Carbon stock and sequestration as a form of payment for environmental services in a sedimentary basin humid forest refuge in brazilian semiarid

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Carbon stock and sequestration as a form of payment for environmental services in a Sedimentary Basin Humid Forest refuge in Brazilian Semiarid

ABSTRACT

Forests function as carbon reservoirs since they act in its sequestration and storage, playing a fundamental role in global climate change mitigation. Payments for this kind of environmental service have emerged as an important means for combating deforestation. This study evaluated the potential of a Sedimentary Basin Humid Forest refuge in a Semiarid Brazilian region (Chapada do Araripe, southern Ceará state) to receive payments for environmental services (PES) for carbon (C) assimilation and storage. The biomass quantification was performed by the non-destructive method and the determination of the C content was carried out using a LECO carbon analyzer to correlate carbon production in different litter components with climate variables. The carbon, carbon increment and stored carbon values were obtained by information collected from a continuous forest inventory. The average carbon content of each litter component and the volume of wood stored in the forest indicated that the fragment has 27.78 $t.ha^{-1}$ of carbon stored in its living biomass and an annual increment of 1.26 $t.ha^{-1}$ year. The carbon sequestered annually totaled 3.99 $t.ha^{-1}$ [carbon incorporated in the litter (2.73 $t.ha^{-1}$) + average annual increment of carbon in the commercial volume (1.26 $t.ha^{-1}$)] indicating that the area sequesters an average of 102.02 $t.ha^{-1}$ CO_2e. Of the three studied compartments, only the leaves component showed a significant correlation with any climatic variable (rainfall). Based on amounts paid per ton of carbon sequestered, it is estimated that the area can earn € 2,583.79.ha^{-1} should it participate in a program of PES for carbon sequestration and storage. This value serves as an incentive for the conservation of biodiversity, promoting environmental benefits and financial advantages compared to other forms of land use.

Key Words: Climate Change Mitigation, Payment for Environmental Services, Sedimentary Basin Humid Forest.

1. INTRODUCTION

Changes in Earth's climate system are natural processes. However, the intensity and speed of these changes in recent decades have caused concern to the scientific community as to the causes and consequences (Deng et al., 2017). The increase in the concentration of Greenhouse Gases (GHG) has been causing changes in the climate and interfering in the radioactive balance of the atmosphere (Reisch, 2021), the main contributor being carbon dioxide (CO_2) (Zahn, 2009). The Intergovernmental Panel on Climate Change (IPCC) predicts that, by 2100, the atmospheric concentration of CO_2 will be almost twice the value of 100 years before (Wang et al., 2018).

Formal discussions resulted in collective efforts in the early 1970s, with the UN (United Nations) being responsible for holding annual conferences on climate change, strengthening scientific understanding on the subject with the leaders of several countries (Lahsen et al., 2020). The Kyoto conference, held in Japan in 1997, resulted in the Kyoto Protocol, which established the concept of “carbon sequestration”, discussing and signing international agreements between member countries, with the purpose of reversing the accumulation of GHGs, establishing reduction goals and flexibilization mechanisms (Kuriyamaa and Abeb, 2018).

The major contributors to the high concentration of CO_2 in the atmosphere are the burning of fossil fuels and changes in land use (deforestation and fires), which increases the planet's ability to retain heat, causing high temperatures (Silva and Moura, 2021). In the world, deforestation, which is one of the most common causes of CO_2 emission, corresponds to 6 to 17% of emissions (Baccini et al., 2012), accounting for about 5,800 million tons of carbon dioxide per year ($MtCO_2/yr^{-1}$) (Waheed et al., 2018).

Forests produce a range of environmental services, including carbon sequestration, which can attenuate climate change, protection of water springs, which is, among other reasons, important for the supply of water, and biodiversity conservation (Schmitt et al., 2009). These services alone are a sufficient justification for the importance of studies concerned with forests (Santiago and Couto, 2020). Forests work as carbon reservoirs and act in their cycle through assimilation and storage (Deng et al., 2017), playing a key role in climate change mitigation, thus contributing to the storage of 80% of the total carbon above the soil in terrestrial ecosystems and 20% of carbon below ground (Li et al., 2018). 8.6 Pg CO_2 are emitted into the atmosphere per year, but due to the efficient role of terrestrial sequestration in the global carbon cycle, only 3.5 Pg CO_2 remains in the atmosphere (Mishra et al., 2020).

With the Paris agreement, forest-based actions gained additional political relevance, and, in view of this fact, many countries began to contribute with forest carbon sequestration activities, in order to reduce net carbon emissions (Favero et al., 2020). Global forests are expected to contribute a quarter of the pledged mitigation under the 2015 Paris Agreement, by limiting deforestation and by encouraging forest regrowth (Grassi et al., 2017). As part of its Nationally Determined Contributions (NDC) to the Paris Agreement, Brazil has pledged to restore and reforest 12 million hectares of forests by 2030 to contribute to net emission reductions (Mma, 2016; Heinrich et al., 2021).

Measurements of carbon content are promising in providing information to evaluate the behavior of plants in terms of climate, biome, conservation status and alteration of forest environments (Anjali et al., 2020). Differences between ecosystems and species are important factors that affect carbon sequestration (Yao et al., 2019; Dong et al., 2022). Litter is directly related to productivity in forest ecosystems and has a diversified production pattern with periods of greater and lesser intensity associated with environmental factors and climatic and genetic seasonality (Giweta, 2020). The variation in quantification of its contribution can be generated by factors such as: precipitation, altitude, latitude, temperature, successional status, water availability, herbivory, wind, moisture and soil nutrient stock (Martins et al., 2018). Its composition induces different structures of the soil microbial community, which leads to different patterns of organic carbon decomposition and, consequently, different sequestration capacities (Yan et al., 2018). Biomass is a variable that reliably estimates the quantification of carbon sequestered and stored in forest ecosystems, enabling the gain of robust and consistent information, and therefore must be determined (Mishra et al., 2020).

To implement biodiversity conservation projects and sustainable management plans, vegetation surveys are necessary on the area of interest, as well as studies on its limitations and resilience capacity (Ferraz et al., 2013; Calixto Júnior et al., 2021). The challenges arising from sustainability and biodiversity conservation also require solutions based on market actions. Payment for Environmental Services (PES) resulted in the “recovery of environmentalism”, formerly seen as defeated due to the constant threats to ecosystems and the services provided by them. PES can be local or expansive, geographic or monetary projects. As an example of the latter, European investments are cited in combat against deforestation and in encouraging the recovery of forest areas in the Brazilian Amazon (Chan et al., 2017). In this sense, the realization of studies that enable the measurement of the amount of carbon stock and increment in forests becomes an important tool, supporting knowledge already acquired and favoring the effectiveness of PES in tropical forests (Paiva et al., 2020).

The Chapada do Araripe, located in the xerophytic domain of the Caatingas, Northeastern Brazil, has a milder climate compared to its semi-arid surroundings (Queiroz et al., 2018). Its high environmental heterogeneity has different vegetation types that are strongly influenced by hydrographic conditions (Alcântara et al., 2020). The Chapada is a geographic accident and paleontological site of relevant ecological value located betweenh the states of Ceará, Pernambuco and Piauí, in the semi-arid region of the Brazilian Northeast (Caatinga biome), with abundant fossil, fauna and plant diversity in different phytophysiognomies (Silva et al., 2022). This research was carried out in a Sedimentary Basin Humid Forest refuge, which has species found in the Cerrado, Atlantic Rain Forest and Amazon, with high levels of heterogeneity and diversity and with a predominance of arboreal, thornless and evergreen plants (Honório et al., 2019).

Considering that studies of biomass quantification and estimates of carbon stock and sequestration are necessary as a support for the conservation of forest areas and as a reference in the elaboration of carbon neutralization projects in the sphere of the Sustainable Development Mechanism (SDM), mitigating impacts of climate change and in combat against global warming, the objective of this study was to obtain baseline responses on carbon stock and carbon increment in a refuge of Sedimentary Basin Humid Forest in the Chapada do Araripe, an area of great cultural and landscape importance and biodiversity in the Brazilian Northeast. Thus, by evaluating the potential for carbon sequestration and storage of this phytophysiognomy, the feasibility of implementing Payments for Environmental Services (PES) through participation in carbon credit projects is sought. This is the first study that covers this theme in this area of Northeastern Brazil.

2.MATERIAL AND METHODS

2.1 Area of study

The study was carried out in a refuge of Sedimentary Basin Humid Forest (Moro et al., 2015), which is characterized as a phytophysiognomy with trees of large size (average height of 11m), consisting of woody vegetation with straight and/or rectilinear stems, tortuous, well-branched and an understory with a low incidence of regeneration (MMA, 2003). The area is located in the Private Reserve of National Heritage – RPPN Oásis Araripe (Figure 1), Chapada do Araripe, Crato municipality, southern Ceará state (7°13'55.09"S; 39°27'56.12"W; elevation 708.36 m.). This reserve is managed by the Associação de Pesquisas e Preservação de Ecossistemas Aquáticos, created for the conservation of the endemic and critically endangered bird, the Araripe Manakin (*Antilophia bokermanni* Coelho & Silva, 1998).

