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Growth and survival of potential tree species for carbon-offset in degraded areas from southeast Brazil

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ABSTRACT

Brazil must restore 12 million hectares of degraded areas by 2030 to meet its goal of the Paris Global Climate Agreement (PGCA). In view of this, the development of mixed planting projects related to carbon-offset in degraded areas is increasing, which demonstrates environmental and social responsibility of corporate and governmental organizations. Despite the great potential of mixed restoration plantations to mitigate climate change, Brazil must overcome major challenges in achieving the ratified goals of the PGCA as well as the effectiveness of its carbon-offset projects. In this context, this study has focused on the evaluation of the growth and survival of tree species in a carbon-offset plantation from a degraded area in southeastern Brazil. Five-hundred-and-nine seedlings (15 forest species) were planted in a completely randomized design. Diameter at the soil level and height of individuals were measured at 40 months. Three individuals of each species were selected and was scaling by a non-destructive method. Timber volume was estimated from the sum of the volume of the sections of the individuals, obtained by the Smalian formula. The average annual carbon increment of the individuals was estimated by the equation adjusted from the Schumacher & Hall model. The potential of carbon-offset of the tested plants was evaluated from the SP and μC analysis. The REML (Restricted Maximum Likelihood)/BLUP (Best Linear Unbiased Prediction) method was used to predict μC values for species ordering with carbon -offset potential. Survival was 47.54% at 40 months. The carbon stock of the planting was 2.60 ± 6.2 Kg C individual^{-1}, and the average annual increase in carbon (AAIC) was 0.78 Kg C individual^{-1}year^{-1}. The AAIC value was lower than the average value stipulated for carbon-offset projects (6.0 Kg CO_2 individual^{-1} year^{-1}). Pioneer species contributed more to carbon storage than non-pioneer species.

1. Introduction

The Paris Global Climate Agreement (PGCA), launched in December 2015, is has the central goal of limiting the global temperature increase between 1.5 and 2.0 °C by 2100, compared to the temperature of the pre-industrial periods (Arantegui and Jäger-Waldau, 2018; Rogelj et al., 2016; Viñuales et al., 2017). The PGCA was ratified in December 2016 and Nationally Determined Contributions (NDCs) were created so that participating nations to achieve their goals by formalizing commitments to GHG (Klein et al., 2017; UNFCCC, 2016; UNFCCC, 2017).

Brazil, which owns a large forest extension, high agricultural production and hosts ecosystems of global relevance, plays a fundamental role in discussing the NDCs related to Land-Use Change and Forestry. According to the PGCA, Brazil aims to restore 12 million hectares with forests for multiple uses up to 2030. This goal is convergent with other objectives of the country such as the environmental regularization agenda of the Forest Code and achieving the Brazilian targets for biodiversity (Brasil, 2012; Conabio, 2013; Brasil, 2015). Alongside these voluntary goals of the country, other initiatives referred to as "carbon-offset plantations", which are gaining prominence in the climate change

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scenario allied to the restoration of degraded areas, are being developed. Carbon-offset plantations are a way used by corporate and public organizations to show concern for the environment, as well as being a marketing mechanism to attract discerning customers and investors (Hassan, 2009). For example, the municipality of São Paulo adopted, through ordinance 06/2007, the mandatory to carbon-offset in 32 municipal parks.

Voluntary projects of biodiversity plantations aiming to remove carbon from the atmosphere had their origin in England and other European countries in the 1980s. In Brazil, the first projects related to this topic started in 2005 (Hassan, 2009; Anderson et al., 2017). The ability of trees to fix carbon and generate other co-benefits makes these projects interesting for forest restoration and climate change mitigation (Ferez et al., 2015). An important experience in this context is the California carbon offset project, which promoted carbon stocks as well as ecological services that positively impacted in the local biodiversity (Anderson et al., 2017).

Brazil must overcome great challenges to achieve the NDC goals related to the restoration and implementation of reliable carbon-offset projects. Among the main challenges can be listed: lack dissemination of the technical knowledge of forest restoration; little attention given to the monitoring and evolution of carbon-offset plantations, as well as the lack of information on the silvicultural behavior of regional native species, definition of baselines for removals from the restoration (tons of CO_2 ha^{-1} $year^{-1}$), indication of coefficients that reduce the risk of non-permanence of carbon stocks by removals in plantations, regulation and transparency and incipient conversion factors (tree/CO_2e) (Hassan, 2009; MMA, 2017). Understanding the behavior of tree species in different situations is fundamental to consolidate the most robust carbon offset programs. The *WebAmbiente* tool is an initiative to subsidize the choice of tree species for forest restoration programs; however, it still lacks of specific carbon storage data by species (WebAmbiente, 2019). The lack of species-level carbon survival and removal indicators for carbon offset programs located within a given region reinforces the importance of conducting research to develop successful carbon offset projects in Brazil, in addition to filling this gap in the technical knowledge (Alves et al., 2010; Vieira et al., 2011; Joly et al., 2014).

Despite evidence that forest restoration in degraded areas is an important tool for increasing carbon stock improving ecosystem benefits (Miranda et al., 2011; Wheeler, et al., 2016), studies focused on determining survival and carbon stock indicators of Zona da Mata (Atlantic Forest) tree are scarce. Therefore, this study aims to contribute with indicators related to these performances, as well as with practical data of forest species to improve the planning of restoration and carbon offset projects. Therefore, the objective was to evaluate the growth and survival, at 40 months, of tree species in a carbon-offset plantation in a degraded area from the southeastern Brazil.

2. Material and methods

2.1. Characterization of the study area

The study area (708 m above sea level) is located in the Espaço Aberto de Evento da Universidade Federal de Viçosa (UFV), Viçosa, MG, Brazil (20° 45′ 37.62″ S and 42° 52′ 29.59″ W) (Fig. 1). The regional vegetation is classified as Semidecidual Seasonal Forest Montana (Atlantic Forest) (Martins & Cavararo, 2012), and climate is classified as Cwa (Köppen) with cold and dry winters and hot and rainy summers. The water surplus from November to March of the region is ~366 mm with hydric deficit in the remaining months, and the annual averages of precipitation and temperature are 1314 mm and 21.8 °C, respectively (Almeida et al., 2016). The annual average precipitation since planting was 1213 mm and temperature was 20.8 °C (UFV, 2017) (Fig. 2).

