+CF: 4.65 m ± 0.36; CF: 4.83 m ± 0.36), representing, on average, 40 % of the total.

The group of pioneer species stood out for Ht, differing from the non-pioneer group at all ages (Figures 4a and 4b). The fertilizer influenced Ht in the pioneer species at 18 and 36 months of age. At 18 months the trees submitted to SF (2.22 m) had the lowest values ($p < 0.10$) in comparison to the trees under OF+CF (2.67 m), OF (2.71 m), and CF (2.76 m). At 36 months of age, the only difference observed for Ht occurred between CF (5.88 m) and SF (5.09 m). The same behavior was observed for the non-pioneer species. The Ht was influenced by the fertilizer at 18 and 36 months. At 18 months, trees submitted to

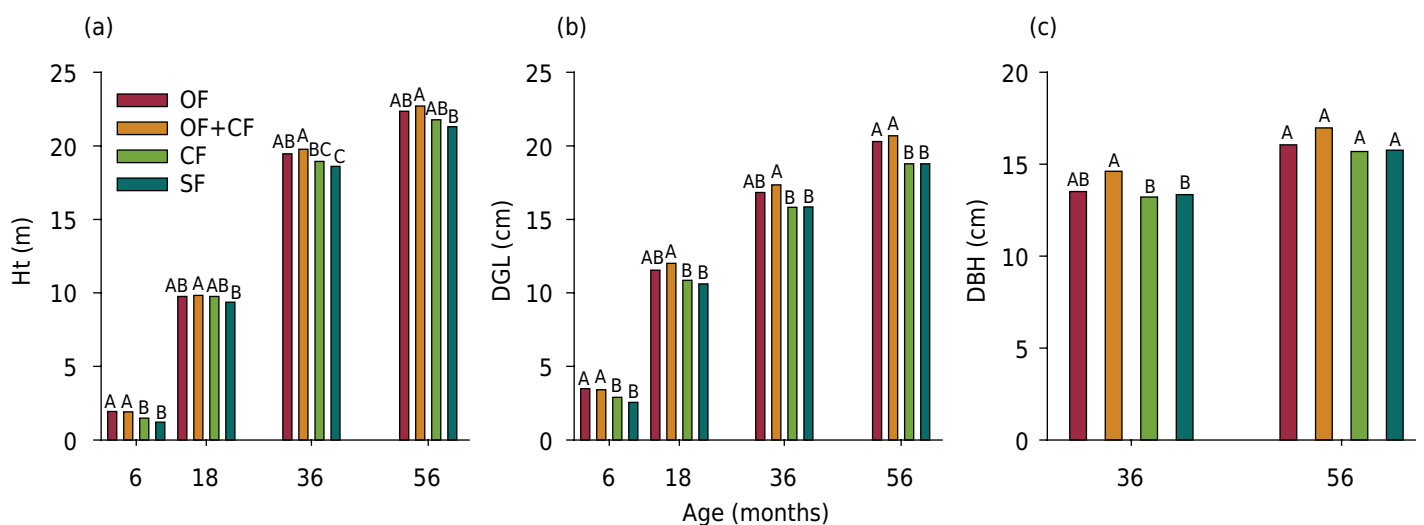


Figure 2. Total growth in height (Ht; a); diameter at ground level (DGL; b); trunk diameter at breast height (DBH; c) in *Eucalyptus* (Euc) from planting to 6, 18, 36, and 56 months of age, submitted to organic (OF), combined organic and chemical (OF+CF), chemical (CF), and standard (SF) fertilizers, planted in an area of bauxite mining. Uppercase letters compare fertilization treatments within the same age and, when equal, indicate no differences between them by the Tukey's test at 10 % probability level.

OF (1.90 m) and OF+CF (1.84 m) grew more in Ht than those under SF (1.34 m) and, at 36 months, the difference occurred between CF (3.76 m) and SF (3.00 m) ($p < 0.10$).

