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FORESTRY SCIENCE

Modeling of biomass and stored carbon in a seasonal semidecidual forest in Brazil

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Abstract: This study estimated biomass and carbon from components, future carbon values and to obtain economic productive value of carbon fixation of a Seasonal Semideciduous Forest. Biomass and carbon were estimated using adjusted equations and selected using regression statistics. The prognosis of the diametric distribution was performed using the movement ratio method. In the economic evaluation, it was estimated productive value of the stand, referring to the current and future carbon fixation capacity. The coefficients of determination (adjusted R^2) of the equations ranged from 0.11 to 0.90 and the standard error of the estimate (Syx) ranged from 41.53% to 141.89% for the biomass of the components, and from 0.03 to 0.87 for adjusted R^2 and from 46.20% to 143.64% for the error, for stored carbon in the components. The total biomass of the tree component estimated was 56.25 t ha^{-1} and 25.88 t ha^{-1} of total carbon. Using the future distributions by the method of the ratio of movements, total stored carbon (aerial + roots) estimated was 14.44 t. ha^{-1} over the 20-year period. The productive value for the fragment reached R$ 299.95 per ha. $year^{-1}$.

Key words: Allometric Equations, carbon credit, forest modeling and simulation, forest management.

INTRODUCTION

Terrestrial ecosystem is one of the most important for the global carbon cycle, among them, forests store a significant amount of carbon and its distribution plays an important global role (Ali et al. 2019). Thus, due to the woody nature of trees, the biomass of forest ecosystems has the capacity to accumulate and to store large amounts of carbon and, therefore, has great potential in the current scenario of discussions on climate change (Adnan et al. 2014), as a potentially significant carbon (C) reserve (Yatskov et al. 2019).

Greenhouse gases (GHG), CO_2 (carbon dioxide), N_2O (nitrous oxide) and CH_4 (methane), which represent approximately 1% in the atmosphere, are the most impactful (Sá et al. 2019) and the largest responsible for raising the temperature on the Earth. These emissions of CO_2 and other greenhouse gases in the atmosphere, as a result of anthropogenic activities, have caused the imbalance on the globe, resulting in global warming and, as a consequence, climate change, which have become priority issues on the world political agenda (IPCC 2014, Olorunfemi et al. 2019).

At the 2015 international climate summit in Paris, the parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed on the objectives of limiting global warming below

2°C and seeking efforts to further limit the increase in temperature at 1.5°C (Volkova et al. 2019). The parties agreed to develop rules and procedures to achieve these goals, to put the world on the right path to avoid dangerous climate change (UNFCCC 2015). The conservation, protection and restoration of native forests was one of the main goals set (Morais Júnior et al. 2020), given their ability to decarbonize the atmosphere, forests are also an important regulatory mechanism of the climate system (Prăvălie 2018). Forests are estimated to store approximately 45% of the carbon (C) of terrestrial systems, represent approximately 50% of net terrestrial primary production and can store more than 25% of anthropogenic annual carbon emissions. In addition, they also mitigate global warming through evaporative cooling, namely the cooling of air determined by high rates of evapotranspiration, as is the case of tropical ecosystems (Bonan 2008).

This alternative to reduce the concentration of carbon dioxide by native forests will be a great opportunity for Brazil, a country with large forest biomes recovering from anthropic disturbances, such as the Seasonal Semideciduous Forest. Specifically in the State of Paraná, this forest formation belonging to the Atlantic Forest biome, which has been reduced to small fragments, and the Reduction of Emissions from Deforestation and Degradation (REDD) can be an economically viable, socially just and ecologically correct alternative (Pelletier et al. 2012, Sheng 2019).

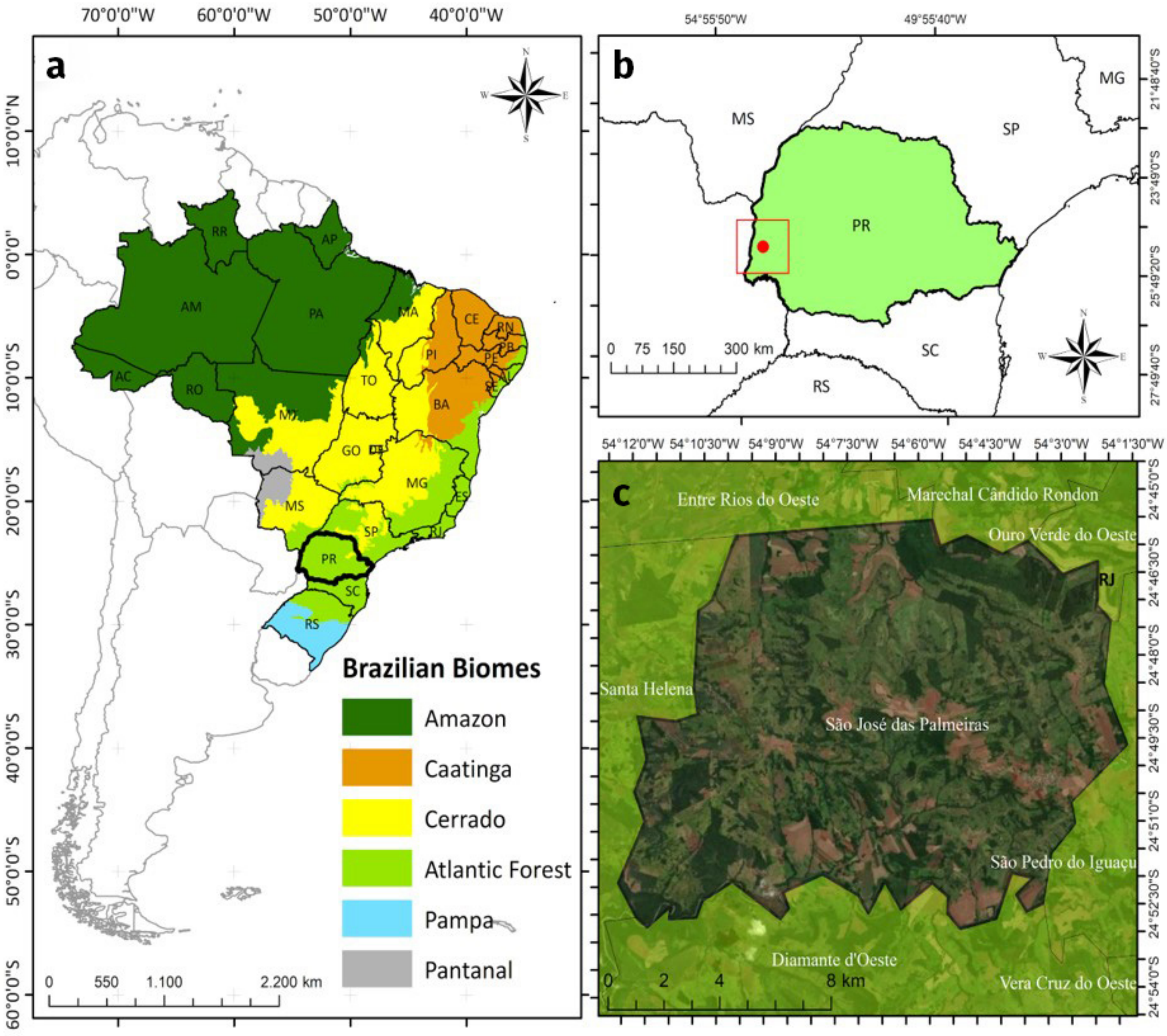
The biomass of tropical and subtropical forests has been studied for several purposes, highlighting the growing demand for information on carbon stocks, growth models and forest dynamics. As a result, the variables total biomass and its components are being included in the forest inventory reports (Affleck & Diéguez-Aranda 2016). Measuring these variables through the destructive path takes a long time and generates high costs, when compared to other dendrometric variables (Balbinot et al. 2017, Behling et al. 2018). An alternative to reduce time and cost is the use of allometric equations, which generally use the diameter at 1.3 m from the ground and the total height of the tree as independent variables in the equations (Brown 1997, Balbinot et al. 2019).