The topography has a pedo-geomorphological gradient with flat tops and dystrophic latosols abundant in aluminum with access to colluvial ramps with shallow, cambic, and groin bottoms with predominance of abundant cambisols and eutrophic in nutrients (Ferreira et al., 2012). Soil samples were collected in the begging of the experiment and analyzed by the certified laboratory of the UFV. The physicochemical characteristics of the soil were: pH (H_2O) 4,46; 0,3 mg P dm^{-3}; 18 mg K dm^{-3}; 0,11, 0,49, 4,6, 0,62, 1,11 and 5,22 cmolc dm^{-3} of Mg^{2+}, Al^{3+}, H + Al, SB (sum of exchangeable bases), t (effective cationic exchange capacity) and T (cation exchange capability), respectively; basal saturation index (V) of 79.7%; and aluminum saturation index (m) of 44,1%. The soil resistance to penetration (Mpa) was measured by using two-point evaluated inside the experiment from 0 to 60 cm (at intervals of 5 cm in depth) (Fig. 3).

The experimental area before 2000 and until 2010 was covered by *brachiaria* and had continuous patches of soils exposed at various points. The construction of a paved road after 2008 contributed to an even greater compaction of the soil by heavy machinery traffic. Before the experiment was implemented, several fire events occurred at the site.

2.2. Implantation of the experiment

Five-hundred-and-nine seedlings of 15 tree species (Table 1) were randomly planted at 2 × 2 m in December 2012 within an area of 2036 m^2. A mowing was done in the area, initially covered by brachiaria (*Urochola decumbens* (Stapf) R.D. Webster) to facilitate the transplant of seedlings. The pits (0.3 × 0.3 × 0.3 m) were fertilized at the bottom with 300 g of 18% P_2O_5. Three superficial cover fertilizations (at 1, 13 and 25 months after planting) were performed with 100 g pit^{-1} of 20–5-20 (NPK) formulation. Weed management and leaf-cutting ants were routinely performed with glyphosate (Original Roundup, 36% m/V; Monsanto do Brasil LTDA, Brazil) and formicide baits (AttaMex-S, 0.3% w/w sulfluramid, Unibrás Agroquímica Ltda, Brazil), respectively.

2.3. Evaluated parameters and analysis

The program "Carbono Zero" of the UFV was created in 2010 to promote the quantification, reduction and offsetting of carbon emissions from the institution events. Carbon offsetting is performed by mixed plantations in degraded area. This program uses the carbon removal index of 6.0 Kg CO_2 $individual^{-1}$ $year^{-1}$ considering a 30-year carbon-offset horizon (Alves, 2018; Carbono Zero, 2019). The average species carbon stock and the average annual increment in carbon were analyzed to evaluate whether the carbon storage occurred as predicted.

Survival, diameter at soil level (DSL) and height (H) were measured at 40 months (3.3 years) of planting age. The DSL was measured with a digital precision caliper and H with a graduated tape measure. Scientific names and classification of the ecological group of the tree species were defined according to the bibliography. The survival percentage (SP) was determined by the equation: SPj = (N*fj*/No*j*) × 100, where: N*fj* = number of surviving individuals of the *j*-th species; N0*j* = initial number of individuals planted in the *j*-th species. The averages and deviations of the diameter were calculated by the soil height (μDSL) and the height (μH) of the species (Table 2). Data of μDSL and μH were presented to provide additional parameters in the growth of arboreal species, but the discussion will be focused on the average estimates of carbon storage (μC).

The average carbon stock of the stem and branches (μC) was estimated from the tree cubage and the determination of timber volume, biomass and carbon thereof. The plants were scaling by a non-destructive method (Morais Junior et al., 2019). Individuals of each species were grouped into diametric classes and three plants per class were scaling. The timber volume of each section was obtained by the Smalian equation; Vj = $((AS_1 + AS_2)/2)xL$), where: V*j* = volume of the *j-th* section in m^3; AS1 = initial sectional area, in m^2; AS2 = final sectional area, in m^2; L = longitudinal section length, in meters. The sections