As observed for the growth in Ht, the pioneer group also displayed the highest values of DGL for each fertilizer under study compared to the non-pioneer group (Figures 4c and 4d). In the pioneer group, the fertilization treatments influenced DGL at 36 and 56 months of age, when the trees submitted to SF (11.29 cm and 13.69 cm, respectively) displayed lower values ($p < 0.10$) of DGL compared to the trees under CF (13.93 and 16.74 cm, respectively). For non-pioneer species, there were no effects of the different fertilization treatments on DGL for the 4 ages studied. The DBH was not influenced by the fertilization treatments at 36 and 56 months of age for both groups (Figures 4e and 4f).

The greatest increment in Ht for non-pioneer species was observed from 18 to 36 months, in all fertilization treatments studied (SF: $1.65 \text{ m} \pm 0.12$; OF: $1.86 \text{ m} \pm 0.22$; OF+CF: $1.82 \text{ m} \pm 0.13$; CF: $1.94 \text{ m} \pm 0.06$). The same result occurred for the pioneer species (SF: $2.88 \text{ m} \pm 0.11$; OF: $3.08 \text{ m} \pm 0.09$; OF+CF: $2.67 \text{ m} \pm 0.29$; CF: $3.12 \text{ m} \pm 0.08$).

In relation to DGL, there was no difference in the increment from 6 to 18 and from 18 to 36 months in the treatments OF ($2.38 \text{ cm} \pm 0.16$ and $2.72 \text{ cm} \pm 0.24$, respectively) and OF+CF ($2.65 \text{ cm} \pm 0.32$ and $2.43 \text{ cm} \pm 0.47$, respectively) and SF (1.89 cm and 1.88 ± 0.23 , respectively) for non-pioneer species. In the treatment CF, the greatest increment in DGL was observed from 18 to 36 months ($2.48 \text{ cm} \pm 0.15$). For the pioneer species, the period from 18 to 36 months had the greatest increment of DGL, regardless of the fertilization treatments, representing on average 47 % of the total.

Estimating volume, biomass, and carbon stocks

The allometric equations obtained by rigorous tree cubing at 56 months of age allowed V to be estimated for each species planted in the experimental area. The values for R^2 were greater than 90 % for most of the species (Table 1).

Among the types of cover planted after bauxite mining, Euc displayed the largest values of V, while there were no differences between Ap and Nat (Figure 5a). For the fertilizers under study, OF+CF ($499.3 \text{ m}^3 \text{ ha}^{-1}$) gave the highest V for Euc, showing no difference from the fertilization with poultry litter (OF) (447.4 m^3), which was statistically similar to SF (402.5 m^3) and CF (419.6 m^3). For Nat and Ap, the fertilizer did not influence V. The estimate for B in Euc (Figure 5b), at 56 months of age, was 250 Mg ha^{-1} under OF+CF.