Currently, there are still scientific gaps regarding the quantification of carbon stocks in different forest formations and other methodological aspects, these being the main scientific obstacles to include the forest issue in an important alternative mechanism. Thus, the objectives of this study were: a) to estimate biomass and carbon; b) future carbon values; c) the economic productive value of carbon fixation for a seasonal semideciduous forest.

MATERIALS AND METHODS

This study was carried out in a Seasonal Semideciduous Forest located in the county of São José das Palmeiras, in the western region of the State of Paraná, Brazil (Figure 1). This region is part of a project aimed at monitoring the forests in Paraná, with units present in the Seasonal Semideciduous Forest and Subtropical Ombrophilous Forest, coordinated by the Rureco Foundation.

Previously, the study area was intended for the commercial production of mint with some scattered trees, and for about 20 years, the site has not been interfered with. According to the Köppen classification, climate in the study area is Cfa, humid subtropical with hot summers, mean annual temperature of 20.8°C, and rainfall distributed throughout all months of the year, with annual precipitation of approximately 1750 mm (Alvares et al. 2013). The predominant soil classes area of the type Nitisols (WRB/FAO 1998) or Ultisols (Soil Taxonomy 2006) or Nitossolos (in portuguese) (SIBCS-EMBRAPA 2013), well developed physically, with high natural fertility (Bhering 2007). A detailed



Geographic Coordinate System / Datum: WGS 1984 / Elaboration: Luciano C. J França / Sources: ESRI images

Figure 1. Location of the study area in the context of the biomes of Brazil (a), State of Paraná (b) and municipality of São José das Palmeiras – PR (c).

characterization of the structure and recognition of soils in the west of the State of Paraná and more information on regional physiography can be seen in Larach et al. (1972).

Thirty-two trees from 29 species were felled for sampling biomass and for adjusting allometric models. Biomass was determined using the destructive method of the individual tree. For the representativeness of the population, the species selection was carried out with the highest importance values obtained through permanent plots. Each tree had its biomass separated into six compartments, namely: stem, bark, live branches, dead branches, leaves and miscellaneous (fruits, flowers, seeds). The weighting of the green biomass of the compartments was carried out using a pole scale. For the bark, the disks in the lower, middle, and upper positions of the tree were collected and weighted, on a precision electronic scale, to determine the proportion between bark and stem wood.

The weight of the root biomass has not been estimated. However, the percentage of total biomass was used, as verified by Brun (2004), in Deciduous Seasonal Forest, with a value of 77.6% of the biomass being found above the ground, and the roots represent about 22.4%, with 20% being added to the value of carbon stored in tree biomass to estimate the total.

Samples of approximately 1 kg were collected from each compartment to determine the dry biomass content, as described in (Miranda et al. 2011). The total biomass determination of different compartments was calculated by the ratio between the weight of dry biomass and of green biomass (Miranda et al. 2012). After drying and grinding the samples in a mill, the organic carbon analyzes in the vegetable tissue were carried out in the laboratory by the WALKLEY-BLACK method, with external heat, proposed by Tedesco et al. (1995).

The diameter at breast height (DBH) and height were measured in each tree. To adjust the equations, 17 models were used to estimate total stored biomass and compartments (Table I).

The statistical criteria for selecting the best models were adjusted determination coefficient (R² aj), standard error of the estimate expressed as a percentage (Syx%). In the models in which the dependent variable underwent logarithmic transformation, R² was recalculated considering the logarithmic discrepancy using the Meyer index (Orellana & Koehler 2008, Miranda et al. 2011).

Table I. Models used to estimate biomass and stored carbon.

N	Mathematical Models
1	$Y = B_0 . d^{B1}$
2	$Y = B_0 + B_1.d + B_2.d^2$
3	$Y = B_0 + B_1.d + B_2.(d^2.h)$
4	$Y = B_0 + B_1.d + B_2.d^2 + B_3(d^2.h)$
5	$Y = B_0 + B_1.d^2 + B_2.(d^2.h)$
6	$Y = B_0 + B_1.d + B_2.h$
7	$Y = B_0.d^{B_1}.h^{B_2}$
8	$Y = B_0 + B_1.d$
9	$Y = B_0 + B_1.d^2$
10	$Y = B_0 + B_1.d^3$
11	$Y = B_0 + B_1.(d^2.h)$
12	$LnY = B_0 + B_1.Ln(d^2.h)$
13	$Y = B_0 + B_1.d + B_2.d^2 + B_3.d^3$
14	$Y = B_0 + B_1.d + B_2.d^2 + B_3.d^3 + B_4.d^4$
15	$Y = B_0 + B_1.d + B_2.d^2 + B_3.d^3 + B_4.d^4 + B_5.d^5$
16	$LnY = B_0 + B_1.Ln(h)$
17	$Y = B_0 + B_1.d^2 + B_2.h^2$

To estimate the amount of total carbon stored in the tree component, the sum of the dry biomass results multiplied by the carbon content of each compartment was analyzed. In estimating the litter component, 50 sample units were installed with an area of 625 cm² (25 x 25 cm) each, allocated in the odd subunits of the permanent sample unit, arranged one at the bottom and another at the top. The material was collected and weighed in the decomposition stage, each with an approximate value of 1 kg, for later drying and carbon content determination. To estimate biomass of the understory component, 25 sample units of 1 m² were installed, arranged in all odd subunits, where the collection and weighing of all living material was carried out, which were dried in the laboratory, and then the dry weight and carbon content were determined. To estimate the amount of carbon dioxide (CO_2)

Table II. Equations for estimating the biomass of live branches.

