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Original Article

Silviculture

Inventory of Organic Carbon in a *Pterogyne nitens* Tul. Plantation in Southwest Bahia, Brazil

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ABSTRACT

Carbon binding capacity varies between forest plantations, mainly in terms of species and climate and soil conditions. The objective of this study was to estimate the amount of organic carbon stored in aerial tree biomass in the litter and soil of a homogeneous planting of *Pterogyne nitens* Tul. located in the Southwest Bahia region of Brazil. The woody biomass was obtained by destructive method. Litter collection was carried out using a wooden template (0.25 m^2). Soil samples were collected at four depths (0-5, 5-10, 10-20 and 20-40 cm). The carbon stored in all studied compartments totaled 47.1 Mg ha^{-1} with a greater contribution from the ground (31.4 t ha^{-1}). The accumulated litter was the lowest carbon compartment, storing about 1.4% of the total. Among the different fractions of the biomass, the stem is the largest carbon reservoir, representing about 46% of fixed C biomass.

Keywords: arboreal biomass, litter, soil, carbon dioxide, native species.

1. INTRODUCTION

Carbon dioxide (CO_2) concentration in the atmosphere has increased over the years, changing from 280 ppmv in 1750 to 367 ppmv in 1999 (Lal, 2004), and reaching the order of 390 ppmv nowadays (Pachauri & Meyer, 2014). CO_2 is considered the most relevant among greenhouse gases due to the increase in its concentration in the atmosphere. Among the alternatives to reduce atmospheric emissions of CO_2, to decrease burning of fossil fuels and deforestation for establishing low productivity farming systems may be highlighted, in addition to promoting large-scale reforestation (Watzlawick et al., 2012).

The forest ecosystem can be a source of replenishing carbon (C) into the atmosphere due to reduced productivity, increased mortality rates and soil exposure as a consequence of anthropic or natural actions such as the use of fire and conventional techniques of soil preparation, suppression of native vegetation, and climate change, among others. On the other hand, it can also contribute to C draining, especially during soil repopulation with forest plantations (Hosokawa et al., 1998). These plantations have great capacity to fix CO_2 in the atmosphere, and for this reason are considered an important strategy for long term C storage in plant biomass, as well as in litter and soil, which constitute reservoirs and potential atmospheric CO_2 sinks (Castro, 1996).

Carbon fixation capacity is highly variable among forest plantations, mainly in relation to the planted species and climate and soil conditions (Masera et al., 2003). Several studies related to the quantification of biomass and carbon stocks have been developed in Brazil, both in native forests (Caldeira et al., 2004; Chambers et al., 2001; Higuchi et al., 2004; Morais et al., 2013; Nelson et al., 1999; Sallis et al., 2006; Scolforo et al., 2016; Silva et al., 2015) and in planted forests of exotic species, mainly of the genera *Eucalyptus* and *Pinus* (Balbinot et al., 2003; Barreto et al., 2014; Dalla-Corte & Sanquetta, 2007; Faria et al., 2008; Gatto et al., 2010; Lima et al., 2016; Watzlawick et al., 2013). However, the number of studies that quantify C-fixation capacity in forest plantations of native species is still limited (Caldeira et al., 2003; Gama-Rodrigues et al., 2008; Thompson, 2009; Watzlawick et al., 2003), in particular under the conditions of the Northeast region of the country.

Among the native species that present potential for use in reforestation programs in the Northeast region of Brazil, the *Pterogyne nitens* Tul., also popularly known as *madeira-nova* and *amendoim-bravo*, stands out for generating wood with economic value for diverse purposes, as it has fast growth and adapts well to the region's environmental conditions (Lorenzi, 1998). Such adaptation is attributed to its ease of establishment in soils which are poor in nutrients and organic matter, due to its ability to fix nitrogen by symbiosis with diazotrophic bacteria and mycorrhizal fungi (Franco et al., 1995). Despite the proven importance of this species, little is known about its ability to fix carbon. In a study carried out in a homogeneous plantation of *Pterogyne nitens* at 6 years of age, Fraga et al. (2014) reported a wood volume of approximately 51 m^3 per hectare, which is an indicative of its biomass accumulation potential, and consequently of C storage.

Given this context, the objective of this study was to estimate the amount and distribution of organic C stored in aerial biomass components, litter and soil of a homogeneous 6-year-old plantation of *P. nitens*.