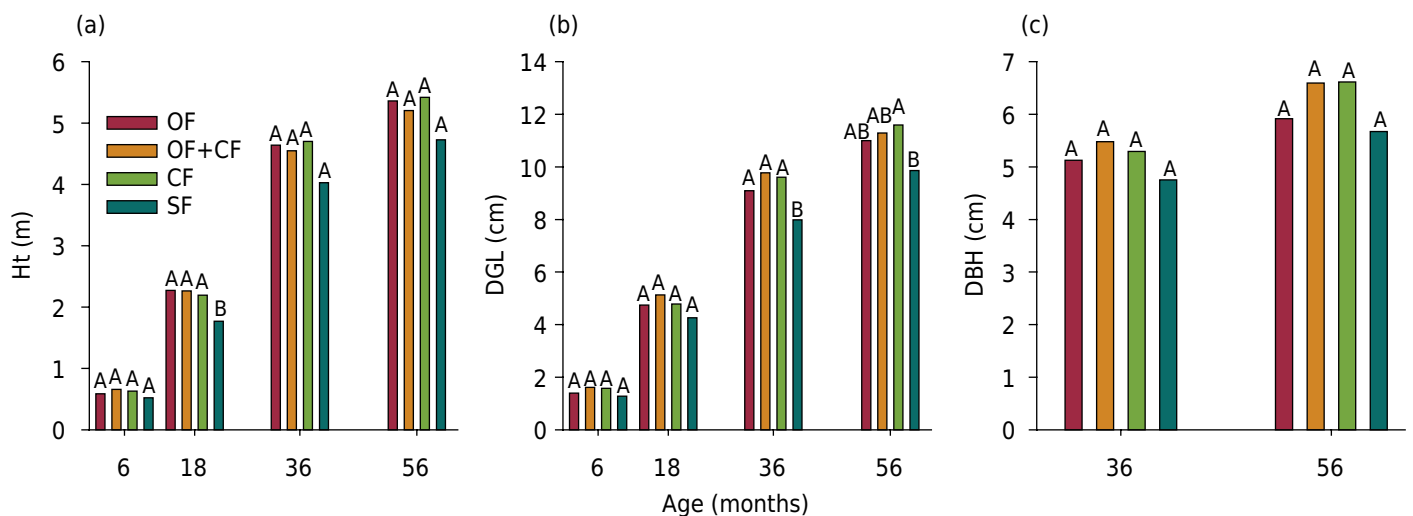


Figure 3. Total growth in height (Ht; a); trunk diameter at ground level (DGL; b); trunk diameter at breast height (DBH; c) in native forest species (Nat) at 6, 18, 36, and 56 months of age, submitted to organic (OF), combined organic and chemical (OF+CF), chemical (CF), and standard (SF) fertilizers, planted in an area of bauxite mining. Uppercase letters compare fertilization treatments within the same age and, when equal, indicate no differences between them by the Tukey's test at 10 % probability level.