	Equations	$R^2_{adjusted}$	S_{yx}%
1	$\log PSgv = -1.2034 + 1.8234 . \log d$	0.36	81.63
2	$PSgv = 3.2389 - 0.4898\ d + 0.066\ d^2$	0.36	83.47
3	$PSgv = -1.022 + 0.4502\ d + 0.0020\ (d^2h)$	0.33	84.92
4	$PSgv = 3.1992 - 0.7600\ d + 0.1412\ d2 - 0.0049(d^2h)$	0.34	84.46
5	$PSgv = -0.589 + 0.0979\ d^2 - 0.004(d^2h)$	0.36	83.05
6	$PSgv = -2.3566 + 1.4059\ d - 0.6582\ h$	0.35	83.64
7	$\ln PSgv = -2.2065 + 2.3848 . \ln(dap) - 0.8485 . h$	0.35	83.85
8	$PSgv = 4.8017 + 1.0626\ d$	0.35	83.72
9	$PSgv = 0.6205 + 0.04660\ d^2$	0.38	81.90
10	$PSgv = 2.5386 + 0.0023\ d^3$	0.38	81.88
11	$PSgv = 1.8643 + 0.0035\ d^2\ h$	0.36	83.43
12	$\ln PSgv = -2.7790 + 0.6174 \ln (d^2\ h)$	0.33	85.08
13	$PSgv = 0.6516 + 0.2632\ d - 0.00015\ d^2 + 0.0018\ d^3$	0.33	85.32
14	$PSgv = 106.5528 - 41.1996\ d + 5.7140\ d^2 - 0.3275\ d^3 + 0.0067\ d^4$	0.34	84.25
15	$PSgv = -5.5624 + 15.5334\ d - 5.2496\ d^2 + 0.6840\ d^3 - 0.0378\ d^4 + 0.0007\ d^5$	0.32	85.98
16	$\ln PSgv = -1.2982 + 1.2157 \ln h$	0.09	98.73
17	$PSgv = 1.4819 + 0.0656\ d^2 - 0.0247\ h^2 - 0.00068\ (d^2\ h)$	0.34	84.40

stored in the forest, total carbon values estimated in the components were used multiplied by the conversion factor obtained by the ratio between atomic mass of carbon dioxide (44) and atomic mass of carbon (12), resulting in a factor of 3.6667. To estimate the productive value of carbon dioxide fixation in the forest, the diametric distribution of the forest for 2031 was first projected using the movement ratio method (Asrat & Tesfaye 2013, Lana et al. 2015). This method consisted of projecting the number of individuals by classes of DBH, based on the periodic increments and adjustment of equations of ingrowth and mortality. For this, a non-linear model developed by Scolforo (1998) was adjusted. The calculation of the forest yield value was based on net revenues and future costs discounted for age of assessment Silva et al. (2005).

Ingrowth Model: $I_i = B_0 . e^{B_1} . d_i$ (1)

Mortality Model: $M_i = B_0 . e^{B_1} . d_i$ (2)

Where: I_i – Ingrowth; M_i – Mortality; d_i – class average diameter B_0 e B_1 – Model coefficients and *ei* – Model error.

RESULTS

Estimation of Biomass and Stored Carbon of Living Branches

The values of the adjusted equations statistics are presented in Table II, where equation 5 stands out from the others and shows a small improvement in the dispersion of residuals and R² adj. (0.36).

Equation 16 provided the lowest performance, having the total height as an independent variable, presenting a low correlation with live branches.

Using equation 5, the fragment living branches biomass was estimated, resulting in 10.1 t.ha^{-1}, in 2007. Brun (2004) evaluating the biomass in Deciduous Seasonal Forest, in Rio Grande do Sul, observed the value of 21.15 t.ha^{-1} for live branches, representing about 21% of the total forest biomass. When considered secondary forest, the live branches had a value of 44.71 t.ha^{-1}, representing 28% of the total biomass.

Martins (2011) evaluating the Mixed Ombrophilous Forest, estimated values for the biomass of live branches at 27.06 t.ha^{-1}. Watzlawick (2003), quantifying the biomass in Mixed Ombrophilous Forest, found that live branches represent 93.42 t.ha^{-1} of dry biomass, a value higher than that observed in the present study. Comparatively, it was observed that the present study had the lowest values for live branches biomass. This fact can be attributed to the morphological characteristics of species present in the study area, or even to the majority presence of small individuals, with small branches and, consequently, lower weights.

Using the average carbon content for live branches of 432.7g.kg^{-1}, it was estimated at 4.37 t.ha^{-1} of organic stored carbon in the vegetation living branches. Comparatively, Watzlawick (2003) evaluating carbon content in the Mixed Ombrophilous Forest found average values of 35.91 t.ha^{-1}. According to the author, in some sample units, carbon content was similar to that observed in the present study, such as 4.60 t.ha^{-1}.

Estimation of foliage biomass and carbon

None of the 17 models adjusted to estimate the foliage biomass presented satisfactory results, as can be seen in Table III. All equations presented low adjusted R^2, ranging from 0.00 to 0.22 and high Syx%, ranging from 132% to 152%. Such results are due to the low correlation between dentrometric variables, such as diameter and height of trees with leaf biomass.

Martins (2011) modeling the foliage biomass in Mixed Ombrophilous Forest, also obtained unsatisfactory results regarding the precision statistics for estimation of this parameter, with adjusted R^2 ranging from 0.393 to 0.391 and high Syx%, ranging from 138.06% to 164.53%. However, Socher (2004) in equations for a Mixed Alluvial Ombrophilous Forest, found adjusted R^2 of 0.705 and Syx% of 62.79%, better results than those found in the present work.

The determination coefficient values are low, and the error values are extremely high, therefore, it was decided not to estimate these parameters in view of the low efficiency of the tested models in representing the real forest values.

Estimate of Biomass and Stored Carbon in the Stem Wood

The statistics values of the adjusted models are presented in Table IV and indicate acceptable values for adjusted R^2. Equation 17 was selected to estimate biomass, with adjusted R^2 of 0.77 and Syx% of 53.91%.

The main stem estimated biomass was 42.11 t.ha^{-1}. Martins (2011) estimated values for stem biomass at 41.04 t.ha^{-1}, a value similar to that obtained in the present study. Watzlawick (2003) observed in the Mixed Ombrophilous Forest, stem wood biomass, of 86.29 t.ha^{-1}, a value considerably higher than that observed in the present study. The author observed that units with vegetation in

Table III. Equations for estimating foliage biomass.

	Equations	$R^2_{adjusted}$	S_{yx}%
1	$\log PSfol = -1.38571 + 1.84757.\log dap$	0.02	146.20
2	$PSfol = -16.7532 + 3.5168\ d -0.1224\ d^2$	0.11	141.89
3	$PSfol= -22.554 + 4.0381\ d - 0.0114\ (d^2h)$	0.22	132.81
4	$PSfol= -18.755 + 3.0034\ d + 0.1163\ d^2 -0.017\ (d^2h)$	0.21	133.82
5	$PSfol = -3.2630 + 0.264327\ .d^2 -0.01875\ (d^2h)$	0.17	137.57
6	$PSfol = 0.2592 + 1.0439\ d -0.6536\ h$	0.06	145.74
7	$\ln PSfol = -2.9415 + 2.1051.\ln dap -0.38184.\ln h$	0.00	151.09
8	$PSfol = -2.2310 + 0.6983\ d$	0.08	144.57
9	$PSfol = 1.9491 + 0.02508 d^2$	0.04	147.28
10	$PSfol= 3.3434 + 0.0010\ d^3$	0.01	149.70
11	$PSfol = 2.9608+ 0.0015\ d^2\ h$	0.01	149.61
12	$\ln PSfol = -3.3236 + 0.6230\ \ln (d^2\ h)$	0.00	140.41
13	$PSfol =-4.8675+0.0840\ d + 0.1811\ d^2 -0.0082\ d^3$	0.08	144.54
14	$PSfol = 166.5397 - 67.1761\ d + 9.4857\ d^2 -0.5470\ d^3 + 0.011\ d^4$	0.13	140.29
15	$PSfol=-83.3571+58.8349\ d -14.7684\ d^2 +1.6813\ d^3 -0.0868\ d^4 +0.00165\ d^5$	0.11	142.12
16	$\ln PSfol = -2.1188+ 1.4192\ \ln h$	0.00	152.84
17	$PSfol = -11.0348+ 0.4044\ d^2 + 0.0865\ h^2 -0.03229\ (d^2\ h)$	0.21	134.30

Table IV. Statistics of the equations for estimating the biomass of the stem wood.