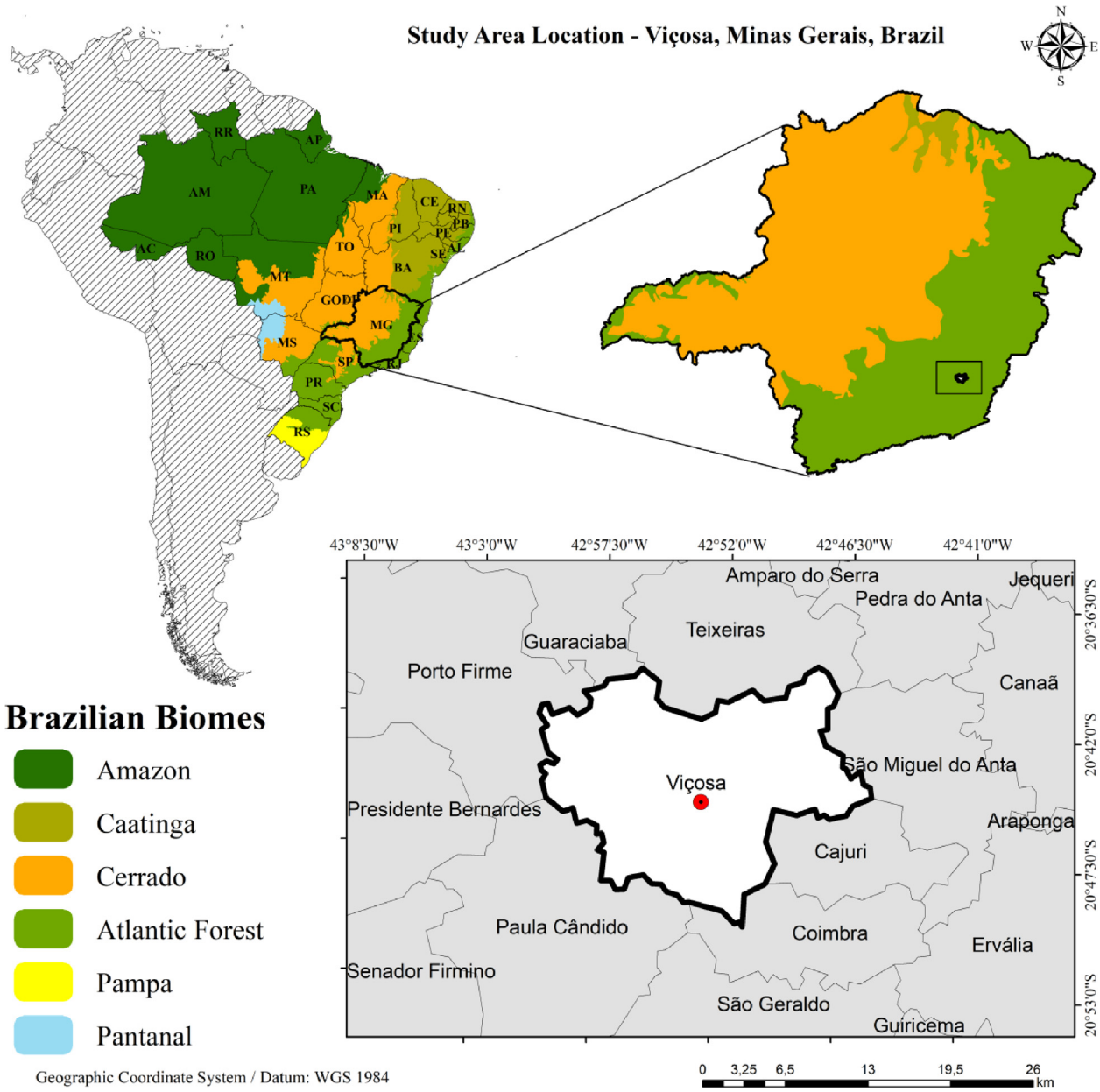

Fig. 1. Location map of the study area in Viçosa, Minas Gerais, Brazil.

were measured up to 5 cm diameter. The sum of the volumes of the sections of the *j*-th individual constituted the total volume of each plant presented by the equation: $Vi = \Sigma_{i=1}^{j} Vj$, where: V*i* = volume of the *i-th* individual, m^3; V*j* = volume of the *j-th* section, in m^3. The biomass of the branches and stem of each plant was obtained by multiplying the basic density of the timber by the total individual volume, using the equation: B*i* = ρ*i*xV*i*, where: B*i* = timber biomass of the stem and branches of the individual of the *i-th* species, in Kg; ρ*i* = basic timber density of *i-th*, in $Kg.m^{-3}$; Vi = volume (m^3) of the *i-th* individual. The basic density of all species/genera was obtained according to Britez (2006).

The conversion of the biomass to carbon was performed with a 48% content (Higuchi et al., 1998). This allowed us to adjust the equation $Cij = (5.85996 \times 10^{-11}) \times (DSL^{0.652085}) x (H^{3.83808})$ (R^2 adjusted = 96.91%), estimation of carbon stock (Kg C $individual^{-1}$) of the stems and branches by species, where: C*ij* = carbon stock of the *i-th* individual of the *j-th* species (kg); DSL = diameter of soil height (mm) and H = total height of the individual (cm). The Schumacher & Hall model (Schumacher & Hall, 1933) was chosen to generate the equation and the R *software* was used to perform the adjustment (R Core Team, 2015). The adjusted equations were used to estimate the carbon stock of all individuals.

The averages of carbon storage (μC) and the Average Annual Increase in Carbon (AAIC) were calculated by species using the equation: AAICj = [((μCj)/Nj))/ (I)], where: I = planting age (3.33 years); Nj = number of individuals of the j-th species; μCj = average of the carbon stock of the individuals of the j-th species, in kg. The conversion of carbon (C) data to carbon dioxide (CO_2) was made by multiplying by 3.67, referring to the conversion between the molecular weights of CO_2 and C (IPCC, 2006). This conversion is adopted to facilitate the discussion of data referring to the factors of carbon dioxide removal, in which they use most of the Carbon Carbon-offset Project.