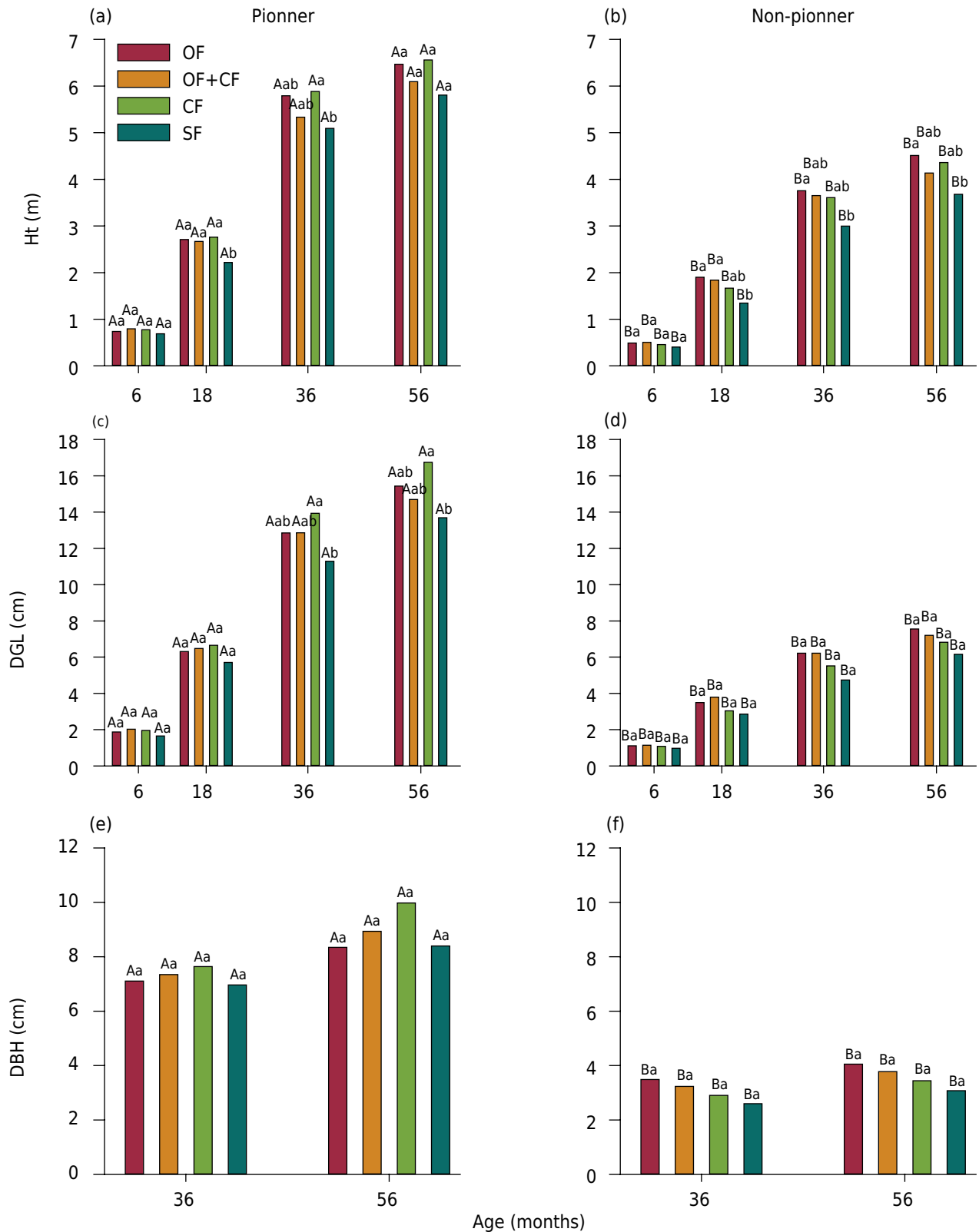


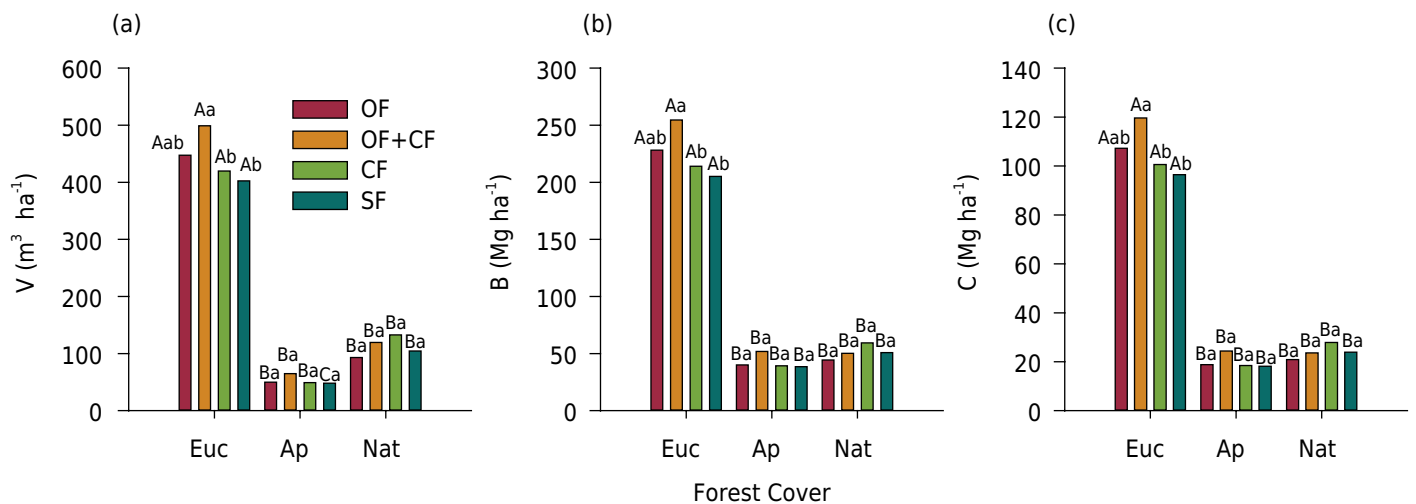
Figure 4. Growth in height (Ht; a) in native pioneer forest species and non-pioneer species (b); trunk diameter at ground level (DGL; c) in native pioneer forest species and non-pioneer (d); trunk diameter at breast height (DBH; e) in native pioneer forest species and non-pioneer species planted in an area of bauxite mining (f) at 6, 18, 36, and 56 months of age, submitted to organic (OF), combined organic and chemical (OF+CF), chemical (CF), and standard (SF) fertilizers. Uppercase letters compare pioneer and non-pioneer species for each age, and lowercase letters compare fertilization treatments within the same age and the same group and, when equal, indicate no differences between them by the Tukey's test at 10 % probability level.