	Equations	$R^2_{adjusted}$	S_{yx}%
1	$\log PSfus= 2.3822 + 3.4323.\log dap$	0.40	87.28
2	$PSfus= -8.487 + 0.5572\ d + 0.1854\ d^2$	0.70	61.63
3	$PSfus= -160383 + 0.7615\ d + 0.2725\ (d^2\ h)$	0.72	59.06
4	$PSfus= -6.6877 + 2.019\ d -0.3072\ d^2 + 0.034\ (d^2\ h)$	0.77	53.70
5	$PSfus= 3.718 -0.2056\ d^2 + 0.0327\ (d^2h)$	0.78	53.15
6	$PSfus= -34.2178 + 4.3537\ d + 0.9305\ h$	0.68	63.15
7	$PSfus= -5.7751+3.1494.\ln dap+0.4286.h$	0.28	95.50
8	$PSfus= -30.63 + 4.8336\ d$	0.69	62.55
9	$PSfus= -5.5095 + 0.2087\ d^2$	0.71	60.47
10	$PSfus= 3.4109 + 0.0139\ d^3$	0.68	63.84
11	$PSfus= -1.3001 + 0.0169\ d^2\ h$	0.77	54.24
12	$\ln PSfus= -6.0829 + 1.2489\ \ln (d^2\ h)$	0.62	69.28
13	$PSfus= 36.1683 -12.365\ d + 1.3326\ d^2 -0.0314\ d^3$	0.70	61.91
14	$PSfus= -335.057 + 133.18\ d -18.7779\ d^2 + 1.13162\ d^3 -0.02382\ d^4$	0.74	57.47
15	$PSfus= 1069.029 -574.97\ d + 117.63\ d^2 -11.4202\ d^3 +0.5283\ d^4 -0.0093\ d^5$	0.81	49.52
16	$\ln PSfus= -4.3659 + 3.0503\ \ln h$	0.47	80.73
17	$PSfus= 7.7789 -0.2749\ d^2 -0.0466\ h^2 +0.0395\ (d^2\ h)$	0.77	53.91

the initial succession stage showed values ranging from 25.55 t.ha^{-1} to 271.47 t.ha^{-1} in areas with more advanced successional stage forest.

The average carbon content for the stem wood was 444.12 g.kg^{-1}, estimating the organic stored carbon in the stem in 2007 at 18.7 t.ha^{-1}. Martins (2011) found a similar value, 18.36 t.ha^{-1}. Watzlawick (2003) observed higher values, with an average of 35.02 t.ha^{-1}, with values ranging from 10.78 t.ha^{-1} to 118.59 t.ha^{-1}.

Estimation of Biomass and Carbon of the Stem Bark

The statistics values of the adjusted models are presented in Table V and indicate high values of the coefficient of determination (adjusted R²) and the values of the standard error of estimate.

Using equation 4, the bark biomass was estimated, which resulted in 4.67 t.ha^{-1}, in 2007. Brun (2004) quantifying the bark biomass in Deciduous Seasonal Forest, found values of 7.68 t.ha^{-1}, in "capoeirão" formations, and found values of 10.65 t.ha^{-1}, in secondary forest. Martins (2011) estimated the bark biomass in remnants of Mixed Ombrophylous Forest, where he found the value of 9.68 t.ha^{-1}. Watzlawick (2003) found an average value of 21.21 t.ha^{-1} for the stem bark biomass in Mixed Ombrophilous Forest, with values ranging from 1.17 to 155.78 t.ha^{-1}.

The low value found for the biomass variable of the bark component cannot be attributed to the small size of the sampled individuals, which do not present thick and abundant bark. As observed by other authors, the bark biomass tends to increase in more advanced successional stages, where the presence of large individuals, with thicker and more abundant barks is greater.

The average carbon content for the bark was 410.52 g.kg^{-1}, obtaining 1.92 t.ha^{-1}, of organic stored carbon from the vegetation stem bark, with Martins (2011) estimating a value of 4.29 t.ha^{-1} for Mixed Ombrophilous Forest. Watzlawick (2003) in the same forest typology found the average for the carbon content of 8.12 t.ha^{-1}, ranging from 0.44 to 63.45 t.ha^{-1}.

The 29 species occurring in the forest presented an estimated content of biomass and carbon, corresponding to 74.8% of the total forest IV (Importance Value), indicating that these species represent well the structure of the remnant, and can be used to estimate these parameters for the rest of the forest. The IVs of each species, as well as the biometric values of DBH and height of each species can be found in Table VI.

Carbon Content by Species and Compartments

The average value of the carbon content was 431.68 g.kg-1. The average values of carbon content vary from 401.32 to 457.71 g.kg-1 among species, and from 410.52 to 444.12 g.kg-1 among compartments. The species Chorisia speciosa had the lowest average carbon content, with a value of 401.32 g.kg-1. The dead branch component was the one with the lowest carbon content (381.83 g.kg-1) being the lowest value observed among the compartments. The species Nectandra megapotamica had the highest average carbon content, with 457.71 g.kg-1. Dead branches presented the highest value with 502.35 g.kg-1. The leaves of Annona rugulosa had the highest carbon content among the compartments (518.42 g.kg-1). The carbon content in the compartments followed the trend: stem wood, foliage, dead branches, miscellaneous, live branches, and bark. The values of the individual carbon content and compartments of each species can be found in the Table VII.

Table V. Statistics of the equations for estimating the biomass of the bark of the bole.