2.4. Statistical analysis and planning of carbon storage

The values predicted for the tree species were obtained by the REML

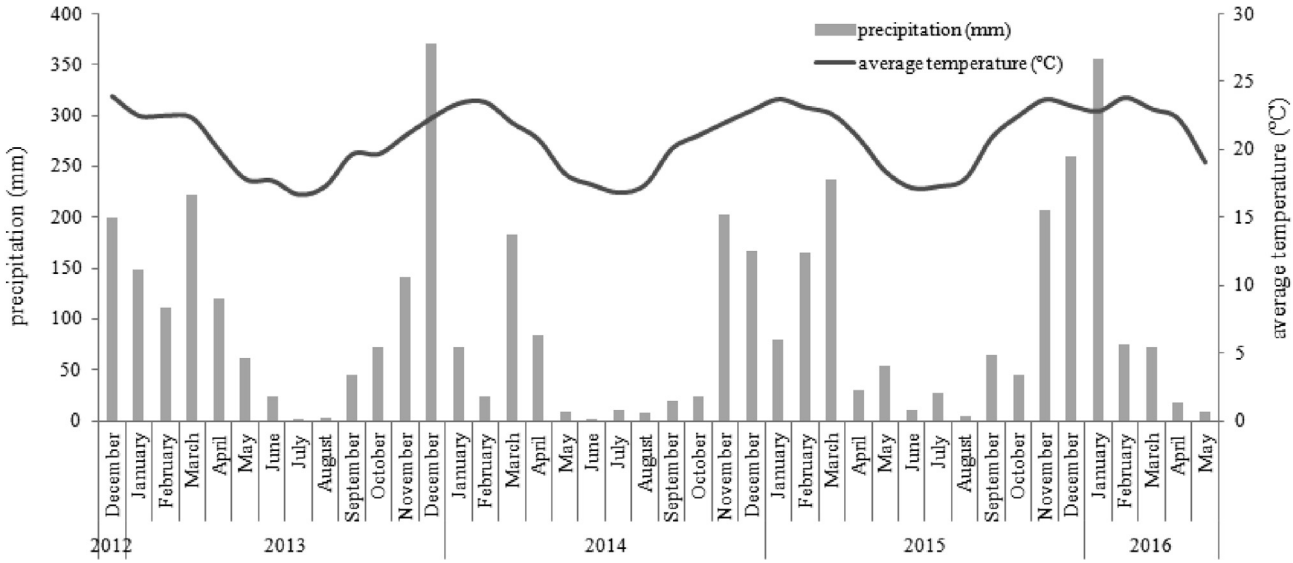

Fig. 2. Accumulated monthly precipitation (mm) and mean temperature (°C) recorded in Viçosa between December 2012 (installation of the experiment) and May 2016 (data collection).

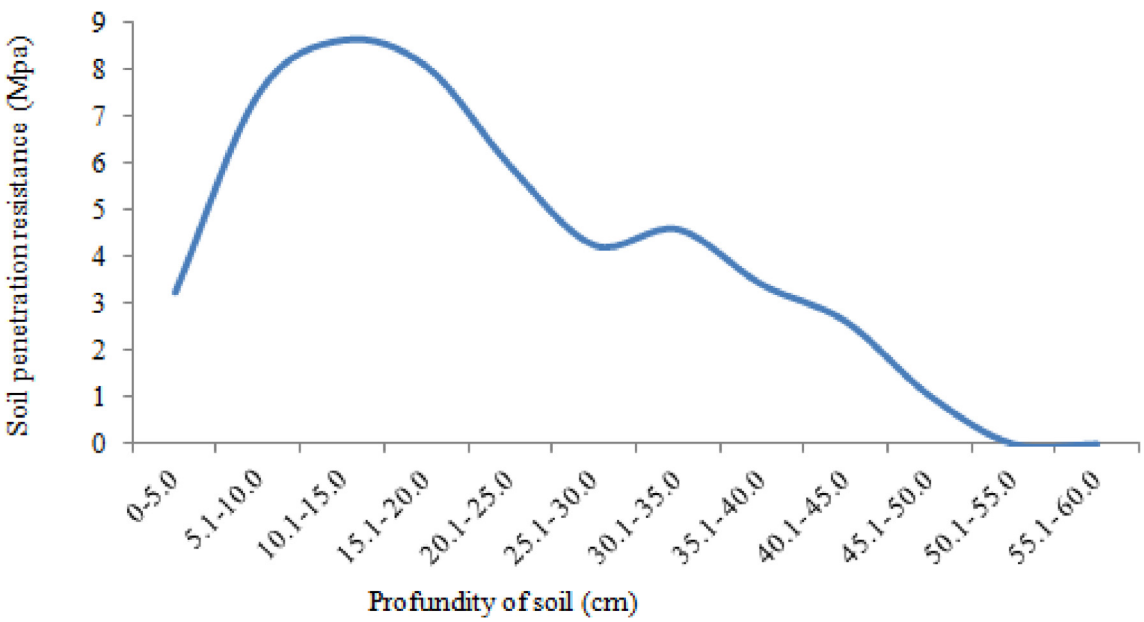

Fig. 3. Physical resistance of the soil to penetration (Mpa) as a function of profundity (0 to 60 cm) in the experiment at 40 months of age.

(*Restricted Maximum Likelihood*) / BLUP (*Best Linear Unbiased Prediction*) method for the variable μC with the following mixed statistical model: $Y = Xu + Za + e$. Where Y is the data vector, u is fixed-effects vector (a general mean), a is the effect vector of the (random) species, and "e" is the (random) vector of residues, X and Z represent the matrices of incidence of the aforementioned effects. The adjustment of the model was done in SELEGEN-REML/BLUP *software* (Resende, 2016). They follow the mean and variance distributions, the mixed model equations and the variance component estimators of aforementioned method.

Mean distribution (E) and variance (Var):

$$E[yae] = [Xu00]\,Var[ae] = [I\sigma_a^2 00 I\sigma_e^2]$$

Mixed model equation:

$$\left[X'XX'ZZ'XZ'Z + I\frac{\sigma_e^2}{\sigma_a^2}\right][\hat{u}\hat{a}] = [X'yZ'y]$$

where

I= Matrix identity;
σ_a^2=Additive genetic variance;
σ_e^2=Residual variance.

Estimators of variance and components of REML via "EM" Algorithm:

$$\sigma_e^2 = \frac{[y'y - \hat{u}X'y - \hat{a}'Z'y]}{[N - r(x)]}$$

$$\sigma_a^2 = \frac{[\hat{a}'\hat{a} + \sigma_e^2 tr(C^{22})]}{q}$$

C^{22}comes from:

$$C^{-1} = [C_{11}C_{12}C_{21}C_{22}]^{-1} = [C^{11}C^{12}C^{21}C^{22}]$$

where

C = Matrix of coefficients of the Mixed Model

Table 1
Variables measured for tree species (N*i* = Number of individuals planted; N*f* = Number of individuals surviving at 3.33 years; μDSH e μH = average the diameter of soil height (mm) e height (cm), respectively at 3.33 years and standard deviation (± SD)). SP = Survival percentage. Determination of the ecological group (G.E) and spelling of the scientific names of the species of agreements with the References GE.