2. MATERIALS AND METHODS

2.1. Study area characterization

This study was carried out in a homogeneous 6-year-old plantation of *Pterogyne nitens* Tul. located in the experimental area of the Universidade Estadual do Sudoeste da Bahia (Uesb), municipality of Vitória da Conquista, BA, Brazil. The plantation was established according to 3 m × 3 m spacing, with seminal seedlings and fertilization located in the pit (100 g of simple superphosphate). Soil preparation consisted of trenching and opening the pits. Weeding the lines and between the lines was carried out for controlling spontaneous weeds at two, six and 12 months after planting.

The region has flat to slightly undulating relief (average altitude of 840 m). The climate is subtropical highland (Cwb) according to Köppen's classification with average temperature and annual rainfall of 25 °C and 850 mm, respectively. The predominant vegetation in the region is classified as Semi-Deciduous Seasonal Forest Montana, known regionally as Liana Forest. The soil of the studied

Table 1. Chemical and granulometric composition of soil under a homogeneous *Pterogyne nitens* plantation in Southwest Bahia, Brazil.

Depth	Clay	Silt	Sand	pH	N	P	K	Ca	Mg	H+Al
cm	------- g kg^{-1} -------				g kg^{-1}	---- mg kg^{-1} ---		----- cmol$_c$ kg^{-1} -----		
0-5	608	12	380	5.57	1.78	1.39	83.82	1.24	1.14	2.86
5-10	547	33	387	5.25	1.31	1.23	44.25	0.97	0.83	3.05
10-20	575	60	365	5.58	1.19	1.33	22.36	1.01	0.75	3.11
20-40	530	35	435	5.25	0.93	1.26	12.42	0.78	0.61	2.91

Analysis performed according to Embrapa (1997): pH (water); P and K extractable by Mehlich-1; Ca, Mg and Al exchangeable by KCl 1 mol L^{-1}.

area is classified as Dystrophic Yellow Latosol (Santos et al., 2006), with a texture ranging from very clayey to clayey (Table 1). Table 1 presents the chemical and granulometric characterization of the soil at depth of 0-40 cm.

2.2. Biomass and carbon

Biomass and C stock quantification were performed in three compartments of the ecosystem: tree biomass, litter and soil.

In order to obtain the diametrical distribution of the trees, the stem diameter at the height of 1.30 m from the soil level (DBH) of all individuals of the stand was measured. Because the species present predominantly more than one stem, the DBH of all stems originating up to 1.30 m were included. The DBH measurements of the stems were grouped into six classes considering an amplitude of 2.1 cm, corresponding to the standard deviation of the obtained DBH measurements.

Eighteen trees were selected for quantifying tree biomass with representative stems from all diametric classes, totaling 54 sampled stems. The number of sampled trees was based on referenced literature studies, which adopted a sample number between 10 and 35 trees (Caldeira et al., 2011; Melo et al., 2014; Moura et al., 2006; Saidelles et al., 2009; Sanquetta et al., 2003; Vieira et al., 2009).

After felling, the sample trees were fractionated considering the simple separation method (Sanquetta et al., 2004). While still in the field, each tree component (leaves, branches and stem with the bark) was weighed using a mechanical scale with a capacity of 150 kg and a precision of 50 g to obtain the fresh biomass of each individual per compartment. After weighing, samples of about 300 g were taken from each tree compartment and taken to the laboratory where they were weighed and kept in a forced circulation drying oven at 60 °C until the stabilization of its dry mass was complete.

The dry biomass of the tree components was estimated by multiplying the wet biomass by the conversion factor (ratio between dry and wet mass of the samples). Thus, the total dry biomass of each tree was obtained by the sum of the dry biomass of all measured compartments. In turn, the total biomass per hectare of each component was calculated by multiplying the mean value of the trees by the estimated number of trees per hectare at 6 years of age (1,000 trees), taking into account the initial planting mortality.

Carbon content of the tree components' biomass samples was determined using a Leco C-144 carbon analyzer at the Center for Excellence in Research on Biomass Carbon Fixation (Biofix) of the Universidade Federal do Paraná (UFPR). Carbon stocks per tree (kg) and area (Mg ha^{-1}) were estimated based on the dry biomass values of the trees and their respective C contents.