	Equations	$R^2_{adjusted}$	$S_{yx}\%$
1	$\log PSc= -2.0419 + 2.3306 \log dap$	0.66	76.67
2	$PSc= -0.6744 + 0.1296\, d + 0.017\, d^2$	0.90	41.56
3	$PSc= -0.451 + 0.1583\, d + 0.0012\, (d^2\, h)$	0.91	39.79
4	$PSc= -0.7287 + 0.2899\, d -0.0289\, d^2 + 0.0031\, (d^2\, h)$	0.91	39.37
5	$PSc= 0.9178 -0.0047\, d^2 +0.00186\, (d^2\, h)$	0.90	40.65
6	$PSc= -4.1944 + 0.7434\, d -0.0783\, h$	0.85	50.68
7	$\ln PSc= -5.5258 +1.8332 \ln dap + 0.9037 \ln h$	0.84	52.06
8	$PSc= -4.6458 + 0.7187\, d$	0.85	50.00
9	$PSc= 0.2091 + 0.0204\, d^2$	0.90	41.26
10	$PSc= 1.6546 + 0.0006\, d^3$	0.86	49.17
11	$PSc= 0.7815 + 0.00151\, d^2\, h$	0.91	39.99
12	$\ln PSc= -5.5325 + 0.9135 \ln (d^2\, h)$	0.85	50.45
13	$PSc= -3.796 + 0.8711\, d -0.0337\, d^2 + 0.00094\, d^3$	0.90	41.53
14	$PSc= 3.296 -1.4782\, d + 0.2291\, d^2 -0.011 d^3 + 0.00017\, d^4$	0.90	41.81
15	$PSc= -53.7505 + 23.014\, d -3.6654\, d^2 + 0.2753\, d^3 -0.0095\, d^4 + 0.00012\, d^5$	0.91	39.60
16	$\ln PSc= -5.2979 + 2.7361 \ln h$	0.40	99.13
17	$PSc= -0.1231 + 0.0035\, d^2 + 0.01094\, h^2 +0.0011\, (d^2\, h)$	0.91	39.50

Table VI. List of species selected to adjust the allometric models.

Popular name	Scientific name	DBH	Ht	IV
catiguá miúdo	*Trichilia elegans* A. Juss.	19.6	5.98	0.15
leiteirinho	*Peschiera australis* (Mart. Ex A. DC.) Standl.	31	11.13	0.15
guaçatunga	*Casearia decandra* Jacq.	22.4	7.47	0.47
ariticum preto	*Anona rugulosa* (Schltdl.)	25.3	3.92	0.62
guabijú	*Myrcianthes pungens* (O. Berg) D. Legrand	35.4	8.86	0.65
pessegueiro bravo	*Prunus brasiliensis* (Cham. & Schlecht.) D. Dietrish	50	12.28	0.73
peroba	*Aspidosperma parvifolium* A. DC.	33.5	9.8	0.74
limão do mato	*Gymnanthes concolor* Spreng.	20.9	7.11	0.75
tapiá	*Alchornea triplinervia* (Spreng.) Müll. Arg.	34.5	8.85	0.81
ipê roxo	*Tabebuia impetiginosa* (Mart. ex A. DC.) Standl.	28.9	9.5	0.97
caliandra	*Calliandra foliosa* Benth.	17.7	5.3	1.18
ariticum	*Anona* sp.	28.4	8.52	1.24
uvaia	*Eugenia pyriformis* Camb.	23.1	8.9	1.35
figueira	*Ficus* sp.	40.7	9.83	1.56
louro	*Cordia trichotoma* (Vell.) Arráb. ex Steud.	34.2	13.17	1.86
guatambú	*Chrysophyllum gonocarpum* (Mart. & Eichl.) Engl.	29.9	8.77	2.38
angico vermelho	*Parapiptadenia rigida* (Benth.) Brenan	45.3	12.22	2.43
café de bugre	*Cordia ecalyculata* Vell.	24.7	7.48	2.55
guaritá	*Astronium graveolens* Jacq.	20.3	6.46	2.95
embaúba	*Cecropia pachystachya* Trécul	45	9.82	3.06
pau amargo	*Picramnia parvifolia* Engl.	23	7.1	3.12
farinha seca	*Albizia cf niopoides* (Spruce ex Benth.) Burkart	41.9	10.02	3.28
guateria	*Guarea kunthiana* A. Juss.	31.1	7.23	3.71
pau marfim	*Balfouridendron riedelianum* (Engl.) Engl.	29.9	12.29	4.26
paineira	*Erythrina falcata* Benth.	103.5	13.32	4.58
cabreúva	*Myrocarpus frondosus* Allemão	23.5	8.89	5.36
sapuva	*Machaerium stipitatum* (DC.) Vogel	37.2	11.91	5.82
canela imbuia	*Nectandra megapotamica* (Spreng.) Mez	61.6	12.05	7.05
lixeira	*Aloysia virgata* (Ruiz & Pav.) Pers.	32	9	11

Table VII. Carbon content for species and their components.

Scientific name	Popular name	Carbon Content - g kg^{-1}						
		Bark	Leaves	Stem	Dead branches	Live Branches	Miscellaneous	Average
Parapiptadenia rigida (Benth.) Brenan	angico vermelho	436.94	453.70	448.32	426.60	436.86	443.00	440.90
Annona sp.	ariticum	402.37	422.52	448.22	438.65	438.29	-	430.01
Annona rugulosa (Schltdl.) H.Rainer	ariticum preto	417.60	518.42	441.69	445.97	445.18	-	453.77
Myrocarpus frondosus Allemão	cabreúva	426.17	416.87	428.65	-	431.93	-	425.91
Cordia ecalyculata Vell.	café de bugre	405.40	428.20	438.23	433.89	433.76	-	427.90
Calliandra foliolosa Benth.	caliandra	405.84	420.45	444.82	-	432.81	437.61	428.30
Nectandra megapotamica (Spreng.) Mez	canela	396.48	482.66	455.22	502.35	451.82	-	457.71
Trichilia elegans A.Juss.	catiguá miúdo	415.95	462.56	447.94	-	443.98	-	442.61
Cecropia pachystachya Trécul	embaúba	399.31	395.11	451.63	431.49	433.24	-	422.16
Albizia cf niopoides (Spruce ex Benth.) Burkart	farinha seca	414.17	478.46	441.18	-	434.11	-	441.98
Ficus sp.	figueira	400.18	428.03	435.77	-	411.79	-	418.94
Myrcianthes pungens (O. Berg) D. Legrand	guabijú	407.26	408.89	451.42	-	423.68	-	422.81
Casearia decandra Jacq.	guaçatunga	389.27	473.44	436.87	423.63	426.50	-	429.94
Astronium graveolens Jacq.	guarita	409.68	457.21	429.23	416.18	428.57	-	428.17
Chrysophyllum gonocarpum (Mart. & Eichl.) Engl.	guatambu	398.18	462.15	443.31	424.61	434.66	-	432.58
Guarea kunthiana A. Juss.	guateria	405.16	385.39	441.78	427.25	409.78	-	413.87
Tabebuia impetiginosa (Mart. ex A. DC.) Standl.	ipê roxo	408.94	425.51	449.35	-	446.38	-	432.55
Peschiera australis (Müll. Arg.) Miers	leiteiro	400.20	439.79	462.96		429.41	-	433.09
Gymnanthes concolor Spreng.	limão do mato	409.27	413.00	435.26	427.71	431.04	-	423.26
Aloysia virgata (Ruiz & Pav.) Pers.	lixeira	411.23		443.97	440.42	441.23	-	434.21
Cordia trichotoma (Vell.) Arráb. ex Steud.	louro	414.23	414.73	453.03	432.79	429.36	448.41	432.09
Chorisia speciosa A.St.-Hil.	paineira	388.26	420.95	413.59	381.83	-	401.96	401.32
Picramnia parvifolia Engl.	pau amargo	402.58	418.04	444.89	430.55	437.70	-	426.75
Balfourodendron riedelianum (Engl.) Engl.	pau marfim	391.48	417.83	441.35	433.55	413.14	-	419.47
Aspidosperma parvifolium A. DC.	peroba	409.88	456.86	458.26	433.10	423.93	-	436.41
Prunus brasiliensis (Cham. & Schlecht.) D. Dietrish	pessegueiro bravo	456.44	467.94	448.82	451.09	447.91	-	454.44
Machaerium stipitatum (DC.) Vogel	sapuva	411.55	433.92	446.42	435.64	432.16	-	431.94
Alchornea triplinervia (Spreng.) Müll. Arg.	tapiá	435.26	465.58	439.13	439.90	436.01	-	443.18
Eugenia pyriformis Camb.	uvaia	402.41	411.08	449.07	441.25	430.25	-	426.81
Average / Component	--	410.52	437.79	444.12	434.49	432.70	432.74	431.68