Species	GE	N*i*	N*f*	SP (%)	μDSH	μH	References GE
Albizia hassleri	P	30	24	80.00	69.49 ± (26.20)	262.63 ± (98.66)	Barbosa, 2015
Andira anthelmia	NP	25	15	60.00	48.43 ± (16.07)	87.46 ± (41.78)	Barbosa, 2015
Anadenanthera macrocarpa	P	50	35	70.00	52.37 ± (33.26)	238.82 ± (130.56)	Barbosa, 2015
Guarea guidonia	NP	25	2	8.00	23.9 ± (13.47)	99.00 ± (12.73)	Barbosa, 2015
Joannesia princeps	NP	25	12	48.00	55.56 ± (34.74)	143.33 ± (100.89)	Barbosa, 2015
Peltophorum dubium	P	25	21	84.00	103.54 ± (36.43)	299.66 ± (100.56)	Barbosa, 2015
Inga vera	P	50	27	54.00	82.15 ± (21.69)	230.77 ± (60.31)	Barbosa, 2015
Syzygium cumini	P	24	19	79.17	73.34 ± (31.57)	259.26 ± (75.03)	Silva et al., 2016
Hymenaea courbari	NP	24	7	29.17	38.92 ± (34.04)	147.42 ± (120.53)	Barbosa, 2015
Genipa americana L.	NP	25	11	44.00	16.48 ± (6.93)	26.58 ± (18.56)	Barbosa, 2015
Ceiba speciosa	NP	26	0	0.0	–	–	Barbosa, 2015
Citharexylum myrianthum	P	46	17	36.96	46.00 ± (34.24)	133.79 ± (115.73)	Barbosa, 2015
Lecythis pisonis	NP	25	12	48.00	36.45 ± (13.56)	137.16 ± (63.33)	Carvalho et al., 2006
Samanea inopinata	NP	49	31	63.27	36.22 ± (28.42)	123.94 ± (130.01)	Cruz et al., 2006
Adenanthera pavonina	P	49	9	18.37	18.79 ± (5.59)	75.86 ± (36.98)	Fonseca and Perez, 2003
Unidentified species	–	11	0	0.00	–	–	–
Total / average overall	–	509	242	47.54	56.58 ± 35.82	186.41 ± 123.02	

tr = dash;
rx = Matrix X rank;
N, q = Total number of individuals and species, respectively.

The species were ranked in descending order of μC according to the predicted values. To verify the significance of the species' effect, the Analysis of deviance (ANADEV) was performed, in which the deviance was obtained with and without the effect of the species (*a*). Subsequently, the *Likelihood Ratio Test* (LRT) test was performed and the values were compared with the chi-square table (3.84) with 5% of type 1 error probability.

3. Results

The SP of trees was 47.5%. The average carbon stock of the plantation was 2.6 ± 6.2 Kg C individual^{-1} and the AAIC was 0.78 Kg C individual^{-1} year^{-1}, corresponding to 2.9 Kg CO_2 individual^{-1} year^{-1} (Table 2). The carbon stock was higher for pioneer species (3.2 kg individual^{-1}) than in non-pioneer ones (0.60 kg C individual^{-1}) (Fig. 4).

Peltophorum dubium, Albizia hassleri and *Anadenanthera macrocarpa* presented the highest SP values (84.0, 80.0 and 70.0%, respectively), and were among the species with the highest carbon storage in the ranking evaluated (Table 1, Table 2 and Fig. 4).

Andira anthelmia, Inga vera and *Samanea inopinata* presented intermediate SP values, (60.0, 54.0 and 63.2%, respectively) (Table 1); however, *A. anthelmia* and *S. inopinata* showed the lowest storage of carbon (0.1 and 2.2 Kg C individual^{-1}, respectively). In contrast, *I. vera* occupied the fourth position in terms of carbon storage among the evaluated species (Table 2 and Fig. 4).

The exotic species *Syzygium cumini* presented a SP of 79.2% and high carbon storage (3.1 ± 4.2 Kg C individual^{-1}); meanwhile, *Adenanthera pavonina,* other exotic species, presented low SP (18.45%) and stored only 0.01 ± 0.0 Kg C individual^{-1} (Table 1 and Table 2).

Joannesia princeps and *Hymenaea courbaril* presented SP of 48.0 and 29.2%, respectively. In addition, they presented intermediate carbon storage (7th and 6th positions) (Table 1 and Table 2).

Lecythis pisonis, Genipa americana and *Citharexylum myrianthum* had SP below 48.0% and low μC (lower than 1.0 Kg C individual^{-1}) (Table 1 and Table 2).

Individuals of *Ceiba speciosa* not survived at the end of the experiment; therefore, there were no data related to the carbon storage for this species (Table 1).

4. Discussion

The World Resources Institute of Brazil (WRI Brazil) lists the main

Table 2
Estimation of average carbon stock (μC) (KgC.individual^{-1}) and standard deviation (± SD) of species. Average Annual Increase in Carbon (AAIC) (KgC. individual^{-1}.year^{-1}) Ranking of species with respect to the predicted value of μC and its accuracy.

Species	μC	AAIC	Predicted value	Accuracy (%)	Position (Ranking)
Peltophorum dubium	7.8(± 13.7)	2.35	2.770	92.4	1°
Albizia hassleri	3.4(± 3.1)	1.02	2.562	92.8	2°
Anadenanthera macrocarpa	5.1(± 9.2)	1.53	2.500	93.3	3°
Inga vera	1.8(± 1.1)	0.55	2.367	92.9	4°
Syzygium cumini	3.1(± 4.2)	0.93	2.350	92.0	5°
Hymenaea courbari	1.4(± 2.5)	0.41	1.671	85.3	6°
Joannesia princeps	1.0(± 1.8)	0.29	1.463	90.1	7°
Lecythis pisonis	0.3(± 0.4)	0.08	1.408	90.1	8°
Citharexylum myrianthum	1.0 ± 2.0	0.30	1.368	91.6	9°
Samanea inopinata	2.2 ± 5.7	0.65	1.330	93.2	10°
Guarea guidonia	0.0 ± 0.0	0.01	1.305	71.6	11°
Andira anthelmia	0.1 ± 0.1	0.02	0.956	91.1	12°
Adenanthera pavonina	0.01 ± 0.0	0.01	0.903	88.4	13°
Genipa americana L.	0.01 ± 0.0	0.00	0.459	89.6	14°
Ceiba speciosa[1]	–	–	–	–	15°
Total	2.6 ± 6.2	0.78	–	–	–

[1]The species *Ceiba speciosa* did not present any surviving individuals so there are no values of the variables evaluated for this species.