In this case, the trees submitted to SF (205 Mg ha⁻¹) and CF (214.1 Mg ha⁻¹) displayed less biomass than the trees under OF+CF. For Ap and Nat, the fertilizer had no influence on the respective biomass. The Euc plantation displayed C stocks of around 119.6 Mg ha⁻¹

Table 1. Estimation equations for trunk volume with bark (V) (m³) in *Eucalyptus* (Euc), *A. peregrina* (Ap), and the 16 native forest species at 56 months of age, planted in an area of bauxite mining

Species	Equation	R ²	Syx
<i>Anadenanthera peregrina</i>	$V = 0.0000461 * DBH^{2.63300} * Ht^{0.48000}$	0.96	0.0081
<i>Annona squamosa</i>	$V = 0.0000517 * DBH^{2.68700} * Ht^{0.38920}$	0.98	0.0049
<i>Ceiba speciosa</i>	$V = 0.0004879 * DBH^{1.19835} * Ht^{1.11988}$	0.91	0.0416
<i>Enterolobium contortisiliquum</i>	$V = 0.002877 * DBH^{1.361393} * Ht^{0.137388}$	0.81	0.0379
<i>Ficus insipida</i>	$V = 0.002025 * DBH^{1.12599} * Ht^{0.200889}$	0.71	0.0063
<i>Inga edulis</i>	$V = 0.000036 * DBH^{1.75500} * Ht^{1.60600}$	0.90	0.0085
<i>Piptadenia gonoacantha</i>	$V = 0.000107 * DBH^{2.13900} * Ht^{0.71090}$	0.80	0.0278
<i>Sapindus saponaria</i>	$V = 0.0001858 * DBH^{1.111359} * Ht^{1.26140}$	0.95	0.0024
<i>Pera glabrata</i>	$V = 0.0003974 * DBH^{1.815447} * Ht^{0.15768}$	0.95	0.0016
<i>Apuleia leiocarpa</i>	$V = 0.00007855 * (DBH^2 * Ht)^{0.95510}$	0.92	0.0014
<i>Caesalpinia equinatha</i>	$V = 0.0008909 * DBH^{1.38518} * Ht^{0.075967}$	0.86	0.0009
<i>Lecythis sp</i>	$V = 0.0007675 * DBH^{1.59705} * Ht^{0.127039}$	0.98	0.0016
<i>Cupania oblongifolia</i>	$V = 0.0004105 * DBH^{1.55291} * Ht^{0.178269}$	0.97	0.0002
<i>Trichilia sp</i>	$V = 0.0004869 * DBH^{1.55045} * Ht^{0.35253}$	0.92	0.0021
<i>Handroanthus chrisotrichus</i>	$V = 0.0004074 * DBH^{1.920903} * Ht^{0.18401}$	0.92	0.0009
<i>Hymenea coubaril</i>	$V = 0.0003974 * DBH^{1.815447} * Ht^{0.15768}$	0.98	0.0009
General equation for native species	$V = 0.0007063 * DBH^{1.52273} * Ht^{0.522145}$	0.91	0.0248
<i>E. urophylla</i> x <i>E. grandis</i>	$V = 0.000065 * DBH^{1.88700} * Ht^{0.98100}$	0.98	0.0197
<i>Anadenanthera peregrina</i> (monocrop)	$V = 0.0001147 * DBH^{2.13900} * Ht^{0.59080}$	0.95	0.0195

DBH: trunk diameter at breast height (cm); Ht: total height (m); R²: coefficient of determination; Syx: residual standard error.