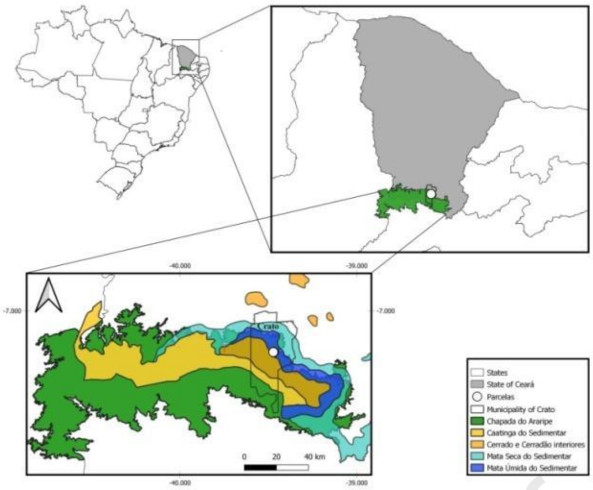


Figure 1. Geographic location of the area of study. Sedimentary basin humid forest refuge in the Chapada do Araripe, Crato, Ceará, Northeastern Brazil.

The history of intervention in the area shows agropastoral use for circa 50 years. The Araripe Oásis Reserve has an area of 66 hectares, 50 ha of which are part of the Reserva Particular de Patrimônio Natural (RPPN) that was created on March 20th, 2015 by Law nº 9,985, which created the Brazilian national conservation unit system. The reserve is located in the surroundings of the Araripe National Forest – FLONA Araripe.

The predominant soil is of the Red-Yellow Latosol (LVA) type with a medium to clayey texture and permeable to rain (Embrapa, 2018) and the climate of the region according to the Köppen classification is of As type (Álvares et al., 2013). The area has characteristics of a tropical wet climate, marked by two well-defined seasons: a rainy season, which extends from December to April, and a dry season, from May to November, despite the transitory nature of the semi-arid climate of Northeastern Brazil (BSw). The average monthly rainfall in the rainy season is 1,033 mm (INMET, 2021) and the annual average temperature is 24°C (Funceme, 2021).

2.2 Annual Periodic Inventory, Increment (IPA) and Statistical Sufficiency

The forest inventory was carried out in a fragment of wet forest six kilometers away from the urbanized area, in a systematic sampling process, following the methodology proposed by Mueller-Dumbois and Ellenberg (1974). In this inventory, thirteen permanent plots measuring 625 m^2 (25m x 25m) were plotted, systematically chosen and with a distance of 50m, demarcated with one-meter-tall stakes, for the monitoring of the forest stand over time for two years (2021/2022). All live trees and shrubs with DBH (diameter at breast height) ≥ 5 cm were measured, as well as total heights. The DBH measurement was performed with a bevel gauge and the total height with a graduated telescopic rod. When individuals had secondary shoots, the one with the largest diameter was measured, meeting the inclusion criteria according to Rodal (1992). Phytosociological parameters were obtained using the Mata Nativa 2 software (Fundação de Ciência e Tecnologia, 2006), which allowed the comparative analysis between general parameters of the community for two years, such as basal area per hectare, volume per hectare, total living biomass and stored carbon. The annual periodic increment was calculated using the following equations:

$$\text{Growth} = C_2 - C_1$$

$$\text{IPA} = \frac{\text{Growth}}{\text{Month interval}}$$

Where:

C_1 and C_2 = Measurements at the end and at the beginning of the period, respectively;

IPA = Annual periodic increment.

Sampling sufficiency was evaluated by standard error and confidence interval with a significance level of 5%. The sampling error was calculated considering a limit of 10%, at 95% probability (Felfili and Rezende, 2003).

2.3 Litter deposition

To collect the senescent litter, five collectors with 1m^2 diameter were installed, 50 m equidistant in the north-south direction, between the plots for the floristic survey. The collectors were made of 5/8 wire, supported by 1½-inch galvanized iron rebar and wires, suspended one meter from the ground level and surrounded by two layers of mosquito net-like mesh, to prevent the loss of smaller material and allow the passage of rainwater.

The senescent material accumulated in the collectors was removed monthly over the period of twelve months (February 2021 to January 2022), packed in identified plastic bags and transported to Laboratório de Estudos da Flora Regional do Cariri – LEFLORE, Universidade Regional do Cariri – URCA, for later separation by compartments: leaves, stems and miscellaneous (flowers, fruits, seeds, feces, insects, etc.). The fractions were measured on a digital scale to three decimal places and kept in an oven at 60ºC until the material reached constant mass in three weighings to determine the dry mass. Then, the material was placed in a Willey type mill and packed in properly identified paper bags. The litter contribution was evaluated monthly, and the total was obtained and determined from the arithmetic mean of the five collectors. Litter production in each collector was based on the model proposed by Ferreira et al. (2014), Ferreira and Uchiyama (2015):

$$\mathrm{PS} = \frac{(\Sigma \mathrm{PMS} \times 10.000)}{\mathrm{Ac}}$$

Where:

PS = Litter production (kg $\mathrm{ha^{-1} year^{-1}}$);

PMS = Monthly litter production (kg $\mathrm{ha^{-1} month^{-1}}$);

Ac = Area of collector ($\mathrm{m^2}$).

2.4 Climatic Variables

To evaluate the influence of abiotic factors (climate) on litter deposition, a Complete Digital Meteorological Station - HM-1080 was installed in the main area of RPPN Oásis Araripe, where data on temperature, humidity and precipitation were collected through monthly averages.

2.5 Carbon Quantification

2.5.1 Element Analysis

The determination of the total carbon content in the compartments of leaves, branches and miscellaneous was carried out at Laboratório de Análise de Solo, Água e Planta da Empresa Brasileira de Pesquisa Agropecuária (Embrapa Caprinos), Sobral, Ceará State, using a LECO carbon analyzer, model C-144. The element analysis method (EA) is based on the complete combustion of the dry sample, in which the elements C, H, N, S and O are quantified. Oxidation occurs at high temperature (from 900°C to 1200°C), the gases formed from the total combustion are separated and the concentrations are measured by different types of thermal conductivity detectors, which are then converted into percentage contents of each element, recorded in a software (Chatterjee et al., 2009; Pereira Júnior et al., 2016).

2.5.2 Forest Stand Biomass and value of C stock

The estimation of carbon sequestration was performed by the non-destructive indirect method, as specified by Salati (1994). The use of the non-destructive method, based on parameter estimations from forest inventories, was used to better adapt to the complexity and floristic conditions of the area, as used by Fajardo and Timofeiczyk Júnior (2015) for the APA Serra de Baturité (Ceará). Forest inventory parameters (diameter and total height of tree individuals included in the inclusion criterion: DBH ≥ 5cm) contributed to the quantification of carbon stored in the standing forest. These parameters were used in the equation by Brown, Gillespie and Lugo (1989) which considers $R^2=0.97$ for the conversion of biomass into carbon stock. This calculation was also used by Waltzlawick et al. (2011) and Embrapa (2008) for Dense Ombrophilous Forest and is described as:

$$\boldsymbol{Y} = \boldsymbol{exp}[-3.1141+0.9719*\mathbf{In}(\boldsymbol{dbh}^{2*}\boldsymbol{htot})]$$

being:
Y= Biomass;
dbh= Diameter at breast height;
htot = Total height.

To calculate the carbon stock, the dry mass of individuals was estimated, considering that the average carbon content in wood is 50% for tropical forests (Brown et al., 1989; Nogueira, 2008). The carbon stock estimate expresses the amount that was removed from the atmosphere, present in the aerial biomass. According to Embrapa (2007), to determine the volume of CO_2 stock, 1 ton (t) of carbon is considered, which is equivalent to 3.67 t of CO_2.

After the quantification of the carbon mass in the litter and in the standing forest, the measurement of the carbon stock value was performed. The value used as a reference corresponds to the carbon credit commodity on the UK stock exchange, estimated at € 83.50.t^{-1} (Lse, 2022).

2.6 Statistical Analysis

Statistical analysis was performed using GramPad Prisma 7.0 software. For climatic variables and significant differences in carbon content between plant compartments (leaves, branches and miscellaneous) the results were analyzed using the nonlinear regression model of the curves, by ANOVA, in two ways. Tukey's test and Pearson's correlation (r) were performed to analyze the influence of each variable on litter production in the compartments, considering that when $p<0.01$, the correlations are significant.

3.RESULTS AND DISCUSSION

3.1 Sampling sufficiency and forest inventory

The intersection was observed in the tenth parcel (with 6,250 m^2 of sampled area) and with 81% of the sampled species. In the last three parcels, there was no increase in the occurrence of species, considering, therefore, that the sampling carried out for the area was considered sufficient.

The inventory showed 1,544 shrubs or trees and generated an estimate of absolute density of 1,997.30 $ind.ha^{-1}$ (CI=±178.49 $ind.ha^{-1}$) at 95% probability and standard error of 5.73% and basal area (dominance) of 32.618 $m^2\ ha^{-1}$ (CI=±5.87 $m^2 ha^{-1}$) at 95% probability and standard error of 7.13%. These values confirm that the sampling precision is considered adequate and comprehensive for the estimation of quantitative variables (Felfili and Rezende, 2003).