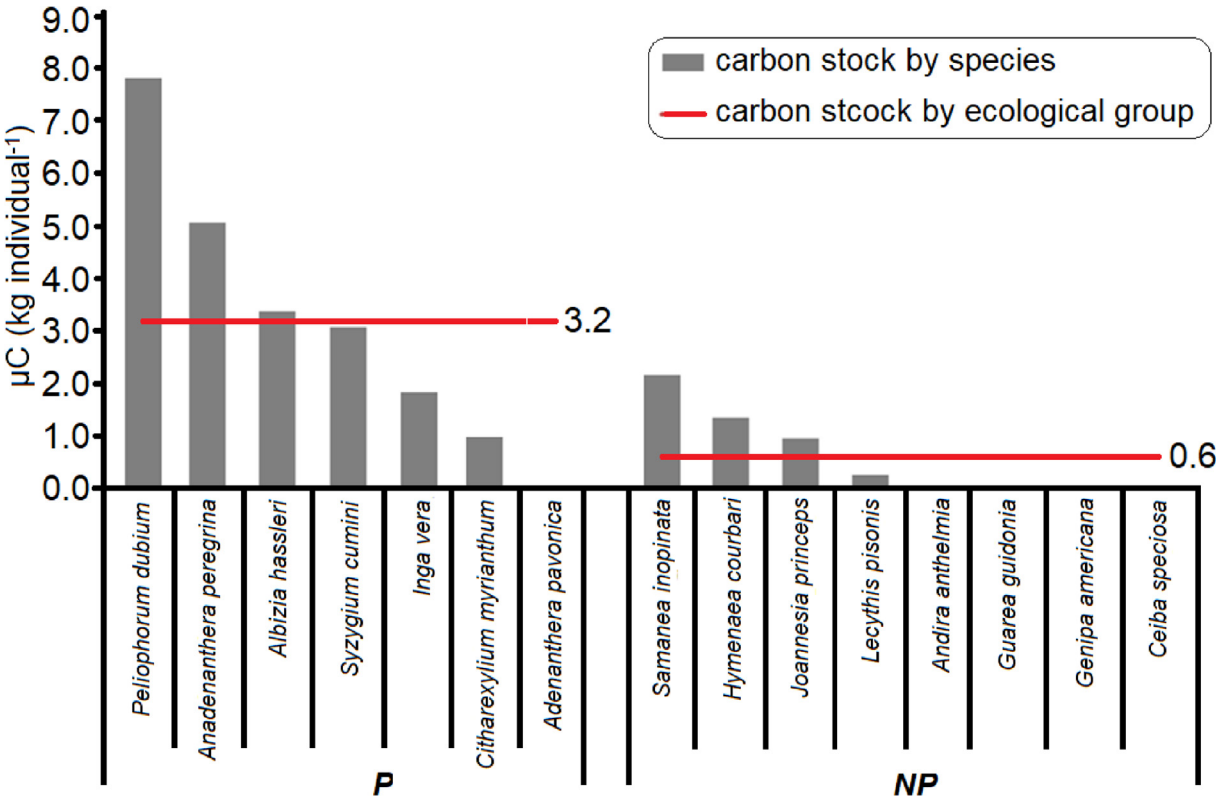

Fig. 4. Average carbon storage µC (kg individual^{-1}) per species for the pioneer (P) and non-pioneer (NP) groups.

native forest species to be considered for restoration projects of degraded areas in different biomes of the country at 40 months (Rolim et al., 2019). This study allowed to verify the survival and growth rates of 15 tree species from Zona da Mata Mineira. In addition, a species-level performance analysis was performed taking into account their ecological and carbon storage relevance. These results can assist decision makers in other forest restoration programs focusing on carbon removal.

The low SP of mixed plantings in restored areas may have high costs associated with the maintaining and monitoring in the long term (Lamb et al., 2005), and may interfere with the final carbon-offset of the project. The "Carbon Zero" Project uses a safety margin of < 20% of seedlings in its carbon-offset plantations, highlighting that plant mortality can exceeded this margin, replanting becomes necessary (Carbono Zero-UFV, 2017).

Low fertility, poor nutrient replacement and high soil acidity may have interfered with poor overall tree survival. Forest restoration projects have as their main objective to offset carbon emissions. These plantations promote nutrient replacement of degraded soils mainly due to irrational and discriminated use of soil conditioners and fertilizers (Resende et al., 2005); therefore, approaches favoring survival and carbon storage of plantation, but at the same time reduce emissions from fertilizations are needed. Localized applications of proper Ca or Mg rates contribute to correct soil acidity avoiding the total liming of the area (Vale et al., 1996; Furtini Neto et al., 1999a). In the present study, soil acidity correction could have favored tree survival and growth, especially of pioneer species that are more sensitivity to acidity (Furtini Neto et al., 1999b). Most tree species in the Atlantic Forest have high nutritional requirements (Gonçalves et al., 1996); therefore, cover fertilizations to increase carbon storage by these plantations are indispensable, especially for pioneer and secondary species that require more nutrients during the first years of life (Silva et al., 1997; Furtini Neto et al., 1999b). The dose of fertilizer applyed per plant (three cover applications) exceeded the established limits of 10–40 g N and P_2O_5 and 0–30 g K_2O for native species (Siqueira et al., 1995). Proper management of nutrient replacement can reduce GHG emissions while optimizing plant carbon storage. The approach of ecological replacement based on ecological groups and other indicators described by Resende et al. (2005) may support the management of fertilization in mixed tree plantations focusing on carbon removal (Fig. 5).