Figure 5. Volume with bark (a), biomass (b), and C stocks in the trunk with bark (c) for *Eucalyptus* (Euc), *A. peregrina* (Ap), and native species (Nat) at 56 months of age, planted in an area of bauxite mining and submitted to standard (SF), combined organic and chemical (OF+CF), organic (OF), and chemical (CF) fertilizers. Uppercase letters compare the mean values for the different forest covers, while lowercase letters compare the fertilization treatments within each type of cover and when equal, indicate the lack of significant difference between them by Tukey's test at 10 % probability level.

and 107.2 Mg ha⁻¹ in the trunk biomass for OF+CF and OF respectively, while the others ranged from 96.5 Mg ha⁻¹ for SF to 110.6 Mg ha⁻¹ for CF. The Ap (19.9 Mg ha⁻¹) and Nat (24.1 Mg ha⁻¹) did not differ for C stocks, but their values were well below those obtained by Euc, irrespective of the fertilizer (Figure 5c).

By analyzing the native forest species planted in the experimental area (Figure 6), it was found that the pioneer group had the largest values for volume ($197.82 \text{ m}^3 \text{ ha}^{-1}$), biomass (79.22 Mg ha^{-1}), and C stocks (37.23 Mg ha^{-1}) compared to the group of native non-pioneer forest species; these showed $26.56 \text{ m}^3 \text{ ha}^{-1}$, 13.68 Mg ha^{-1} , and 6.43 Mg ha^{-1} respectively, with the fertilization treatments not having any significant effect.

DISCUSSION

A. peregrina (Ap) has been used in the revegetation of sites degraded by bauxite mining in south-eastern Brazil due to its good adaptation to soils of low fertility with physical properties considered unfavorable to plant growth (Tótola and Borges, 2000), together with the fact that it is a legume associated with N_2 -fixing bacteria, which makes it important in the rehabilitation of degraded areas (Santos et al., 2008). Despite being a native pioneer species considered to be relatively fast growing, its nutrient demand is low when compared to Euc, which resulted in the same growth in Ht for the fertilizers under study at all ages. Paiva and Poggiani (2000) evaluated the growth of Ap intercropped with other species at 12 months and found a value close to that observed in the present study as early as 6 months of age.

Eucalyptus (Euc) is a species of rapid growth, with a large initial spurt and, consequently, a greater demand for nutrients. This condition probably reflected in the growth response in Ht and DGL when the fertilizers were applied. Fertilization with more nutrients, OF+CF and OF, improved plant growth compared to those plants under SF in most of the months under study.

In the early stages of tree growth in the field, fertilizers rich in nitrogen compounds may accelerate the growth rate, increasing N availability at a stage when the mineralization rates of this nutrient in soil and plant residue does not meet the high demand of the trees (Jesus et al., 2012). Nitrogen is a nutrient of low availability in the soil, which coupled with the great demand of plants, makes it one of the most limiting nutrients in productivity for most crops (Barker and Bryson, 2006; Kiba and Krapp, 2016). The fact that fertilization with poultry litter (OF) gave similar results to those caused by OF+CF underlines the fact that the growth of the Euc may be a reflection of the low levels of soil organic matter (SOM), a characteristic of soils degraded by mining activities. The low