3.2 Litter production

Table 1 shows the average contributions of the plant compartments (leaves, branches and miscellaneous). The total litter deposition was 5,560.40 kg $ha^{-1}year^{-1}$. Senescence occurred throughout the year with different values for the compartments. In almost every month, except February/2021, the leaf fraction quantitatively prevailed. The value found in this study for annual leaf deposition was 3,859.64 kg/$ha^{-1}year^{-1}$ (±2.787), equivalent to 69.39% of the total. The second highest quantitative importance was related to the branch fraction, with annual deposition equivalent to 15.61% and the miscellaneous fraction represented 14.96% of the total senescent litter (Table 1).

Table 1. Total deposition of senescent litter in kg ha^{-1} collected in a sedimentary basin humid forest refuge in Chapada do Araripe, Crato, Ceará, Northeastern Brazil.

Month	**Leaves** **kg $ha^{-1}yr^{-1}$**	**Branches** **kg $ha^{-1}yr^{-1}$**	**Miscellaneous** **kg $ha^{-1}yr^{-1}$**

Feb/21	78.5	101.60	132.96
Mar/21	64.5	23.56	34.92
Apr/21	66.0	26.00	54.02
May/21	66.0	54.00	50.46
Jun/21	178.0	48.02	20.02
Jul/21	494.0	196.60	23.20
Aug/21	637.20	80.80	25.00
Sep/21	791.20	90.20	86.80
Oct/21	638.20	103.20	96.80
Nov/21	492.60	90.20	84.60
Dec/21	245.00	15.60	115.20
Jan/22	108.40	38.60	108.40
Total	**3,859.6**	**868.4**	**832.4**
Mean	**321.6**	**72.4**	**69.4**
SD	**±2.787**	**±5.024**	**±3.962**

For Werneck et al. (2001), in conserved tropical forest ecosystems, litter production also occurred throughout the year and according to Carvalho et al. (2019) the total amount of litter produced at different times varied with patterns determined by the type and composition of the vegetation studied. This difference was also evidenced by different proportions of the fractions, and the leaf component was also found as the most significant portion by Scoriza and Piña-Rodrigues (2014) and Toscan et al. (2017), in which the litter is composed of 65% and 58.52% of leaves, respectively, in collections carried out in areas of semideciduous forest in the Brazilian states of São Paulo (southeast) and Paraná (south). Also corroborating the results obtained in this study, Sloboda et al., (2017) found 73% of leaves in total litter produced in an area of Dense Ombrophilous Forest, in an Environmental Protection Area, in the municipality of Antonina, on the northern coast of Paraná State.

Converting the unit of measurement from kilogram (kg) to ton (t), the average annual litter production observed in this study was equivalent to 5.47 t.ha^{-1}yr^{-1}, within the ranges found by Araújo (2010), in litter from tropical forests in Brazil, which ranged from 3.0 to 10.5 t.ha^{-1}year^{-1} and 4.7 to 9.0 t.ha^{-1}.year^{-1} in Natural Atlantic Rain Forest and 3.0 to 10.1 t.ha^{-1}.year^{-1} in revegetated areas. Higher litter values were observed in the Atlantic Rain Forest, in forest environments of different successional stages; they have an average value of 8.0 t.ha^{-1}year^{-1} (Martinelli et al., 2017). Studies from the last 20 years in dense and semideciduous forests in Brazil show values between 4.7 and 8.44 t.ha^{-1}year^{-1}: Scheer et al. (2011) with 6.40 t.ha^{-1}year^{-1}; Sloboda et al., (2017) with 8.44 t.ha^{-1}year^{-1}, both for Dense Ombrophilous Forest and Scoriza and Piña-Rodrigues (2014) with 6.90 t.ha^{-1}year^{-1} and Bianchi et al. (2016) with 4.70 t.ha^{-1}year^{-1} for Semideciduous Forest.

Observations point that precipitation can influence the litter contribution both in terms of volume and in the variation of the litter compartment type throughout the year. The highest litter deposition occurred during the dry period (May to November), caused by leaf senescence, corroborating data obtained by Barbosa et al. (2017) who verified in their research that the amount of deciduous material throughout the year is mainly related to climatic conditions.

The average annual temperature of the period was 25.2°C. The hottest month was August, with an average of 28.2°C and the coldest was June (21.8°C). The annual average of humidity was 62.24%, with the highest percentage recorded in March (73.4%) and the lowest percentage in August (52.93%). The total rainfall in the period was 1392.86 mm and the monthly average was 115.98 mm (Table 2).

Table 2. Values of climatic variables (temperature, humidity and precipitation) during the period from February 2021 to January 2022, in a refuge of sedimentary basin humid forest in Chapada do Araripe, Crato, Ceará, Northeastern Brazil.

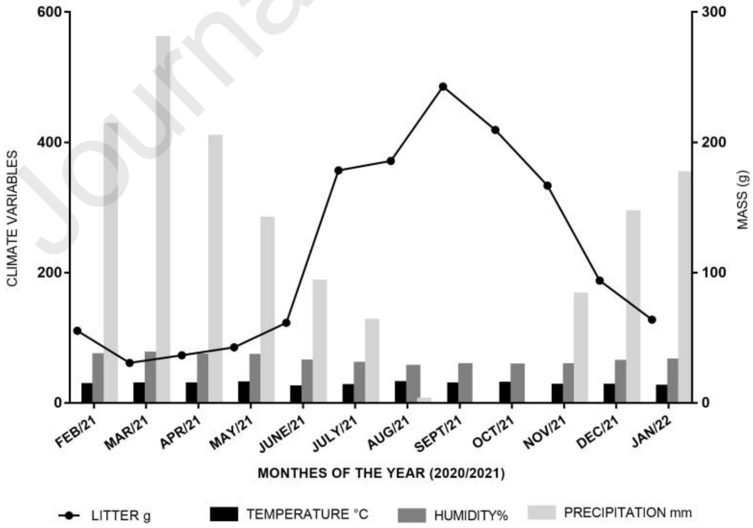
Month/Year	Temperature (°C)	Humidity (%)	Rainfall (mm)
Feb/21	25.1	71	212.3
Mar/21	26	73.4	279
Apr/21	26.2	70.5	203
May/21	27.5	70	140.2
Jun/21	21.8	61.3	92
Jul/21	23.5	57.8	62
Aug/21	28.2	52.93	1.28
Sep/21	26.2	55.79	0.05
Oct/21	27.1	55.3	0.03

Nov/21	24	55.5	82
Dec/21	24.3	60.7	145
Jan/22	22.5	62.76	175

When analyzing the monthly totals, the rainy season (December to April) had the highest record in March (279 mm), while in the dry period (May to November), the precipitation had the lowest record in the months of September and October (n=0.05 mm and n=0.03 mm, respectively) (Table 2).

The Figure 2 presents values of climatic variables (temperature, humidity and precipitation) and their correlation with the production of senescent litter collected during the study period.

Figure 2. Contribution of senescent litter against climatic variables (temperature, humidity and precipitation) in the period from February 2021 to January 2022 in a sedimentary basin humid forest refuge in Chapada do Araripe, Crato, Ceará, Northeastern Brazil.



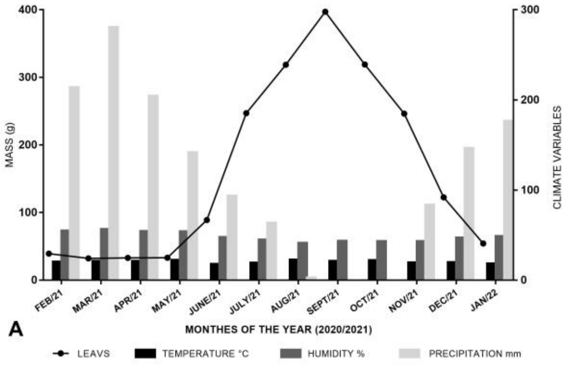
Values were expressed as mean ± S.E.M. with nonlinear regression of curves, analyzed by two-way ANOVA, following Tukey's test. Considering p< 0.01 (equivalent to the 99% interval).

Temperature and humidity showed little variation over the period studied, unlike precipitation (Figure 2). The growth curve for litter in relation to leaves increased in

June with the decrease in rainfall (Figure 3A). Litter contribution from the leaves component reaches its maximum in September with a total of 968 kg ha^{-1}year^{-1}. Following the decline in litter supply, the rainy season begins. Vogel et al. (2015) found similar results, where precipitation showed to regulate the contribution of litter and also observed an increase in litter deposition in the dry season and a decrease during the rainy season, evidencing the transition from the resumption of structural growth with the renewal of the canopies. Rainfall showed direct influence over the deposition of all litter fractions, mostly in its main component (leaf) (Figures 3A, 3B and 3C), with a substantial contribution in the dry period, when the lowest precipitation values occur (July to November).

The significative presence of branches in the litter was observed in the month of July (Figure 3B), which is justified by the higher wind speed in the region in this period. On a global scale, litter production peaks are correlated to temperature, precipitation, radiation and wind speed, due to the diversity of the species component with different responses to the environmental conditions to which they are subjected (Zhang et al., 2014; Martinelli et al., 2017; Bazi, 2019).

The miscellaneous compartment did not show significance in the correlation to climatic variables, however, there was a major increase in its production in the dry period (Figure 3C). Factors that contribute to higher values of this fraction are related to the diversity of the regional floristic composition, species with diversified reproductive elements and more robust fruits. According to Pedro et al. (2019) the highest production is expected to occur at the end of the dry season, which corroborates the results of this study.