The average carbon storage estimated for the tree species assessed in this study (was 2.6 ± 6.2 Kg C individual^{-1}) was lower than those considered by the "Carbon Zero" Program and the most of carbon-offset projects (6.0 Kg CO_2 individual^{-1} year^{-1}) (Carbono Zero-UFV, 2017). Data on carbon removal factors are still controversial and lack accurate information and regulations for projects related to carbon-offset (Hassan, 2009). However, even when carbon was not stored as expected, there are some aspects that should be considered. Firstly, this study only quantified the carbon stored in the trunks and branches, but did not consider carbon stored in litter, roots, thin branches and leaves, which may represent an increase in the total carbon storage. In a study that evaluated the carbon storage at 6 years, conducted in restored areas from São Paulo, Brazil, the thick root compartments, soil organic horizon and herbaceous vegetation contributed in 57.0 and 36.8% to the total carbon storage in traditional and intensive forestry systems, respectively (Ferez et al., 2015). Our plantation was only 3.3 years old (40 months) and the trees had not yet reached constant growth rates; however, it is necessary to determine these indicators in early growth stages (Morais Junior et al. 2019), because they can contribute to address some guidelines for current projects, which can be redefined in future research with trees of more advanced ages. This means that further researches are needed to determine the long-term carbon removal potential by trees to mitigate GHG emissions (Silver et al., 2000; Wheeler et al., 2016).

Pioneer species store more carbon (especially during the first 37 years) than to non-pioneer species (Shimamoto et al., 2014). This trend corroborated in this study, where *P. dubium* and *A. macrocarpa* stored more than 5 Kg C individual^{-1}. However, this trend is inverse in

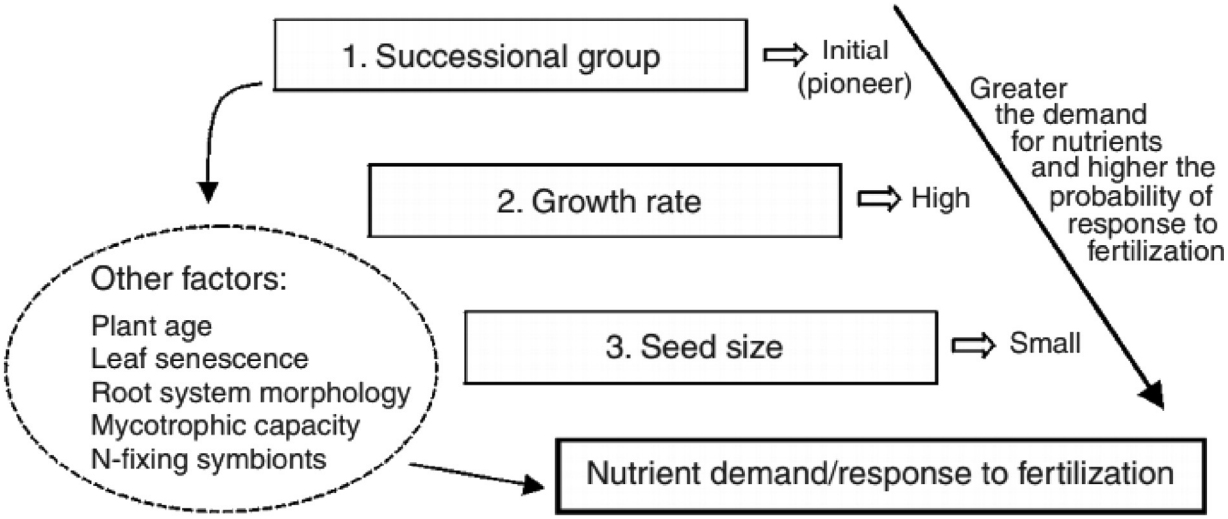

Fig. 5. Nutritional replacement approach described por Rezende et al., (2005).

the long term (over 60 years) because non-pioneer species may contribute twice as much to the forest storage (Shimamoto et al., 2014). Thus, the use of different successional groups in carbon-offset plantations is important to keep the carbon stocked for long periods (Shimamoto et al., 2014; Silva et al., 2016). The success of *P. dubium* to store the highest carbon rates may be related to: its intrinsic rusticity, ability to withstand high rates of light and temperature incidence, as well as to be very adapted to different environmental situations and little demanding in soil fertility (Donadio & Demattê, 2000; Inoue & Galvão, 1986; Lima et al., 2015). This species showed 100% of SP in other carbon-offset areas of the Zero Carbon Project at 17 months (Morais Junior et al., 2017). In several restored areas from the State of São Paulo, at ages varying from 4 to 20 years, *P. dubium* was one of the main contributors to carbon storage (Stucchi, 2013).

Albizia hassleri is a species with potential to recover degraded areas and fixes high concentrations of atmospheric nitrogen (Fowler et al., 2006). The higher growth of this species (2.6 m) compared to other species assessed can be explained by these traits. However, studies evaluating the adaptability and growth of *A. hassleri* are scarce. In addition, this species is listed as endangered one in Brazil (Gonzales et al., 2010). This suggests that carbon carbon-offset plantations can contribute to the conservation of endangered tree species.

The SP of *A. macrocarpa* was high as expected since it is a common species in areas near to the experimental site, showing that *A. macrocarpa* is successfully adapted to the conditions of the region (Amaro, 2010; Torres, 2011; Peloso, 2012). The favorable establishment and growth of this species was due to tolerates compacted and poorly drained soils with medium to clayey texture, besides being able to do symbiosis with nitrogen-fixing bacteria (Barberi et al., 1998; Carvalho, 2003). However, the use of this species in mixed plantations of carbon-offset should be judicious, since *A. macrocarpa* can have a strong dominance and allelopathic behavior, which may result in a decreasing the diversity of mixed plantations and, therefore, in carbon storage (Souza et al., 2012). We believe that *A. macrocarpa* can coexist in balance with the other ones, since in the nearby landscape there are no dominion records of this species.