For soil sample collection, four plots of 21 m × 21 m dimensions were established, which were randomly distributed within the plantation area. The sampling was performed at four depths (0-5, 5-10, 10-20 and 20-40 cm). Four trenches of 0.4 m × 0.4 m were randomly opened in each plot from which simple samples were collected and then gathered to form a composite sample of each depth. In addition, an undeformed sample was also taken by depth using a volumetric ring to determine soil density.

For the sampling of accumulated litter on the soil surface, 20 plots of 15 m × 15 m were demarcated according to a random walk through the stand. Collection was carried out in each plot with the aid of a wooden mold in 0.25 m^2 of useful area (0.5 m × 0.5 m) which was randomly cast onto the soil with three repetitions that were then pooled to form a composite sample. The material circumscribed by the mold was carefully removed, avoiding collection of soil and live roots. All deciduous plant material deposited on the soil at different degrees of decomposition was considered litter. After collection, the sampled material was screened (five fractions were separated: leaves, branches, bark, reproductive structures and amorphous material), dried in a forced ventilation oven (at 60 °C until constant weight), weighed on a precision scale (0.01 g) and milled to the consistency of powder using a six-knife mill and metal sieves. The dry mass results (g) of the sum of the three samples from each plot were converted to Mg ha^{-1}.

The determination of organic C from soil and litter was carried out by oxidation in acid medium using $Na_2Cr_2O_7$ 4 N (Embrapa, 1997) and $K_2Cr_2O_7$ 4 N (Anderson & Ingram, 1996), respectively. Soil density was calculated based on the Kopecky ring method (Embrapa, 1997).

Carbon stocks at each soil depth were estimated according to the equation $CS = C \times Sd \times Tck \times 10$, in which CS represents C stock in Mg ha^{-1}; C, the content of this element in g kg^{-1}; Sd, soil density in kg dm^3; and Tck, the thickness of the layer under analysis in meters. To verify trends of C increase or reduction in different soil depths, and considering that the analyzed layers presented variable thickness, an estimate of stored C per centimeter of depth was performed (Mg ha^{-1} cm^{-1}) by dividing the C stock by the thickness (cm) of each layer, as adopted from Barreto et al. (2011).

3. RESULTS AND DISCUSSION

3.1. Diameter distribution

The studied stand had trees with a minimum diameter of 1.8 cm and a maximum of 13.6 cm. The frequency distribution of the individuals by grouping into six diametric classes with amplitude of 2.1 cm corresponded to normal distribution according to the Shapiro-Wilk normality test, with a higher concentration of individuals in more central classes (of 4.2 and 6.3 cm) (Figure 1), a characteristic pattern of even-aged forest stands (Machado & Figueiredo Filho, 2003).

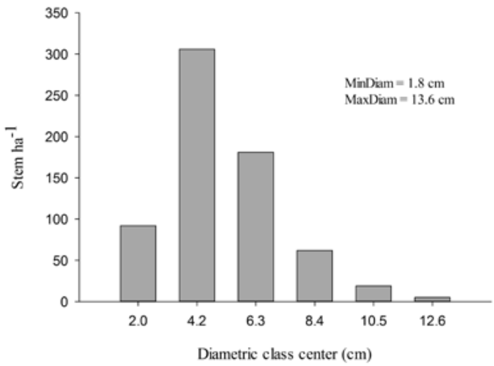

Figure 1. Diametric distribution of stems in a homogeneous *Pterogyne nitens* plantation.

3.2. Organic carbon in aerial biomass

The C stock of tree biomass in all components totaled approximately 15.0 Mg ha^{-1} (Table 2). The component with the highest participation was the stem, with 7.2 Mg ha^{-1}, which represented about 46% of the total C stock in the biomass. This was followed by the branches (43%) and leaves (12%). This same distribution sequence was observed by Caldeira et al. (2003) in a 6-year-old *Acacia mearnsii* stand and by Watzlawick et al. (2003) in a 30-year-old *Araucaria angustifolia* plantation. The contribution proximity of the tree and branch components in the total biomass composition (both with a share of over 40%) is possibly related to the fact that the species exhibit several stems and bifurcations in virtually all stems. Therefore, this anatomical characteristic would be responsible for the high branch biomass (12.6 kg $tree^{-1}$).

Leaves presented the highest levels of C (48%) among the aerial biomass components, followed by branches and stems (46%) (Table 2). In analyzing several species of Dense Tropical "Terra Firme" Rainforest in the Amazon region, Higuchi & Carvalho (1994) found mean C contents of 48% for stem and branches and 39% for leaves. Dallagnol et al. (2011) found higher levels in *Araucaria angustifolia* needles (47%) and in *Populus* sp. branches (45%).