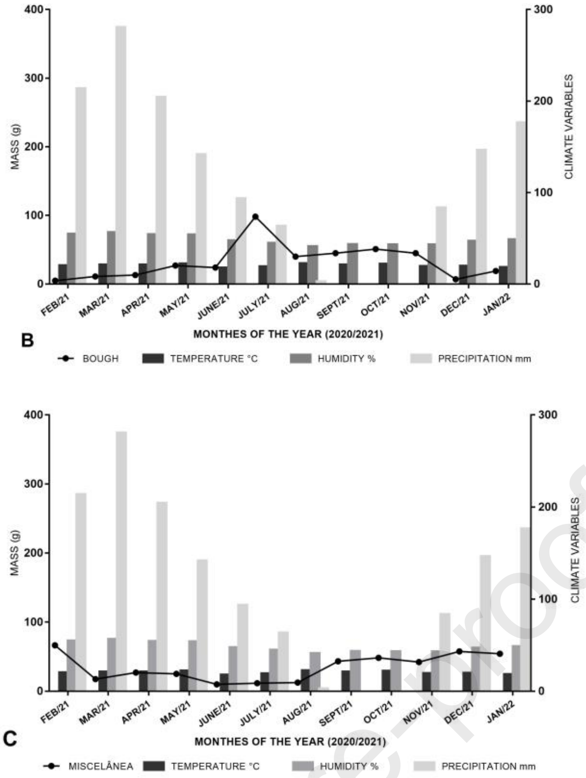


Figure 3. Values of climatic variables (temperature, humidity and precipitation) and contribution of senescent litter in the leaves, branches and miscellaneous compartments, during the period from February 2021 to January 2022, in a relict of humid forest of the sedimentary basin in Chapada do Araripe, Crato, Ceará, Northeastern Brazil.
Values were expressed as mean ± S.E.M. with nonlinear regression of curves, analyzed by two-way ANOVA, following the Tukey test, considering $p<0.01$ (equivalent to the 99% interval). Where: A: leaves, B: branches and C: miscellaneous.

Of the three studied compartments, only the leaves component showed a significant correlation with some climatic variable (rainfall). Precipitation is a fundamental variable for causing leaf abscission, mainly due to mechanical force (Lima et al., 2021), thus, variations in litter production are stimulated by some meteorological factors (Ferreira et al., 2014).

The studied phytophysiognomy showed a negative correlation between leaf mass and precipitation and humidity and a positive correlation with temperature (Table 3). According to Ferreira et al. (2014), in the dry season there is greater dehiscence of leaves, an adaptive characteristic associated with the evolutionary strategy of the species due to water stress, which guarantees the photosynthetic process and the survival of individuals during the dry season.

Table 3. Correlation values of litter production with climatic variables (temperature, humidity and precipitation) during the period from February 2021 to January 2022, in a refuge of sedimentary basin humid forest in Chapada do Araripe, Crato, Ceará, Northeastern Brazil.

	Climatic Variables		
Compartments	**Temperature**	**Humidity**	**Rainfall**
Leaves	0.27	-0.88**	-0.90**
Branches	-0.02	-0.62	-0.66*
Miscellaneous	-0.08	0.03	0.13

Where: * p<0,001 **p<0,0001

3.3 Annual Carbon Increment

The growth rate of individual trees in a forest is represented by the Annual Periodic Increment (IPA). Based on the forest inventory carried out in January 2021, there are results regarding annual ingress rates (Table 4) with periodic annual increment for DBH per cm, basal area per hectare, volume per hectare, total living biomass and carbon stocked.

The forest accumulated biomass during the period evaluated, since all the parameters considered showed an increase in values (Table 4). According to Vatraz, Alder and Silva (2018), the annual periodic increment (IPA) represents the individual growth rate of trees in the forest. In tropical forests, tree species have a variable growth rate due to several factors such as environmental heterogeneity, intra and interspecific characteristics and biotic and abiotic disturbances (Alder, 1995).

The IPA value for average diameter observed in this study (Table 4) is close to values found by several authors, such as Vidal et al. (2002) who studied an increase in the forest area in the Amazon, in the municipality of Paragominas, northeastern State of Pará (IPA=0.33 cm.year^{-1}); Valtraz et al. (2018) in Dense Ombrophilous Forest in the Amazon (IPA=0.27 cm.year^{-1}); Paiva et al. (2020) in a Dense Ombrophilous Forest remnant in Parauapebas, Pará (IPA=0.39 cm.year^{-1}) and Figueiredo Filho et al. (2010) in a remnant of Mixed Ombrophylous Forest in the Irati National Forest (FLONA de

Irati) in the municipalities of Teixeira Soares and Fernandes Pinheiro, central-south region of the State of Paraná (IPA=0.24cm.year^{-1}).

The value observed for basal area in this work (Table 4) is higher than the values found by Bezerra et al. (2018) in the Tapajós National Forest, State of Pará (0.44 m^2.ha^{-1}) and those found by Souza et al. (2012) in the Experimental Forest of Embrapa Amazônia Ocidental in Manaus (0.33 m^2.ha^{-1} and 0.12 m^2.ha^{-1}) with trees with inclusion criteria of DBH $\geq$ 10, as well as values found in Mixed Ombrophilous Forest from southern Brazil, in the works of Schaaf (2001), in São João do Triunfo, Paraná (0.24 m^2.ha^{-1}); Figueiredo Filho et al. (2010) in Irati, Paraná (0.23 m^2.ha^{-1}) and Cubas et al. (2016) in the municipality of Três Barras in Santa Catarina (0.28 m^2.ha^{-1}).

The value of the average annual volumetric increment (4.4 m^{3}ha^{-1}year^{-1}) found (Table 4) is similar to those found in managed forest areas in the Western Amazon, State of Pará (main wood producer) as presented by Ribeiro et al. (2009) (4.67 m^{3}ha^{-1}year^{-1}) and Souza et al. (2017) (4.63 m^{3}ha^{-1}year^{-1}) with a result obtained in an area of 18 years after exploration.

The high IPA values for the variables studied, when compared to the literature for primary forests, are justified by the high number of recruited individuals (which reach the minimum inclusion diameter for the inventory) and the low mortality in the forest fragment. The high recruitment rate observed in this research is a common situation in forests that have suffered higher disturbances in the past, as the increase in the number and/or size of gaps and secondary forest formations in which pioneer species develop results in the inclusion of new individuals.

The average biomass stored in the study period, considering the total area evaluated (0.8 ha), was 55.07 t.ha^{-1}, of which 27.53 t.ha^{-1} is organic carbon, which corresponds to 50% of the total biomass, maintained in accordance with the estimate proposed by the IPCC of 50% of carbon in relation to dry biomass. This result is the average of the values of total carbon stock in the living biomass found in studies carried out in Dense Ombrophilous Forest, in different fragments of Atlantic Rain Forest in Brazil, ranging from 51.20 to 136.68 t.ha^{-1} (Vieira et al., 2011; Marchiori et al., 2016; Azevedo et al., 2018).

The Cerrado biome, the second largest in Brazil and with different phytophysiognomies that extend into the Chapada do Araripe, has estimated values for biomass that vary between 5.50 and 62.96 t.ha^{-1}, being higher for forest formations. (Roquette, 2018). According to Souza et al. (2012) storage and carbon sequestration are related to phytosociological structure, floristic composition and forest successional stage.

Table 4. Values of mean diameter, basal area, volume, live biomass, stored carbon and annual periodic increment (IPA) found in a sedimentary basin humid forest refuge in Chapada do Araripe, Crato, Ceará, Northeastern Brazil, between 2021 and 2022.

Variables	**2021**	**2022**	**IPA**
Average diameter (cm)	9.93	10.28	0.35
Basal area ($m^2.ha^{-1}$)	10.56	11.07	0.51
Volume ($m^3.ha^{-1}$)	92	96.4	4.4
Stocked carbon ($t.ha^{-1}$)	27.14	28.43	1.26
Living biomass ($t.ha^{-1}$)	54.28	56.87	2.59

The average biomass obtained was 55.57 $t.ha^{-1}$, with an average carbon stock of 27.78 $t.ha^{-1}$ and an average of 102.02 $t.ha^{-1}$ of CO_2 removed from the atmosphere (Table 5). The difference between the biomass values in the 12-month period predicts the potential for carbon sink on a regional and global scale.

Table 5. Average annual values of biomass, carbon stock and atmospheric CO_2 stock found in a sedimentary basin humid forest refuge in Chapada do Araripe, Crato, Ceará, Northeastern Brazil.

Year	**Biomass** ($t.ha^{-1}$)	**C stock** ($t.ha^{-1}$)	**CO_2e stock** ($t.ha^{-1}$)
2021	54.28	27.14	99.6
2022	56.87	28.43	104.44
Mean	55.57	27.78	102.02

The C and CO_2 stock averages presented in this study are superior to the estimates made in other forest formations in Brazil, such as those of a dense forest remnant in the Amazon region (25.45 $t.ha^{-1}$ C and 93. 40 $t.ha^{-1}$ CO_2) (Paiva et al., 2020);

of Ombrophilous Forest of Ibaté, São Paulo, Atlantic Rain Forest biome (26.19 t.ha^{-1} C and 96.15 t.ha^{-1} CO_2) (Lacerda et al., 2009) and in forest fragments of humid forest at Serra do Baturité, north-central region of Ceará, with average values estimated at 23 t.ha^{-1} C and 84.63 t.ha^{-1} CO_2 (Fajardo and Timofeiczyk, 2015). In tropical forests, soil CO_2 concentrations can change markedly on weekly, monthly and seasonal timescales, with high CO_2 levels in wet periods and low levels in drier periods (Barcellos et al., 2018; Fernandez-Bou et al., 2018).