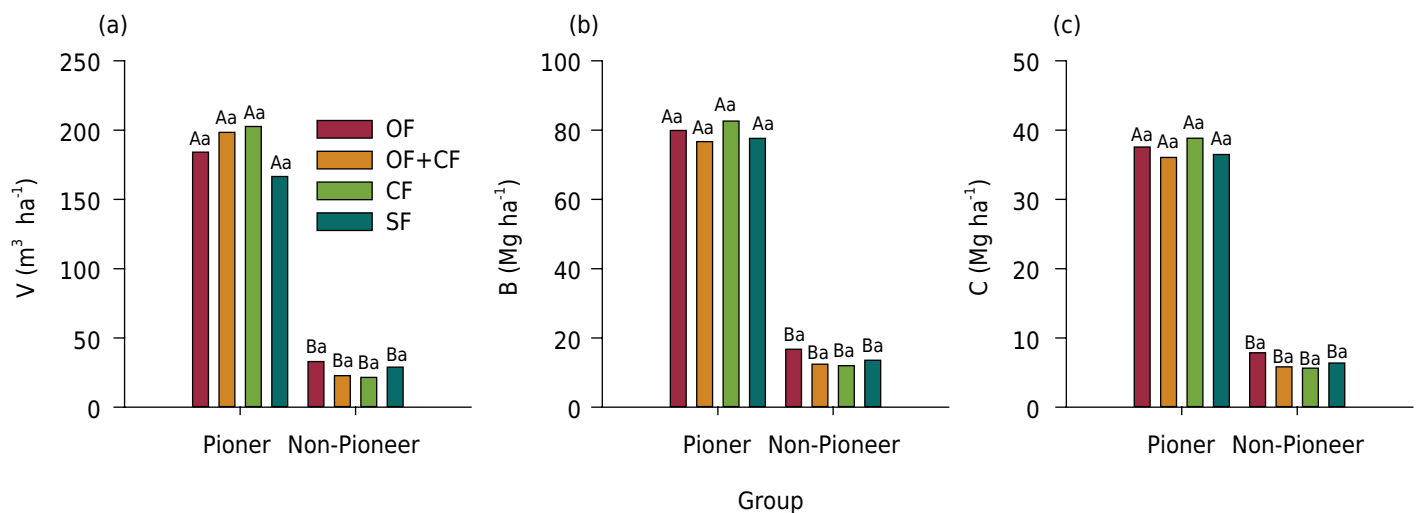


Figure 6. Volume (v; a), biomass (b), and carbon stocks (c) in native pioneer forest species and native non-pioneer forest species at 56 months of age, planted in area of bauxite mining and submitted to standard (sf), combined organic and chemical (of+cf), organic (of), and chemical (cf) fertilizers. Uppercase letters compare the mean values for the groups (pioneers and non-pioneers) within the same fertilizer, while lowercase letters compare the fertilization treatments within the same group and, when equal, indicate the lack of significant difference between them by Tukey's test at 10 % probability level.

fertility of such soils makes the *Eucalyptus* more responsive to fertilization (Ferreira et al., 2015). In degraded environments and soils of low fertility, fertilizer is necessary for the satisfactory development of forest plantations (Florentine and Westbrooke, 2004; Gonçalves et al., 2015).

The native pioneer species showed more accelerated growth in height and diameter at ground level than the non-pioneer species (Benvenuti-Ferreira et al., 2009; Carnevali et al., 2016). The growth potential of pioneer species is restricted when cultivated in poor soils, and they are more responsive to fertilization than non-pioneer species, in which the growth stimulus provided by fertilization is less pronounced and sometimes non-existent, a tendency that in part can be attributed to slower growth (Santos et al., 2008). At a more advanced age, non-pioneer species tend to acquire more pronounced growth, unlike pioneer species, as seen by Ferreira et al. (2007), 58 months after planting.

Brazilian forests have the potential to store C in their biomass, thus contributing to the mitigation of atmospheric CO₂ and improving the quality of forest soils through nutrient input. According to Sanqueta et al. (2018), in 2016 Brazilian forests stored in their biomass about 612 million tons of C. In this context, Eucalyptus plantations have the main role, contributing with 71 % of this value. Due to its rapid growth, it has a high potential for capturing C by storing it in the biomass, functioning as a C sink, and can immobilize about 50 t ha⁻¹ yr⁻¹ of atmospheric CO₂ (Gatto et al., 2010). This potential increases with fertilization, as observed in the present study.