3.3. Organic carbon in litter

The total dry biomass of litter on the soil was 1.5 Mg ha^{-1} and it had 42% of C content, which corresponds to 0.7 Mg of C ha^{-1} (Table 3). This content is higher than

Table 2. Dry biomass, concentrations and amounts of organic carbon components of 6-year-old *Pterogyne nitens* trees.

Component	Biomass		Carbon			% of total carbon
	kg tree^{-1}	Mg ha^{-1}	%	kg tree^{-1}	Mg ha^{-1}	
Leaves	3.24 (0.64)	3.60	48.46	1.57 (0.31)	1.74	11.59
Branches	12.57 (2.6)	13.97	46.06	5.79 (1.18)	6.43	42.84
Stems	13.37 (1.5)	14.85	46.07	6.16 (0.70)	6.84	45.57
Total	29.18	32.42		13.52	15.01	100.00

%: carbon concentration; % of total carbon: proportion of total carbon fixed in tree biomass; values in parentheses refer to the mean standard error (n = 18).

that indicated by the Intergovernmental Panel on Climate Change (Eggleston et al., 2006), which suggests 37% for the litter. Torres et al. (2013) observed an average of 52% of C content in the litter in a Semi-Deciduous Seasonal Forest in Minas Gerais. On the other hand, Higuchi & Carvalho (1994), in a Tropical Forest in the Amazon Region, and Morais et al. (2017), in the Cerrado vegetation of the state of Minas Gerais, found mean C contents in the litter of 39% and 44%, respectively.

The amount of C stored in the litter found in the present study (Table 3) was similar to the amount found by Gama-Rodrigues et al. (2008) in Claraíba stands (*Cordia trichotoma* (Vell.) Arrab.) in the Southeast of Bahia at 22 years of age (1.4 Mg of C ha^{-1}). However, higher values have been reported in other studies, such as those by Watzlawick et al. (2002) in a Mixed Ombrophilous Forest Montana in Paraná (2.90 Mg ha^{-1}), and by Schneider et al. (2005) in 4-year-old *A. mearnsii* stands in Rio Grande do Sul (2.26 Mg ha^{-1}).

The fraction that most contributed to the total litter composition were the branches (Table 3), which can be attributed to the fact that these components are made of woody materials which are more resistant to decomposition than non-lignified leaves and tender branches (Swift et al., 1979). These results contrast with those found by Schumacher et al. (2004), Pires et al. (2006) and Ferreira et al. (2007), who found a greater contribution of the leaves in the accumulated litter in Araucaria, Restinga and Sabia forests, respectively. It is probable that the lower participation of the leaves in the litter composition in this study has been determined by a low C/N ratio, and consequently a higher decomposition rate of the leaf component, since the studied species is a nitrogen fixation legume (Silva et al., 2004).

Similarly to what was observed for dry biomass, the branches component had the highest amount of C fixed per hectare, representing more than 60% of the carbon stored in the litter (Table 3). However, the C content of this component (45%) was similar to that found in the leaves (46%), which contributed 37% of the litter C. The other components had small participation in the total C composition: bark (0.5%), reproductive structures (0.6%) and amorphous material (1.5%).

3.4. Organic carbon in soil

The amount of C stored in soil up to 40 cm was 31.4 Mg ha^{-1}, with contents between 6.5 and 10.4 g kg^{-1} (Table 4). Caldeira et al. (2003) observed lower results for the same depth under 6-year-old *A. mearnsii* plantation soils in Rio Grande do Sul (19.7 Mg ha^{-1}). However, Balbinot et al. (2003) observed superior results (148 Mg ha^{-1}) in soils under 5-year-old *Pinus taeda* plantations.

Variations between forest stands and their capacity to store carbon in the soil can be attributed to differences in the amount and quality of litter that contributed to the soil over the years, as well as to root turnover. Thus, the C stock of 10.2 Mg ha^{-1} found in the 0-10 cm layer of soil could be a consequence of an accumulation of 1.5 Mg ha^{-1} of litter (Table 4). In soils with similar granulometric composition, a more easily decomposable litter generally results in lower C accumulation when compared to a more recalcitrant litter composed of more resistant substances to decomposition (Gama-Rodrigues et al., 1999).