Aboveground Biomass Estimate and Total Stored Carbon Estimate

Based on biomass and carbon data of the trees, models were adjusted to estimate total biomass and carbon and for the compartments. The statistics of the best-adjusted equations to estimate the tree component biomass are presented in Table VIII.

It was observed that for the biomass estimation in different compartments, the best performance, considering the adjusted R² was presented for stem bark. However, the compartment whose estimates presented the lowest standard error was the stem biomass. The adjusted equation for estimating leaf biomass was the one with the worst results. Thus, it was found that there is great variability due to the low correlation between the analyzed variables, which is considered normal in studies of natural forests. In the graphical analysis of the residues (Figure 2) it shows greater dispersion of the data in relation to the others, therefore, equation 2 was selected, with adjusted determination coefficient (R² adj.) In the value of 0.70 and standard error of the estimate 50.98%, showing more uniform distribution of waste compared to the others. On the other hand, equation 16, which had the total height as an independent variable, was the one with the worst results, with R² adj. = 0.39 and Syx% of 70.09%.

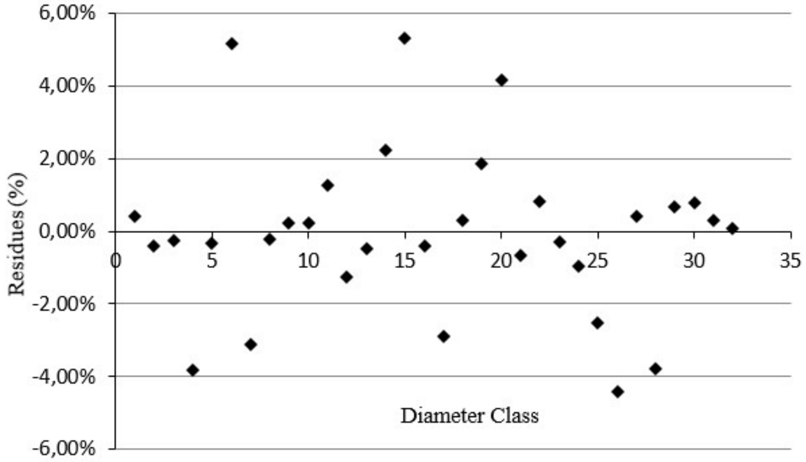
In view of the above, Figure 3 shows the biomass and carbon stocks in the compartments with the best results in adjusting the models, excluding the leaf and miscellaneous compartment due to insufficient data. In this Figure, it is observed that the concentration of biomass and carbon stocks are distributed as follows: stem wood, live branches, stem bark and dead branches. Stem biomass represented 74.8% of the total, and carbon 75.8%, highlighting this component as the main responsible for the accumulation of biomass and carbon in the forest.

The relationship between biomass and carbon, for the stem, live branches and for the total, were similar, of 0.47, 0.46 and 0.46, respectively, being slightly lower for the stem bark and dead branches, 0.40 and 0.37. Figure 4 shows the biomass and carbon values for the different components of the forest evaluated.

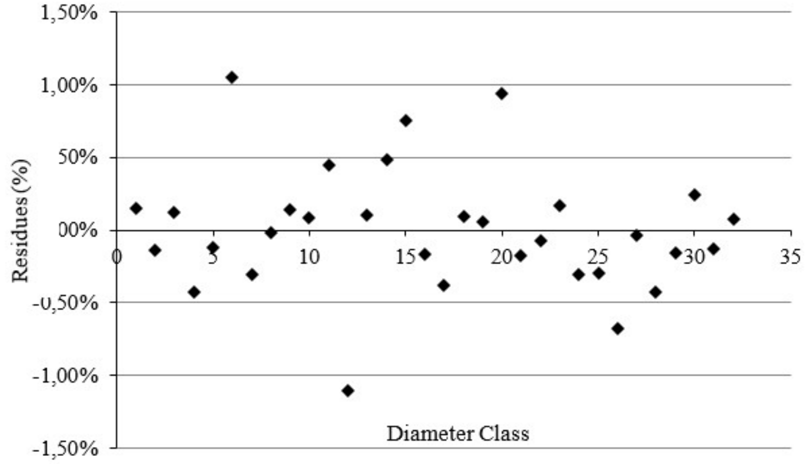
The estimated biomass and carbon values for the arboreal, litter and understory component were 90.79 t.ha^{-1} accumulated. For carbon, the total value considering the different components was 39.48 t.ha^{-1}. The tree component was the one that most contributed to the stock of biomass and carbon, representing 62% and 66%, respectively. On the other hand, the vegetation of the understory was the one that made the smallest contribution to the biomass and carbon stock with approximately 4%. It was also observed that the biomass/carbon ratio for the components was higher for tree vegetation and lower for litter.

Table VIII. Selected equations for aboveground biomass and regression statistics.

Arboreal component	Equation	Adjusted R²	Syx %
Total Biomass	$PS = -4.8639 + 0.3981.\ d + 0.2625\ d^2$	0.70	50.98
Live Branches	$PS = -0.589 + 0.0979\ d^2 - 0.004(d^2h)$	0.36	83.05
Dead Branches	$PS = -2.0051 + 0.1431\ d + 0.0611\ d^2 -0.0047\ (d^2h)$	0.76	48.39
Stem Bark	$PS = -3.7956 + 0.8711\ d - 0.0337\ d^2 + 0.00094\ d^3$	0.90	41.53
Leaves	$PS = -16.7532 + 3.5168\ d -0.1224\ d^2$	0.11	141.89
Stem	$PS = -\ 1.3007 + 0.0169\ d^2\ h$	0.77	28.00



Best performing model 2: PStotal = -4.8639 + 0.3981. d + 0.2625 d^2 / R^2 Adj. 0.70 Syx% 50.98



***Worst performing model 16*:** 16 ln PStotal = -1.34567 + 2.0084 ln h x 1.2877 / R^2 Adj. 0.39 / Syx% 70.09

Figure 2. Graphical analysis of the residues. *In order to select the best equations, the following statistical regression criteria were analyzed: adjusted coefficient of determination (R^2 aj.), Standard error of the estimate expressed as a percentage (Syx%) and graphical distribution of the residuals by diameter class.