Volume, biomass, and carbon stocks in the Euc were four times greater at 56 months of age compared to the other two forest covers under study. Euc was the only cover that showed a difference in biomass due to the fertilization treatments. The OF+CF fertilizer (255 Mg ha⁻¹) gave a value for trunk biomass with bark greater than those found under CF (214 Mg ha⁻¹) and SF (205 Mg ha⁻¹) in Euc. The results for estimated biomass in Euc at 56 months of age in an area recovering from bauxite mining were higher than those found in unmined areas by some researchers, such as Santana et al. (2008), on the northern coast of the State of Espírito Santo (100.9 Mg ha⁻¹) at 60 months, or Gatto et al. (2011), in some regions of the state of Minas Gerais, such as Cocais (78.5 Mg ha⁻¹), Rio Doce (139.5 Mg ha⁻¹), and Sabinópolis (104.1 Mg ha⁻¹) in plantations at 60 months of age, as well as results found by Stape et al. (2008), with trunk biomass reaching 140 Mg ha⁻¹ in plantations at 5.5 years of age.

Determining tree biomass allows obtaining the potential emission of C that could be released to the atmosphere due to deforestation activities or changes in land used, which is of great importance in studies on global warming and environmental degradation (Manickam et al., 2014). Estimates of biomass and C stocks in the Atlantic Forest biome are scarce in the literature, especially in areas rehabilitated after mining, which makes the present study an important tool of future prediction of mitigation of greenhouse gases with the planting of forests in degraded areas.

The results found in the present study are higher than those found by the above-mentioned authors, but it is important to point out that the results of this study were obtained from experimental plots in the field, where conditions are more homogeneous, i.e. the quality of the sites is similar, mainly due to the high application of nutrients through fertilization.

The results obtained for trunk biomass with bark in Nat (51 Mg ha⁻¹) and Ap (42.5 Mg ha⁻¹) at 56 months were also higher than those found by Campoe et al. (2010) in plantations composed of 20 forest species native to the Atlantic Forest, at different spacings and under different management activities. Increases in the intensity of silvicultural practices, such as fertilization and the control of plant competition, favor tree growth and C sequestration in the biomass (Campoe et al., 2014; Ferez et al., 2015; Brancalion et al., 2019), leading to a positive effect on the restoration of degraded areas. The average value for C stocks found in the present study (24 Mg ha⁻¹) was also higher than that found by Ferez et al.

(2015) (16 Mg ha^{-1}) at an age of 5 years. However, studies show that in Atlantic Forest fragments with an approximate age of 40 years, trunk biomass can reach 158 Mg ha^{-1} (Cunha et al., 2009) and, at 100 years of age, it is possible to find trunk biomass and C stocks of about $166.67 \text{ Mg ha}^{-1}$ and 84.34 Mg ha^{-1} , respectively (Ribeiro et al., 2010).

The pioneer species showed better results in growth, biomass, and C stocks, as also seen by Campoe et al. (2014). Pioneer forest species have the potential for allocating nutritional resources and energy for the rapid growth of their seedlings, thus promoting rapid new ground cover and the formation of forest structure in addition to increased seed production and availability, compared to non-pioneer species (Souza and Batista, 2004), an important characteristic for rehabilitation programs in degraded areas. Pioneer species probably include the greater allocation of biomass to the aerial part among their survival strategies, guaranteeing light capture in the face of other competing species. Non-pioneer species, however, as they naturally occur in more shaded environments, tend to invest more in the root system, while waiting for the appearance of a clearing.

CONCLUSIONS

Fifty-six months after planting the three types of forest cover in an area of bauxite mining, it can be concluded that:

The applied fertilizers favored growth in height and diameter in each type of forest cover, especially Euc, which showed the largest growth, mainly under the combined organic+chemical, and organic fertilizers;

The estimation equations for volume developed for all the forest species under study showed a high predictive capacity (given the values of R^2 and S_{yx}) and only depend on variables that are easily measured in the field, such as total height and diameter at breast height (DBH);

Trunk biomass and C stocks in the forest cover under study showed higher values due to the homogeneity of the site and the increased application of nutrients from the fertilization carried out in the experimental area;

Eucalyptus has great potential for CO_2 sequestration and C storage in the form of wood.

APPENDIX A. SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://www.rbcjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-43-e0180212/1806-9657-rbcs-43-e0180212-suppl01.pdf

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