On a global scale, surveys using biomass density data from 413 areas from a forest inventory assessed carbon and biomass stocks in dense forests in Tibet, resulting in a range of biomass density from 20 to 170 t.ha^{-1} in a ten-year interval (2001 to 2010) (Sun et al., 2016). The same authors estimated the total forest carbon stock at 16.6% from 831.1 Tg C in 2001 to 969.4 Tg C in 2050. In a study on forest carbon storage in southeastern Australia from 2010 to 2015, Aponte et al. (2020) presented values of 178 t C ha^{-1} for humid forests and 109 t C ha^{-1} for forests with a drier climate.

It is important to point out that the study area is considered a refuge of Humid Forest, of secondary formation, in the midst of a semiarid scenario, although it already presents clear penetration of tree species from the surrounding Mata Seca vegetation in the Chapada do Araripe (Cerradão). There are differences observed in terms of biomass, carbon stock and sequestration in relation to different areas, expressed according to the tree composition of the community, with a high value of total basal area, its history of disturbance and of more than 50 years of recovery (inserted in a Conservation Unit) and its successional stage as a function of the diversification and abundance of species.

3.4 Chemical Analysis of Organic Carbon Content

There was similarity in the carbon content of the three compartments, which indicates homogeneity in the carbon absorption of the forest (Table 6). Carbon contents may vary across different compartments; regarding information on potential carbon stocks, sampling and analysis separated into leaves, branches and miscellaneous helps to reduce uncertainties in regional carbon stock estimates (Sun et al., 2016).

Table 6. Mean values of litter mass, carbon content and mass accumulated in a Dense Ombrophilous Forest refuge (Sedimentary Basin Humid Forest) in Chapada do Araripe, Crato, Ceará, Northeastern Brazil.

Compartments	**Mass of Litter** (t.ha^{-1})	**Carbon Content** (%)	**Carbon Mass** (t.ha^{-1})
Leaves	3.863	55.58	1.931
Branches	0.776	55.12	0.388
Miscellaneous	0.832	56.08	0.416
Total	5.471	55.59	2.735

Despite the similarity in the values of carbon content of the compartments observed in this study, a higher percentage is seen in the miscellaneous component, which corroborates the results found by Batista et al. (2020) in an urban forest fragment in Curitiba, Paraná, in which they indicated a significantly higher average carbon content for the miscellaneous component (44.46%) in relation to the others (leaves - 43.73% and branches - 43.80); as well as Paiva et al. (2020), when studying carbon stock in a dense forest remnant in the Brazilian Amazon (48.03% - miscellaneous, 47.85% - leaves and 46.87 - branches). This slightly higher value may be related to the fact that the miscellaneous component is composed of a high diversity of organic matter present in structures such as: flowers, fruits, diaspores, excrements, body parts of different animals and organic material dispersed by them.

In a study carried out by Watzlawick et al. (2011) with leaves and branches of tree species from the Mixed Ombrophilous Forest in the State of Paraná, the highest average values of carbon content were found in the foliage, in the same way that the lowest were found in the branch component, a fact that occurred due to the greater metabolic activity of the leaf, where transpiration and photosynthetic processes take place. Vieira et al. (2009), when studying carbon content in the Cerrado and Caatinga biomes, found values of 43.24% and 47.39% for the leaves and branches, respectively, with average levels of 42.06% and 44.68%. The leaf senescence process may be related to the influence of carbon, since senescent leaves tend to have a higher content, as observed by Alves et al. (2021), in riparian forest of Amazonian streams in Santarém region, Brazil.

In a dataset of eight ecosystems in eastern China, Zhu et al. (2017) present values of carbon concentration in compartments of leaves, branches, trunk and root, with records lower than those in this study for leaves (23.68%) and higher for branches (60.12%). In riparian forests located along water channels in relatively cold and humid temperate regions (53 areas of Tropical Forest of the Olympic Peninsula, Washington, USA), average carbon stock values of 63 t C ha were observed (Dybala et al., 2019).

3.5 C Stock Value

Considering the amounts currently paid per ton of carbon sequestered, it is estimated that the 27.14 $t.ha^{-1}$ of carbon stored in the living biomass (commercial volume) represent a total of 2,252.62 $€.ha^{-1}$. The carbon sequestered annually totaled 3.99 $t.ha^{-1}$ [carbon incorporated in the litter (2.73 $t.ha^{-1}$) + average annual increment of carbon in the commercial volume (1.26 $t.ha^{-1}$)], totaling a value of € 331.17.ha^{-1}. Adding the two values, the studied fragment could receive a total of € 2,583.79.ha^{-1} if it participated in a carbon sequestration and storage payment program.

Similar to what is portrayed in other works, such as in the Amazon Forest (Paiva et al., 2020), the great potential for receiving PES from the analyzed fragment lies in the maintenance of the carbon stock of living biomass, accounting for 87.18% of the total value that can be received, and not in the carbon sequestration itself. This infers that the insertion of the humid fragment in the Chapada do Araripe into a PES program means, in addition to a broad environmental benefit, financial advantages in relation to other forms of land use. Added to this, there is the possibility of another source of income: the exploitation of non-timber forest products (NTFP).

According to Grassi et al. (2017), forest-based climate mitigation may occur through conserving and enhancing the carbon sink and through reducing greenhouse gas emissions from deforestation. Yet the inclusion of forests in international climate agreements has been complex, often considered a secondary mitigation option. In the context of the Paris Climate Agreement, countries submitted their (Intended) Nationally Determined Contributions ((I)NDCs), including climate mitigation targets. Assuming full implementation of (I)NDCs, the authors showed that the forests, in particular, emerge as a key component of the Paris Agreement: turning globally from a net anthropogenic source during 1990–2010 (1.3 ± 1.1 $GtCO_2e\ yr^{-1}$) to a net sink of carbon by 2030 (up to −1.1 ± 0.5 $GtCO_2e\ yr^{-1}$) and providing a quarter of emission reductions planned by countries. Therefore, studies, such as this one, are essential in this regard.

It is important to point out that the values presented in this study refer only to the constant carbon in the living biomass above ground, as well as the annual increase in litter. The quantification of carbon in the soil, in the biomass below the ground, in the existing litter and in the canopy of the forest has not been observed. This leads to an underestimation of the real potential that the forest has to receive carbon credits.

This is the first study focusing on estimating carbon stock and sequestration in the Chapada do Araripe. The results obtained here denote the importance of the forest area studied in this process. The analyses of estimates of CO_2 and of sequestered and stored carbon which have been carried out here, in addition to being unprecedented for forest inventory data in the region, are also relevant for comparative analyses in future studies regarding the values of GHGs that are no longer emitted.

4. CONCLUSION

In the interior of Brazil, estimates of the profitability of environmental services are still little explored. The price stipulated in euros for the study area points to the potential of environmental services programs as important agents for biodiversity conservation and reveals an alternative that can be more advantageous than other forms of land use and occupation.

The carbon stored with the maintenance of living biomass in the forest refuge of Humid Forest of the Sedimentary Basin in the Chapada do Araripe presents great potential as a carbon sink, sequestering an average of 102.02 $tCO_2.ha^{-1}$and thus contributing more than 85% to the total carbon stocked, highlighting the importance of proper management to favor the development of the forest and the guarantee of forest cycling processes.

Biomass quantification studies and carbon stock and sequestration estimates like this one, analyzing the different compartments, are examples of how forestry projects can be used to contribute to climate change mitigation (in carbon neutralization under the Sustainable Development Mechanism - SDM), serving as starting points for the evaluation of other GHG emission reduction projects. However, future work is recommended on the modeling of a sensitivity analysis that considers the possibilities of risks and uncertainties in the carbon market performance.

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5. REFERENCES

ALCÂNTARA, M.C., LUCENA, C.M., LUCENA, R.F.P., CRUZ, D.D, 2020. Ethnobotany and Management of *Dimorphandra gardneriana* in a Protected Area of Chapada do Araripe Semiarid Ceará, Northeastern Brazil. Environmental Management. 65, 420-432. https://doi.org/10.1007/s00267-020-01253-0

ALDER, D., 1995. Growth modelling for mixed tropical forests Oxford. University of Oxford, Tropical forestry papers.