Figure 3. Stock of biomass and organic carbon in the tree component. Note: Percentage in relation to the estimated total.

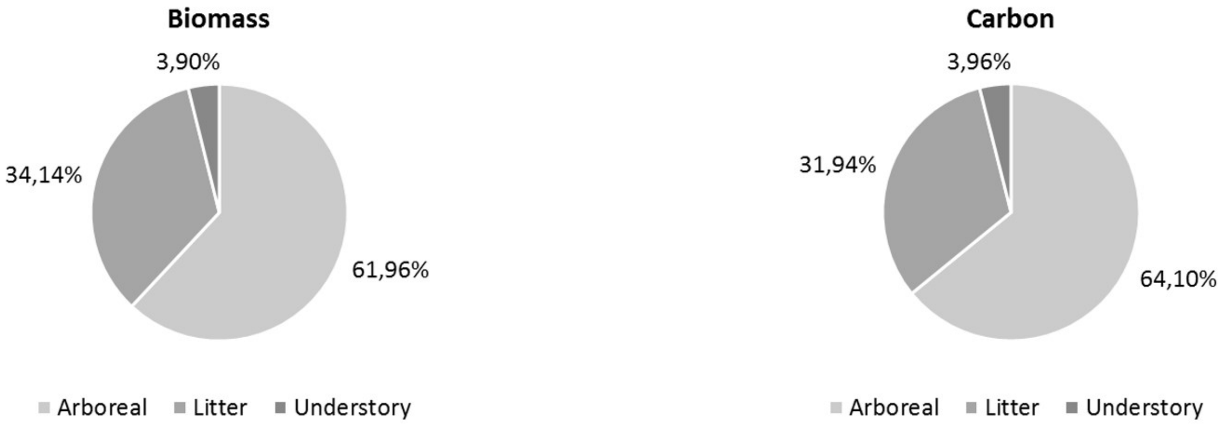


Figure 4. Estimated biomass and carbon for the components.

Effectively Sequestered Carbon Dioxide and amount generated in 40 years Projection

Using future distributions, total stored carbon (aerial + roots) was estimated every four years, until reaching 20 years of age, in 2031 (Figure 5). It was observed that there was a decrease in the carbon stored only in the first diametric class. As expected, in the other classes there was an increase in stored carbon.

The prognosis performed, estimated 14.44 t.ha^{-1} accumulated in the next 20 years. For the analysis of the economic valuation in the study area, this productive value (Vp) resulting from the carbon fixation by the forest was used, considering the increasing value observed in the forest.

The value of the carbon credit has fluctuated considerably in recent months, so we used the last value registered on the stock exchange, of US$ 9.28 t.year^{-1}, and the commercial dollar exchange value, of R$ 1.71. Thus, the productive value for the stand reached R$ 299.95 ha.year^{-1}.

DISCUSSION

Carbon Content by Species and Components

Ferez (2010) evaluating the carbon in recovery plantations of degraded areas of the Atlantic Forest, found that, on average, the carbon content in the species evaluated was 460 g.kg^{-1}. Weber et al. (2006) evaluating the differences between the carbon concentrations in six species of the Mixed Ombrophilous Forest (*Myrsine ferruginea, Ocotea porosa, Mimosa scabrella, Styrax leprosus, Symplocos uniflora* and *Ilex paraguariensis*), found that, on average, the foliage is the component with the highest content carbon (442.0 g.kg^{-1}), while the miscellaneous presented the lowest levels (339 g.kg^{-1}). Watzlawick et al. (2011) evaluating the carbon content in species of the Mixed Ombrophilous Forest, from Paraná, observed that the highest values were observed in the species *Prunus brasiliensis*, *Ocotea puberula* and *Drimys cf. angustifolia*. The lowest levels were found in the species *Persea major*, *Myrcia* sp. and *Lamanonia ternata*. Therefore, it was observed that the conversion factor of 0.50 widely recommended for the estimation of carbon in forest biomass (IPCC 2014), is not recommended for several species analyzed, including for the species of the present study, which can lead to considerable errors, causing overestimation of the observed values. However, the results obtained in the present work

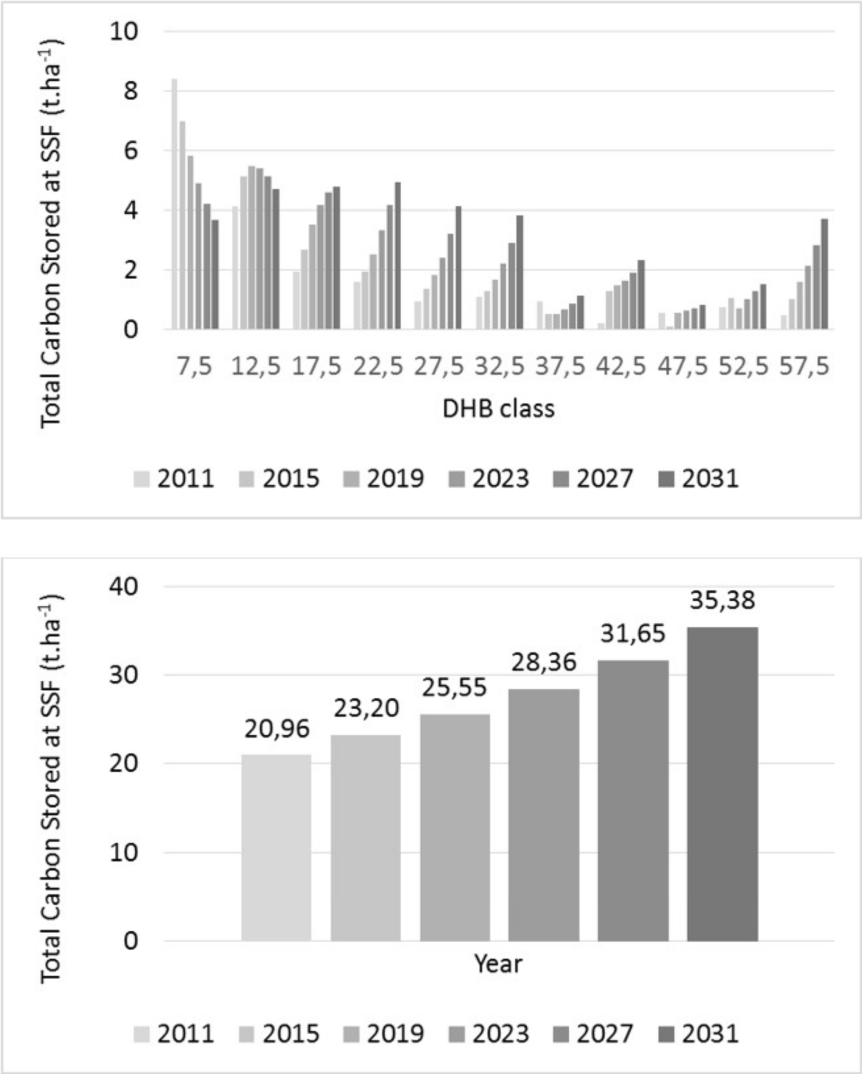


Figure 5. Projection of the Distribution of Total Stored Carbon by diameter class and year, respectively.

are similar to those presented in other studies, with a lack of studies that contemplate the carbon content in species of the Semideciduous Seasonal Forest in initial and medium stages of forest succession.