The C soil stock was higher in the surface layers and decreased with increasing depths (Table 4). By adding carbon accumulations (Mg ha^{-1}) of the first three soil layers, it can be noted that the 0-20 cm layer stores about 60% of the total stored in the 40 cm profile (Table 4), and that shows the strong influence of forest cover on C distribution in the soil. In evaluating the carbon stocks at 100 cm depth of soil under *Pinus*

Table 3. Dry biomass levels and amounts of organic carbon components of accumulated plant litter in homogeneous 6-year-old *Pterogyne nitens* plantation.

Component	Biomass Mg ha^{-1}	Carbon		% of total carbon
		%	Mg ha^{-1}	
Leaves	0.527 (0.07)	45.94 (1.04)	0.242	37.17
Branches	0.888 (0.17)	44.99 (1.25)	0.392	60.22
Bark	0.007 (0.01)	43.48 (1.09)	0.003	0.46
RS	0.010 (0.01)	42.91 (1.18)	0.004	0.61
AM	0.064 (0.05)	30.12 (1.83)	0.010	1.54
Total	1.496		0.651	100

% of total carbon: proportion of total carbon fixed in the litter biomass; RS: reproductive structures; AM: amorphous material. Values in parentheses refer to the standard error of the mean (n = 20).

Table 4. Organic C content (g kg^{-1}) and stocks (Mg ha^{-1}) from depths of 0-5, 5-10, 10-20 and 20-40 cm soil under homogeneous *Pterogyne nitens* plantation.

Depth	Sd	Carbon			% of total carbon
cm	kg dm^{-3}	g kg^{-1}	Mg ha^{-1}	Mg ha^{-1} cm^{-1}	
0-5	1.11 (0.01)	10.40 (1.37)	5.77 (0.69)	1.04 (0.14)	17.22
5-10	1.00 (0.04)	8.81 (1.21)	4.41 (0.61)	0.88 (0.12)	14.57
10-20	1.06 (0.04)	8.29 (0.14)	8.79 (0.14)	0.83 (0.01)	27.46
20-40	1.01 (0.04)	6.15 (1.38)	12.42 (1.1)	0.62 (0.14)	40.74
Total			31.39		100.00

% of total carbon: proportion of total carbon fixed at 0-40 cm depth of soil; Sd: soil density. Values in parentheses refer to the mean standard error (n = 4).

taeda planting, Balbinot et al. (2003) found that 37% of the carbon was accumulated in the 0-20 cm layer.

It was also possible to observe a higher fertility level in the soil surface layer (0-5 cm) and a decrease in higher depths (Table 1). This distribution corroborates previously discussed results, evidencing the important contribution of the vegetation cover to improve soil characteristics, given the continuous deposition of organic residues which favors C storage and nutrient cycling in the most superficial layers. Similar results were found by Neves et al. (2004), Grimm et al. (2008), Qiji et al. (2008) and Neumann-Cosel et al. (2011). According to Gama-Rodrigues et al. (2008), it is common to verify the increase of the sum of bases in the superficial soil layers in tree legume plantations soon after the beginning of crop stabilization.

3.5. Total carbon stock

The C stored in all studied compartments totaled 47.1 Mg ha^{-1}, with the highest contribution from soil (31.4 Mg ha^{-1}), corresponding to 66.7%, followed by aerial biomass (15.0 Mg ha^{-1}) (31.9%) and litter (0.7 Mg ha^{-1}) (1.4%). These results confirm the premise that the soil compartment constitutes the main C sink of the atmosphere (Lal, 2004; Nair et al., 2009) and are in agreement with results reported by several studies such as by Caldeira et al. (2003) in an *A. mearnsii* stand in Rio Grande Sul, by Gatto et al. (2010) in *Eucalyptus* plantations in the Central-West region of Minas Gerais and by Gama-Rodrigues et al. (2011) in agroforestry systems in the South of Bahia, which verified C stocks in the soil on the order of 101, 122 and 300 Mg ha^{-1}, respectively.

4. CONCLUSIONS

The carbon stocked in all studied compartments totaled 47.1 Mg ha^{-1}, with greater contribution from soil (31.4 Mg ha^{-1} at 0-40 cm depth) and less from litter (0.7 Mg ha^{-1}). The stem constitutes the largest C reservoir of aerial tree biomass, representing around

46% of total fixed C (15.0 Mg ha^{-1}). A higher proportion of the total C stored in the soil up to 40 cm is in the 0-20 cm layer (about 60%).

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