ALVES, M., MARTINS, R.T., COUCEIRO, S.R.M., 2021. Breakdown of green and senescent leaves in Amazonian streams: a case study. Limnology. 22, 27-34. https://doi.org/10.1007/s10201-020-00626-y

ÁLVARES, C.A., STAPE, J.L., SENTELHAS, P.C., GONÇALVES, J.L.M, SPAROVEK, G., 2013. Köppen`s climate classification map for Brazil. Meteorologische Zeitschrift. 22(6), 711-728. https://doi.org/10.1127/0941-2948/2013/0507

ANJALI, K., KHUMAN, Y., SOKHI, J., 2020. A Review of the interrelations of terrestrial carbon sequestration and urban forests. AIMS Environmental Science, 7(6), 464-485. https://doi.org/10.3934/environsci.2020030

APONTE, A., KASEL, S., NITSCHKE, C.R., TANASE, M.A., VICKERS, H., PARKER, L., FEDRIGO, M., KOHOUT, M., RUIZ-BENITO, P., ZAVALA, M.A., BENNETT, L.T., 2020. Structural diversity underpins carbon storage in Australian temperate forests. Global Ecology Biogeography. 29, 789–802. https://doi.org/10.1111/geb.13038

ARAÚJO, K.D., 2010. Análise da vegetação e organismos edáficos em áreas de caatinga sob pastejo e aspectos socioeconômicos e ambientais de São João do Cariri-PB, PhD thesis, Natural Resources Program – Universidade Federal de Campina Grande, Centro de Tecnologia e Recursos Naturais, Campina Grande, PB.

AZEVEDO, A.D., FRANCELINO, M.R., CAMARA, R., PEREIRA, M.G., LELES, P.S.S., 2018. Estoque de carbono em áreas de restauração florestal da Mata Atlântica. Floresta 48(2), 183-194. http://dx.doi.org/10.5380/rf.v48i2.54447

BACCINI, A., GOETZ, S., WALKER, W., LAPORTE, N.T, SUN, M., SULLA-MENASHE, D., HACKLER, J., BECK, P.S.A., DUBAYAH, R., FRIEDL, M.A., SAMANTA, S., HOUGTON, R.A., 2012. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. Nature Climate Change. 2**,** 182-185. https://doi.org/10.1038/nclimate1354

BARBOSA, V., BARRETO-GARCIA, P., GAMA-RODRIGUES, E., DE PAULA, A., 2017. Biomassa, Carbono e Nitrogênio na serrapilheira Acumulada de Florestas Plantadas e Nativa. Floresta e Ambiente. 24, e20150243. https://doi.org/10.1590/2179-8087.024315

BARCELLOS, D., O'CONNELL, C.S., SILVER, W., MEILE, C., THOMPSON, A. 2018. Hot Spots and Hot Moments of Soil Moisture Explain Fluctuations in iron and carbon cycling in a humid tropical forest soil. Soil Systems 2(4), 59. https://doi.org/10.3390/soilsystems2040059

BATISTA, D.B., DACOL, F., CORTE, A.P., MARTINI, A., REIS, A.R., 2020. Aporte de serapilheira e teor de carbono orgânico em um fragmento florestal urbano. Nature and Conservation. 13(4), 22-30. http://doi.org/10.6008/CBPC2318-2881.2020.004.0003

BAZI, C.A., 2019. Produção e decomposição de serrapilheira em um fragmento urbano de Mata Atlântica. Master's degree thesis - Instituto de Botânica da Secretaria de Infraestrutura e Meio Ambiente, São Paulo, SP.

BEZERRA, T.G., LIMA, A.O.S., ARAÚJO, J.T.R., SANTOS, M.G.S., NEVES, R.L.P., MORAES, G.C., MELO, L.O., 2018. Estrutura e dinâmica de uma área manejada na Floresta Nacional Do Tapajós. Agroecossistemas. 10(2), 94-112. http://dx.doi.org/10.18542/ragros.v10i2.5131

BIANCHI, M.O., SCORIZA, R.N., CORREIA, M.E.F., 2016. Influência do clima na dinâmica de serrapilheira em uma floresta estacional semidecidual em Valença, RJ, Brasil. Revista Brasileira de Biociências. 14(2), 97-101.

BROWN S., GILLESPIE A.J.R., LUGO A. E., 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. Forest Science. 35, 881-902.

CALIXTO JÚNIOR, J.T., MOURA, J.C., LISBOA, M.A.N., CRUZ, G.V., GONÇALVES, B.L.M., BARRETO, E.S.S.T., BARROS, L.M., DRUMOND, M.A., MENDONÇA, A.C.A.M., ROCHA, L.S.G., SILVA, M.A.P., CORDEIRO, L.S., 2021. Phytosociology, diversity and floristic similarity of a Cerrado fragment on Southern Ceará state, Brazilian Semiarid. Scientia Forestalis. 49(130), e3459. https://doi.org/10.18671/scifor.v49n130.01

CARVALHO, F.F., BARRETO-GARCIA, P.A.B., ARAGÃO, M.A., VIRGENS, A.P., 2019. Litterfall and Litter Decomposition in Pinus and Native Forests. Floresta e Ambiente. 26(2), e20170165. https://doi.org/10.1590/2179-8087.016517

CHAN, K.M.A., ANDERSON, E.K., CHAPMAN, M., JESPERSEN, K., OLMSTED, P., 2017. Payments for ecosystem services: Rife with problems and potential for transformation towards sustainability. Ecological Economics. 140, 110-122. https://doi.org/10.1016/j.ecolecon.2017.04.029

CHATTERJEE, A., LAL. R., WIELOPOLSKI, L., MARTIN, M.Z., EBINGER, M. H., 2009. Evaluation of different soil carbon determination methods. Critical Reviews in Plant Science. 28, 164-178. https://doi.org/10.1080/07352680902776556

CUBAS, R., WATZLAWICK, L.F., FIGUEIREDO FILHO, A., 2016. Incremento, ingresso, mortalidade em um remanescente de Floresta Ombrófila Mista em Três Barras-SC. Ciência Florestal. 26(3), 889-900. https://doi.org/10.5902/1980509824216

DENG, L., HAN, Q., ZANG, C., TANG, Z., SHANGGUAN, Z., 2017. Above-Ground and Below-Ground Ecosystem Biomass Accumulation and Carbon Sequestration with *Caragana korshinskii* Kom Plantation Development. Land Degradation & Development. 28, 906-917. https://doi.org/10.1002/ldr.2642

DONG, L., LI, J., LIU, Y., HAI, X., LI, M., WU, J., WANG, X., SHANGGUAN, Z., ZHOU, Z., DENG, L., 2022. Forestation delivers significantly more effective results in soil C and N sequestrations than natural succession on badly degraded areas:

Evidence from the Central Loess Plateau case. Catena**.** 208, 1-10, 2022. https://doi.org/10.1016/j.catena.2021.105734

DYBALA, K.E., MATZEK, V., GARDALI, T., SEAVY, N.E., 2019. Carbon sequestration in riparian forests: A global synthesis and meta-analysis. Global Change Biology. 25(1), 57-67. https://doi.org/10.1111/gcb.14475

EMBRAPA., 2007. Dinâmica espaço temporal do carbono aprisionado na fitomassa dos agroecossistemas no nordeste do Estado de São Paulo. Campinas: Embrapa Monitoramento por Satélite.

EMBRAPA., 2008. Estoques de carbono do estrato arbóreo de cerrados no pantanal da Nhecolândia. Corumbá, MS: Embrapa; Comunicado Técnico n. 68.

EMBRAPA., 2018. Sistema Brasileiro de Classificação de Solos. 5. Ed. Brasília, DF: Embrapa.

FAJARDO, A.M.P., TIMOFEICZYK JUNIOR, R., 2015. Avaliação Financeira do Sequestro de Carbono na Serra de Baturité, Brasil. Floresta e Ambiente. 22(3), 391-399.

FAVERO, A., DAIGNEAULT, A., SOHNGEN, B., 2020. Forests: Carbon sequestration, biomass energy, or both?. Science Advances. 6(13), 1-13. https://doi.org/10.1126/sciadv.aay6792

FERRAZ, R.C., MELLO, A.A., FERREIRA, R.A., NACIMENTO-PRADA, A.P., 2013. Levantamento Fitossociológico em área de caatinga no monumento natural Grota do Angico, Sergipe, Brasil**.** Revista Caatinga. 26(3), 89-98.

FERREIRA, M.L., SILVA, J.L., PEREIRA, E.E., LAMANO-FERREIRA, A.P.N., 2014. Produção e decomposição de serrapilheira em um fragmento de Mata Atlântica secundária de São Paulo, SP, Sudeste do Brasil**.** Revista Árvore. 38(4), 591-600. https://doi.org/10.1590/S1676-06032012000300016

FERREIRA, M.L., UCHIYANA, E.A., 2015. Litterfall assessement in a fragment of secondary tropical forest, Ibiúna, SP. Revista Árvore. 39(5), 791-799. https://doi.org/10.1590/0100-67622015000500002

FERNANDEZ-BOU, A.S., DIERICK, D., SWANSON, A.C., ALLEN, M.F., ALVARADO, A.G.F., ARTAVIA-LEON, A., CARRASQUILLO-QUINTANA, O., LACHMAN, D.A., OBERBAUER, A., PINTO-TOMAS, A.A., RODRIGUEZ-REYES, Y., RUNDEL, P., SCHWENDENMANN, L., ZELIKOVA, T.J., HARMON, T.C., 2018. The Role of the Ecosystem Engineer, the Leaf-Cutter Ant *Atta cephalotes*, on Soil CO_2 Dynamics in a Wet Tropical Rainforest. Journal of Geophysical Research: Biogeosciences. 123, 260-273. https://doi.org/10.1029/2018JG004723

FIGUEIREDO FILHO, A., DIAS, A.N., STEPKA, T.F., SAWCZUK, A.R., 2010. Crescimento, mortalidade, ingresso e distribuição diamétrica em floresta Ombrófila Mista. Floresta. 40(4), http://dx.doi.org/10.5380/rf.v40i4.20328

FUNCEME - Fundação Cearense de Meteorologia e Recursos Hídricos. Calendário chuvoso. http://www.funceme.br/ (Acessed 18 December 2021)

FUNDAÇÃO DE CIÊNCIA E TECNOLOGIA (RS). Software Mata Nativa 2: manual do usuário. Viçosa: Cientec, 2006. 295 p.