Because *Andira anthelmia* and *Samanea inopinata* are non-pioneer species it was expected that they showed low initial carbon storage. The identification and use of potential non-pioneer species is essential to the long-term carbon removal, improving efficiency in the use of resources (water, light and nutrients) (Redondo-Brenes & Montagnini, 2006; Shimamoto et al., 2014). Both *A. anthelmia* and *S. inopinata* occur preferentially in wetlands (floodplains and wetland valleys); therefore, it can be inferred that SP can be higher in reforestation ciliary plantations (Giachini et al., 2010; Lorenzi, 1992). However, according to their SP and μC performances, *A. anthelmia* and *S. inopinata* also have the potential to succeed in carbon-offset projects in less humid areas.

Inga vera is also a species adapted to moist soils with great potential in carbon-offset projects in ciliary forests (Lorenzi, 1992), which can explain the moderate survival observed in the study. The species has large and leafy crowns, performs nitrogen fixation and removes high carbon rates (Carpanezzi, 2005; Faria and Franco 2002), being a species facilitating the succession (Marcuzzo and Viera, 2015; Ricklefs, 2003). Thus, the use of *I. vera* in mixed carbon-offset plantations will allow a high initial carbon storage and, at the same time, provide conditions for the late succession species to develop later promisingly.

The exotic species *Syzygium cumini* presented high SP and carbon storage, but this species should be avoided in carbon-offset plantations because may present dominant behavior forming homogeneous stands (Marcuzzo and Viera, 2015; Nóbrega et al., 2008). By contrary, *Adenanthera pavonina* presented low SP and carbon storage at 20 months. Although this species is wel adapted in Brazil (Corrêa, 1984), the present study showed no or low potential for carbon carbon-offset projects. The use of Brazilian exotic species in carbon-offset and forest restoration projects should be done with caution, evaluating whether the behavior and capacity of dominance of the species in the area in which was inserted can bring losses to diversity.

The low SB of the non-pioneers species *Joannesia princeps* and *Hymenaea courbaril* may be related to their low intrinsic tolerance to luminosity (Martínez-Garza et al., 2013).

Lecythis pisonis, G. americana, C. myrianthum and *G. guidonia* did not have a satisfactory adaptation, possibly because they are more adapted to riparian areas (Baylão et al., 2013; Campos and Landgraf, 2001; Lorenzi, 1992). In addition, *C. myrianthum* and *G. americana* prefer fertile soils, an antagonistic characteristic in degraded areas. In addition, there are records of inadaptability for the latter species in mixed plantations with high competition for water and nutrients (Durigan, 1990; Petit & Montagnini, 2006). These species may have high SP rates in carbon-offset plantations in areas with higher soil moisture and fertility, but their use may substantially burden the project costs.

Ceiba speciosa showed the worst performance of SB and carbon storage, an unexpected result, because this non-pioneer species usually tolerates adverse conditions (lack of water and high incidence of light) by its high phenotypic plasticity (Contin et al., 2014). This species presented SB of 78.9% and one of the greatest growths among 18 species at 17 months in a carbon-offset plantation close to our study area (Morais Junior et al., 2017). *Ceiba speciosa* is very preferred by leaf-cutting ants (Morais Junior et al., 2019). In areas close to the

experiment there are some fragments of *Mabea fistulifera,* a species symbiotically associated with these insects (Ferreira, 2015; Peternelli et al., 2004), which may have contributed to intensify of attacks at certain times of the year. This could explain the mortality of *C. speciosa* trees, even when a high frequency of attacks by leaf-cutting ants is necessary to cause definitive death. Therefore, if this species is selected to constitute mixed plantings, the ant control must be a priority issue.

Several factors can affect the survival and storage of carbon in degraded areas; therefore, it is necessary to build a database with information on the behavior of the species under different field conditions to increase the success of these projects (Pilon & Durigan, 2013; Moscogliato & Torezan 2017). The individual evaluation of tree species in their early stages of life is important to choice the most suitable one for mixed carbon-offset plantations and restoration of degraded areas. Thus, this study becomes a constituent part of the formation of this database.

5. Conclusion

The tree survival of the mixed carbon-offset plantation was low, requiring of replanting or planting a large number of seedlings to increase the probability of success of the project. The average annual carbon removal was less than the established in most of carbon-offset projects. Pioneer species stored more carbon than non-pioneer species in early stages of growth, but the use of the two functional groups is important to get a continuous storage of carbon for long periods.

The pioneer species *P. dubium, A. hassleri* and *A. macrocarpa* are promising for the composition of mixed plantations in degraded areas, mainly to provide a rapid removal of carbon and trigger important environmental roles in the landscape restoration. The use of these species must be moderate and interspersed with other species of slower growth to ensure a continuous carbon stock in the long term. *Peltophorum dubium, Albizia hassleri, Anadenanthera macrocarpa, Andira anthelmia, Samanea inopinata* and *Inga Vera* are promising to constitute carbon-offset plantations, while *Adenanthera pavonina, Joannesia princeps, Hymenaea courbaril, Lecythis pisonis, Citharexylum myrianthum, Genipa americana* and *Guarea guidonia* have the lowest survival and growth. *Syzygium cumini* showed good performance but its use deserves attention due to the intrinsic dominance behavior. The performance of *Ceiba speciosa* requires further studies.

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CRediT authorship contribution statement

Vicente Toledo Machado de Morais Junior: Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Laércio Antônio Gonçalves Jacovine:** Conceptualization, Funding acquisition, Supervision. **Eliana Boaventura Bernardes Moura Alves:** Supervision, Writing - original draft, Writing - review & editing. **Carlos Moreira Miquelino Eleto Torres:** Visualization, Writing - original draft, Writing - review & editing. **Isabella Salgado Faustino:** . **Luciano Cavalcante de Jesus França:** Investigation, Methodology, Project administration. **Samuel José Silva Soares da Rocha:** Investigation, Methodology, Project administration. **Guilherme Ferreira Simiqueli:** Investigation, Methodology, Project administration. **Lauana Blenda Silva:** Writing - original draft, Writing - review & editing. **Ricardo Alcántara-de la Cruz:** Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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