Aboveground Biomass Estimate and Total Stored Carbon Estimate

The high variation found in native forests, which have great heterogeneity of species, of different sizes and variable wood density, it is also common to find crooked trees, with small stem and large crown size, is reflected in high variation in the determination of biomass and carbon. Based on the selected equation, the aboveground component biomass per hectare was estimated at 56.25 ton. ha^{-1} in the year 2007. Bonan (2008) evaluating the arboreal component biomass of a remnant of Semideciduous Seasonal Forest in Minas Gerais, in the initial succession stage, observed that the total ranged from 69.17 t.ha^{-1} to 73.39 t.ha^{-1}, over five years. These values are close to those observed in the present study, highlighting that in the research, the area also had no human intervention for 20 years, similar to this study. Based on the obtained estimates, there is a trend in the concentration of biomass and carbon stocks as follows: stem wood, live branches, stem bark and dead branches. The stem biomass represented 74.84% of the total, and the carbon presented a close value in relation to the total, 75.81%, highlighting this component as the main responsible for accumulation of biomass and carbon in the forest.

In a mature Montana Semideciduous Seasonal Forest in Minas Gerais, approximately 100 years old without human intervention, Ribeiro et al. (2009), estimated 166.67 t.ha^{-1} of aerial biomass. Watzlawick (2003) carried out studies to quantify the biomass and carbon in tree species of a fragment of Mixed Ombrophilous Forest, in General Carneiro, PR, noting that the average biomass produced by the forest was 250.90 t.ha^{-1}. Thus, it appears that the accumulated biomass in different forest types is variable and greatly influenced by the vegetation succession stage. Thus, forest formations in more advanced stages of succession, with the presence of large individuals, tend to accumulate a greater amount of biomass, whereas in forests in early stages they have the lowest accumulation, as observed in this study.

The average carbon content for the total was 431.68 g.kg^{-1} and the organic carbon in the aerial part was 24.28 t.ha^{-1}. Bonan (2008) evaluating carbon stocks in SSF in the initial succession stage, found that the accumulated values ranged from 36.70 t.ha^{-1} to 44.44 t.ha^{-1}. Martins (2011) estimated similar values in a fragment of the Mixed Ombrophilous Forest in early stages of succession, with 26.36 t.ha^{-1} of stored carbon. Mognon (2011) evaluating carbon stocks in a fragment of Mixed Ombrophilous Forest, observed that the accumulated values ranged from 74.07 t.ha^{-1} to 77.53 t.ha^{-1} over 10 years, resulting in an increase 0.31 t.ha.year^{-1}. It can be inferred that the capacity of forests to accumulate carbon is variable, depending on their succession stages and characteristics specific to each evaluated area. Although the amount of stored carbon is not as great as in advanced stage forests, in the early stage formations the dynamic processes are more accentuated. As the accelerated growth of pioneer species, high rates of mortality and recruitment, favor greater capacity of accumulation, constituting in important sinks of CO_2. In this context, the forest under study is in dynamic balance.

Estimates of Biomass and Organic Carbon in the Litter

Based on the collected litter samples, the average biomass estimated was 31 t.ha1. Caldeira et al. (2007) in studies of accumulated biomass in Mixed Ombrophilous Forest found an average of 7.99 t.ha-1, ranging from 4.43 t.ha-1 to 13.71 t.ha-1. Watzlawick (2003) quantifying the litter biomass in Mixed Ombrophilous Forest, found values from 2.69 t.ha-1 to 15.05 t.ha-1, and an average value of 8.01 t.ha-1. Martins (2011) also studying the Mixed Ombrophilous Forest, found the value of 18.69 t.ha-1 for biomass. Observing the works cited, the estimated values for the litter biomass of the present study were considerably higher. This can be attributed to the intense leaf deposition, as it is a Semideciduous Forest, where 20 to 50% of individuals tend to lose their leaves in winter. The high mortality rates observed for the forest can also contribute to the greater accumulation.

Another aspect that may be related to the larger accumulation of litter than in the study area, is that the decomposition of the deposited material is slow, affected by factors such as the high C:N ratio (Tian et al. 1992), or aspects related to soil water saturation (Terror et al. 2011). Therefore, more in-depth studies may be conducted to identify these aspects more appropriately.

In relation to the carbon stored in litter, this was estimated at 12.1 $t.ha^{-1}$. Martins (2011) found the value of 7.04 $t.ha^{-1}$. Watzlawick (2003) found an average value of 3.06 $t.ha^{-1}$, with Caldeira et al. (2007) found similar values of 3.03 $t.ha^{-1}$, in the same typology forest. Comparatively, the aforementioned works showed less carbon accumulation in the litter than in the present study, a fact attributed to the same conditions already discussed for the biomass of this component.

Biomass and Carbon in the Understory

Based on the samples collected from the understory vegetation, the biomass of the forest remnant was estimated at 3.54 t.ha-1. This value was lower than that obtained by Martins (2011) at MOF, who estimated the biomass in this component at 4.92 t.ha-1. Watzlawick (2003) found the averages to be much higher, with a value equal to 21.85 t.ha-1, ranging from 2.30 t.ha-1 to 80.83 t.ha-1, according to the successional stage of the forest. Regarding the carbon stored in the forest understory, the estimate obtained in the present study was 1.50 t.ha-1. Martins (2011) found the value of 2.21 t.ha-1, while Watzlawick (2003) found the average value of 8.71 t.ha-1.

The low intensity of natural regeneration and/or herbaceous vegetation in the study area interfered with the amount of biomass and carbon stored in this component, which we can attribute this characteristic to aspects of vegetation, such as density of individuals and characteristics of the evaluated species.

Effectively Sequestered Carbon Dioxide and amount generated during 40 years Projection

There is much controversy about how to determine the appropriate discount rate for analyzing forest projects. Rates arbitrarily chosen in the range of 4 to 15% per year have been used (Lima Junior et al. 1997). In this study, the discount rate of 6% was used, and the eventual annual cost of R$ 50.00, proceeding with the economic calculations per ha.year-1.

CONCLUSIONS

There is some difficulty in accurately estimating the amount of biomass and carbon stored in the tree component, due to the high variability found in natural forests. The vegetation stage in the study area allowed the lowest accumulation of biomass and carbon in most components, when compared to other formations in more advanced stages of succession. The made projections show that there would be an increasing accumulation of biomass and carbon, which could constitute an alternative income for the owners, in the projects of forests that generate carbon credits, if they are implemented.

Our study can assist in other scientific investigations and new verifications and validations related to the carbon stock in Seasonal Semi Deciduous Forest, and can be useful to interested parties in the field of measuring impacts regarding the role and dynamics of forests and climate change.

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