GIWETA, M., 2020. Role of litter production and its decomposition, and factors affecting the processes in a tropical forest ecosystem: a review. Journal of Ecology and Environment. 44, 11. https://doi.org/10.1186/s41610-020-0151-2

GRASSI, G., HOUSE, J., DENTENER, F., FEDERICI, S., DEN ELZEN, M., PENMAN, J., 2017. The key role of forests in meeting climate targets requires science for credible mitigation. Nature Climate Chang*e* **7**, 220–226.

HEINRICH, V.H.A., DALAGNOL, R., CASSOL, H.L.G., 2021. Large carbon sink potential of secondary forests in the Brazilian Amazon to mitigate climate change. Nature Communications 12, 1785. https://doi.org/10.1038/s41467-021-22050-1

HONÓRIO, A.C., QUARESMA, A., OLIVEIRA, C.T., LOIOLA, M.I.B., 2019. Flora do Ceará, Brasil: *Mikania* (Asteraceae: Eupatorieae). Rodriguésia. 70, 1-15. https://doi.org/0.1590/2175-7860201970003

INSTITUTO NACIONAL DE METEROLOGIA - INMET. Normas Climatológicas do Brasil. Ministério da Agricultura, Pecuária e Abastecimento: Instituto Nacional de

Meteorologia, 2021. http://www.inmet.gov.br/portal/index.php?r= (Acessed 23 September 2021)

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories. 2014. v. 4. https://www.ipccnggip.iges.or.jp/public/2006gl/vol4.html (Acessed 22 August 2021)

KURIYAMAA, A., ABEB, N., 2018. Ex-post assessment of the Kyoto Protocol – quantification of CO2 mitigation impact in both Annex B and non-Annex B countries. Applied Energy. 222, 286-295. https://doi.org/10.1016/j.apenergy.2018.03.025

KÖPPEN, W., GEIGER, R., 1928. Klimate der Erde. Gotha: Verlag Justus Perthes.

LACERDA, J.S., COUTO, H. T. Z., HIROTA, M. M., PASISHNYK, N., POLIZEL, J. L., 2009. Estimativa da Biomassa e Carbono em Áreas Restauradas com Plantio de Essências Nativas. METRVN: Emendabis Mensvram Silvarvm. 5, 1-23.

LAHSEN, M., COUTO, G.A, LORENZONI, I., 2020. When climate change is not to blame: Disaster attribution policy from an international perspective. Climatic Change. 158, 213-233. https://doi.org/10.1007/s10584-019-02642-z

LI, Q., JIA, Z., FENG, L., HE, L., YANG, K., 2018. Dynamics of biomass and carbon sequestration across a chronosequence of *Caragana intermedia* plantations on alpine sandy land. Scientific Reports. 8, 12432. https://doi.org/10.1038/s41598-018-30595-3

LIMA, R.B., FERREIRA, R.L.C., SILVA, J.A.A., ALVES JÚNIOR, F.T., OLIVEIRA, C.P., 2021. Estimating Tree Volume of Dry Tropical Forest in the Brazilian SemiArid Region: A Comparison Between Regression and Artificial Neural Networks. Journal of Sustainable Forestry. 3(48), 281-289. https://doi.org/10.1080/10549811.2020.1754241

LSE - LONDON STOCK EXCHANGE. Prices & markets. 2022. <http://www.londonstockexchange.com> Acesso?

MARCHIORI, N.M., ROCHA, H.R., TAMASHIRO, J.Y., AIDAR, M.P.M., 2016. Tree community composition and aboveground biomass in a secondary Atlantic Forest, Serra do Mar State Park, São Paulo, Brazil. Cerne**.** 22(4), 501-514. https://doi.org/10.1590/01047760201622042242

MARTINELLI, L.A., LINS, S.R.M., SANTOS, J.C., 2017. Fine litterfall in the Brazilian Atlantic Forest. Biotropica. 49, 443-451. https://doi.org/10.1111/btp.12448

MARTINS, W.B.R., FERREIRA, G.C., SOUZA, F.P., DIONÍSIO, L.F.S., OLIVEIRA, F.A., 2018. Deposição de serrapilheira e nutrientes em áreas de mineração submetidas a métodos de restauração florestal em Paragominas, Pará. Floresta**.** 48(1), 37-48. https://doi.org/10.5380/rf.v48%20i1.49288

MINISTÉRIO DO MEIO AMBIENTE (MMA). REDD+ and Brazil’s Nationally Determined Contribution. http://redd.mma.gov.br/en/redd-and-brazil-s-ndc (2016).

MISHRA, A., KUMAR, M., MEDHI, K. SHEKHAR, I., 2020. Biomass energy with carbon capture and storage (BECCS). Current Developments in Biotechnology and Bioengineering. 399-427. https://doi.org/10.1016/b978-0-444-64309-4.00017-9

MORO, M.F., MACEDO, M.B, MOURA-FÉ, M.M., CASTRO, A.S.F., COSTA, R.C., 2015. Vegetação, unidades fitoecológicas e diversidade paisagística do estado do Ceará. Rodriguésia**.** 66(3), 717-743. http://dx.doi.org/10.1590/2175-786020156630

MULLER-DOMBOIS, D., Ellenberg, H., 1974. Aims and Methods of Vegetation. Ecology, New York. John Wiley & Sons.

NOGUEIRA, E.M., 2008. Densidade de madeira e alometria em árvores de florestas do “arco do desmatamento”: implicações para biomassa e emissão de carbono a partir de mudanças de uso da terra na Amazônia brasileira. PhD thesis, Tropical Forest Science Program – Instituto Nacional de Pesquisas da Amazônia – INPA. Manaus, Cap. 1, 23-45.

PAIVA, W.S., CAMELO, G.C.C., ARAÚJO,R.F., GOULART, S.L., ABRÃO, S.F., EBLING, A.A., 2020. Pagamento por serviço ambiental em floresta ombrófila densa secundária no sudeste do Pará. Biofix scientific Journal. 5(1), 114-120. http://dx.doi.org/10.5380/biofix.v5i1.68458

PEDRO, C.M., SILVA, F.C.S., BATISTA, A.C., VIOLA, M.R., COELHO, M.C.B., GIONGO, M., 2019. Supplying and decomposition of burlap in a fragment of cerrado *sensu stricto*. Floresta. 49(2), 237-246.

PEREIRA JUNIOR, L.R., ANDRADE, E.M., PALÁCIO, H.A.Q., RAYMER, P.C.L., RIBEIRO FILHO, J.C., PEREIRA, F.J.S., 2016. Carbon stocks in a tropical dry forest in Brazil. Revista Ciência Agronômica. 1, 32-40. https://doi.org/10.5935/1806-6690.20160004

REISCH, R.D.N., 2021. The brazilian potential in generating carbon credits through forest conservation, reforestation and sustainable agriculture. Humboldt - Revista de Geografia Física e Meio Ambiente. 1(3), e61662.

QUEIROZ, R.T., CORDEIRO, L.S., SAMPAIO, V.S., RIBEIRO, R.T.M., LOIOLA, M.I.B., 2018. A Região Nordeste. *In:* Coradin, L.; Camillo, J.; Pareyn, F.G.C. (Eds.) Espécies nativas da flora brasileira de valor econômico atual ou potencial: plantas para o futuro: região Nordeste. Ministério do Meio Ambiente, Brasília, 73-104.

RIBEIRO M.C., METZGER, J.P., MARTENSEN, A.C., PONZONI, F.J., HIROTA, M.M., 2009. The Brazilian Atlantic Forest: How much is left, and how is the remaining forest disturbed? Implications for conservation. Biological Conservation. 142 (6), 1141 -1156. https://doi.org/10.1016/j.biocon.2009.02.021

ROQUETTE, J.G., 2018. Distribuição da biomassa no cerrado e a sua importância na armazenagem do carbono. Ciência Florestal. 28(3), 1350-1363. https://doi.org/10.5902/1980509833354

SALATI, E., 1994. Emissão x sequestro de CO_2 – uma nova oportunidade de negócios para o Brasil. *In:* Anais do Seminário emissão x sequestro de CO_2 – uma nova oportunidade de negócios para o Brasil. Rio de Janeiro: CVRD; 15-37.

SANTIAGO, A.R., COUTO, H.T.Z., 2020. Socioeconomic development versus deforestation: considerations on the sustainability of economic and social growth in most Brazilian municipalities. Environmental Development, 35, 100520. https://doi.org/10.1016/j.envdev.2020.100520

SANTOS, F.G., CAMARGO, P.B., OLIVEIRA JÚNIOR, R.C., 2018. Estoque e dinâmica de biomassa arbórea em floresta ombrófila densa na Flona Tapajós:

Amazônia Oriental. Ciência Florestal. 28(03), 1049-1059. https://doi.org/10.5902/1980509833388

SCHAAF, L.B., 2001. Florística, estrutura e dinâmica no período 1979-2000 de uma Floresta Ombrófila Mista localizada no sul do Paraná. Master's degree thesis (Forest Engineering), Setor de Ciências Agrárias, Universidade Federal do Paraná, Curitiba.

SCHEER, M.B., GATTI, G., WISNIEWSKI, C., 2011. Fluxos de nutrientes na serrapilheira de uma floresta pluvial aluvial secundária no sul do Brasil. Revista de Biologia Tropical. 59(4), 1869-1882.

SCORIZA, R.N., PIÑA-RODRIGUES, F.C.M., 2014. Influência da precipitação e temperatura do ar na produção do ar na produção de serrapilheira em trecho de floresta estacional em Sorocaba, SP. Floresta. 44(4), 687-696. http://dx.doi.org/10.5380/rf.v44i4.34274

SILVA, J. M.; MOURA, C.H.R., 2021. Análise da vegetação de um remanescente de Floresta Atlântica: subsídios para o projeto paisagístico. Revista Brasileira de Meio Ambiente. 9(1), 002-024.

SILVA, L.V.A., ARAÚJO, I.F., BENÍCIO, R.M.A., NASCIMENTO, A.S., MORAIS, H.N., MORAIS, S.C.O., LISBOA, M.A.N., CRUZ, G.V., FABRICANTE, J.R., CALIXTO-JÚNIOR, J.T., 2022. Plantas exóticas na Chapada do Araripe (Nordeste do Brasil): ocorrência e usos. Revista Brasileira de Geografia Física. 15(03), 1239-1259. https://doi.org/10.26848/rbgf.v15.3.p1239-1259

SLOBODA, B., 2017. Litterfall and Nutrient Dynamics in a Mature Atlantic Rainforest in Brazil. Floresta e Ambiente. 24, e20160339. http://dx.doi.org/10.1590/2179-8087.033916

SCHMITT, C.B., BURGESS, N.D., COAD, L. BELOKUROV, A., BESANÇON, C., BOISROBERT, L., CAMPBELL,A., FISH, L., GLIDDON, D., HUMPHRIES, K. KAPOS, V., LOUCKS, C., LYSENKO, I., MILES, L., MILLS, C., MINNEMEYER,S., PISTORIUS, T., RAVILIOUS, C., STEININGER, M., WINKEL, G., 2009. Global analysis of the protection status of the world's forests, Biological Conservation, 142, 10, 2122-2130. https://doi.org/10.1016/j.biocon.2009.04.012

SOUZA, M.A.S., AZEVEDO, C.P., SOUZA, C.R., FRANÇA, M., VASCONCELOS NETO, E.L., 2017. Dinâmica e produção de uma floresta sob regime de manejo sustentável na Amazônia central. Floresta. 47(1), 55-63. http://dx.doi.org/10.5380/rf.v47i1.43312

SOUZA, A.L., BOINA, A., SOARES, C.P.B., VITAL, B.R., GASPAR, B. de O., LANA, J.M., 2012. Estrutura fitossociológica, estoques de volume, biomassa, carbono e dióxido de carbono em Floresta Estacional Semidecidual. Revista Árvore 36 (1), 169-179. https://doi.org/10.1590/S0100-67622012000100018

SOUZA, C.R., AZEVEDO, C.P., ROSSI, L.M.B., SILVA, K.E., SANTOS, J., HIGUSHI, N., 2012. Dinâmica e estoque de carbono em floresta primária na região de Manaus/AM. Acta Amazônica. 42(4), 501-506. https://doi.org/10.1590/S0044-59672012000400007

SUN, X., WANG, G., HUANG, M., CHANG, R., RAN, F., 2016. Forest biomass carbon stocks and variation in Tibet’s carbon-dense forests from 2001 to 2050. Scientific Reports. 34687. https://doi.org/10.1038/srep34687

TOSCAN, M.A.G., GUIMARAES, A.T.B., TEMPONI, L.G., 2017. Caracterização da produção de serrapilheira e da chuva de sementes em uma reserva de floresta estacional semidecidual, Paraná. Ciência Florestal. 27(2), 415-427. https://doi.org/10.5902/1980509827725

UNITED NATIONS. Framework Convention on Climate Change. Kyoto protocol. *In*: http://unfccc.int/kyoto_protocol/items/2830.php. Acess. Jun 5th, 2022.

VATRAZ, S.; ALDER, D.; SILVA, J.N.M., 2018. Autocorrelação temporal do incremento em diâmetro e as diferenças de crescimento entre grupos de espécies em uma floresta ombrófila densa. Revista Brasileira de Biometria. 36(1), 56-73. https://doi.org/10.28951/rbb.v36i1.118

VIDAL, E., VIANA, V.M., BATISTA, J.L.F., 2002. Crescimento de floresta tropical três anos após colheita de madeira com e sem manejo florestal na Amazônia Oriental. Scientia Forestalis. 61, 133 -143.

VIEIRA G., SANQUETTA C.R., WAMBIER KLÜPPEL M.L., BARBEIRO L.S.S., 2009. Teores de carbono em espécies vegetais da caatinga e do cerrado. Revista Academica Ciência Animal. 7(2), 145-5. https://doi.org10.7213/cienciaanimal.v7i2.9846

VIEIRA, S.A., ALVES, L.F., DUARTE-NETO, P.J., MARTINS, S.C., VEIGA, L.G., SCARANELLO, M., PICOLLO, M., CARMAGO, P., CARMO, J., SOUSA NETO, E., SANTOS, F., JOLY, C., MARTINELLI, L., 2011. Stocks of carbon and nitrogen and partitioning between above - and belowground pools in the Brazilian coastal Atlantic Forest elevation range. Ecology and Evolution 1 (3), 421-434. https://doi.org/10.1002/ece3.41

VOGEL, H.L.M., LORENTZ, L.H., OLIVEIRA, F.P., 2015. Produção de serrapilheira em mata nativa na região Central da Depressão-RS. Revista Ecologia e Nutrição Florestal. 2(3), 84-92.

WANG, K., HU, D., DENG, J., SHANGGUAN, Z., DENG, L., 2018. Biomass carbon storages and carbon sequestration potentials of the Grain for Green Program-Covered Forests in China. Ecology and Evolution. 15, 7451-7461. https://doi.org/10.1002/ece3.4228

WAHEED. R., CHANG, D., SARWAR, S., CHEN, W., 2018. Forest, agriculture, renewable energy and CO_2 emission. Journal of Cleaner Production. 172, 4231-4238. https://doi.org/10.1016/j.jclepro.2017.10.287

WATZLAWICK, L.F., EBLING, A.A, RODRIGUES, A.L., VERES, Q.L., LIMA, A.M., 2011. Variação nos Teores de Carbono Orgânico em Espécies Arbóreas da Floresta Ombrófila Mista. Floresta e Ambiente. 8(3), 248-258. http://dx.doi.org/10.4322/floram.2011.045

WERNECK, M.S., PEDRALLI, G., GIESEKE, L.F., 2001. Produção de serrapilheira em três trechos de uma floresta semidecidual com diferentes graus de perturbação na Estação Ecológica de Tripuí, Ouro Preto, MG. Revista Brasileira de Botânica. 24, 195-198. https://doi.org/10.1590/S0100-84042001000200009

YAN, J.A., WANG, L., HU, Y., TSANG, Y.F., ZHANG, Y., WU, J., FU, X., SUN, Y., 2018. Plant litter composition selects different soil microbial structures and in turn drives different litter decomposition pattern and soil carbon sequestration capability. Geoderma. 319, 194-203. https://doi.org/10.1016/j.geoderma.2018.01.009

YAO, Y., GE, N., YU, S., WEI, X., WANG, X., JIN, J., LIU, X., SHAO, M., WEI, Y., KANG, L., 2019. Response of aggregate associated organic carbon, nitrogen and phosphorous to re-vegetation in agro-pastoral ecotone of northern China. Geoderma 341, 172-180. https://doi.org/10.1016/j.geoderma.2019.01.036

ZHANG, H., YUAN, W., DONG, W., LIU, S., 2014. Seasonal patterns of litterfall in forest ecosystem wordwide. Ecological Complexity. 20, 240-247.

ZHU J., HE, N., ZHANG, J., WANG, Q., ZHAO, N., JIA, Y., GE, J., YU, G., 2017. Estimation of carbon sequestration in China's forests induced by atmospheric wet nitrogen deposition using the principles of ecological stoichiometry. Environmental Research Letters 12(11), 1-9. https://doi.org/10.1088/1748-9326/aa94a4

ZAHN, R., 2009. Beyond the CO_2 connection. Nature. 460, 335-336. https://doi.org/10.1038/460335a

Author Statement

This is to certify that the reported work in the paper entitled “**Carbon stock and sequestration as a form of payment for environmental services in a Sedimentary Basin Humid Forest refuge in Brazilian Semiarid”** submitted for publication is an original one and has not been submitted for publication elsewhere. I/we further certify that proper citations to the previously reported work have been given and no data/tables/figures have been quoted verbatim from other publications without giving due acknowledgement and without the permission of the authors.

The consent of all the authors of this paper has been obtained for submitting the paper to the ‘Environmental Development (ED).

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Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: