ANE CRISTINE FORTES DA SILVA

CARBON STOCK AND QUALITY IN FOREST AND AGRICULTURAL ENVIRONMENTS

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Dissertation submitted to the Graduate Program in Forest Sciences at the Federal Rural University of Pernambuco, as part of the requirements for obtaining the title of PhD in Forest Sciences.

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CARBON STOCK AND QUALITY IN FOREST AND AGRICULTURAL ENVIRONMENTS

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To my parents, Eliane and Luiz Henrique (*in memoriam*)

To my family in Texas, George and Monica Lyerly (*in memoriam*)

I DEDICATE

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ABSTRACT

The present study aimed (i) to quantify the carbon stocks (C) in the biomass, litter and soil reservoirs in forest and agricultural ecosystems, (ii) to quantify the stocks and carbon quality in the soil, (iii) to evaluate the effects of changes in land use in the C reservoirs, and (iv) to quantify and evaluate the seasonal variation of carbon flows through litter input in forest ecosystems in Dry Tropical Forest and Tropical Rainforest environments in Northeast Brazil. The biomass of leaves, wood/manioc/stem and total biomass of species with the highest absolute density in forest environments and in agricultural crops of cassava and sugarcane were estimated. In addition, the accumulated litter biomass in forest environments was estimated. Soil samples from six layers up to 1.0 m deep were collected to determine the carbon content and density of the soil and to estimate the soil's organic carbon stock. The carbon content and stocks of each compartment were determined by species and by the type of land use in each area. Deformed and undisturbed soil samples were collected at 0.00 - 0.05; 0.05 - 0.10; 0.10 - 0.20 m deep layers. The contents of total organic carbon, carbon of humic substances (fulvic acids, humic acids and humine), labile carbon and fractions of oxidizable carbon were estimated. Carbon stocks, as well as carbon recovery and depletion rates were calculated. Contribution of litter was evaluated using 20 collectors of 1.0 m², installed in the center of the plots. Material deposited in the collectors was taken at 45; 90; 135; 180; 225; 270 and 315 days after its installation in April 2017 and in April/2018, totaling 18 collections per area. The litter was separated into leaves, branches+bark and miscellaneous material. The dry and total litter biomass of each fraction was determined, as well as the carbon content. The land-use change in the dry and humid environment represented significant effects for the carbon stock in the soil up to 1.0 m deep. Conversion of forest to agricultural cultivation in the humid environment altered carbon content and stock in the soil, especially in the top layers, which was mainly related to a decrease in litter supply and agricultural cultivation practices. Changes in land use reduced the carbon recovery rate from fractions of fulvic acids, humic acids, humine and total humic substances in the surface layers in the dry environment. The leaf biomass contributed the most to total carbon in litter among years in the humid environment (~70% of the total C contributed). The largest contributions of C trough litter occurred during the period of water limitation and is related to the leaf senescence of Caatinga species. The peaks of C input through litter in the rainforest occured during winter and spring, the driest period.

Keywords: carbon *pools*, soil organic carbon, forest carbon sequestration, land-use change, humic fractions, oxidizable carbon, plant litter carbon.

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RESUMO

O presente estudo teve por objetivo quantificar os estoques de carbono (C) nos reservatórios da biomassa, serapilheira e solo em ecossistemas florestais e agrícolas, quantificar os estoques e qualidade do carbono no solo e avaliar os efeitos das mudanças do uso do solo nos reservatórios de C em e, por fim, quantificar e avaliar a variação sazonal dos fluxos de carbono via aporte de serapilheira nos ecossistemas florestais em Floresta Tropical Seca e Floresta Tropical Úmida no Nordeste do Brasil. Estimou-se a biomassa das folhas, lenho/maniva/colmo e total das espécies de maior densidade absoluta nos ambientes florestais e em cultivos agrícolas de mandioca e cana-de-açúcar. Estimou-se a biomassa acumulada de serapilheira nos ambientes florestais. Amostras de solo de seis camadas até 1,0 m de profundidade foram coletadas para determinações do teor de carbono e densidade do solo e estimativa do estoque de carbono orgânico do solo. Foram determinados os teores e estoques de carbono de cada compartimento por espécie, por área uso do solo. Amostras deformadas e indeformadas de solo foram coletadas nas camadas de 0,00 - 0,05; 0,05 - 0,10; 0,10 - 0,20 m. Foram estimados os teores de carbono orgânico total, carbono das substâncias húmicas (ácidos fúlvicos, ácidos húmicos e humina), carbono lábil e frações do carbono oxidável. Os estoques de carbono, assim como a taxa de recuperação e esgotamento do carbono foram calculadas. O aporte de serapilheira foi avaliado por meio de 20 coletores de 1,0 m², instalados no centro das parcelas. O material depositado nos coletores foi coletado aos 45; 90; 135; 180; 225; 270 e 315 dias após sua instalação em abril de 2017 e o ciclo de coletas foi repetido no ano seguinte (abril/2018), totalizando 18 coletas por área. A serapilheira aportada foi fracionada em folhas, galhos + cascas e miscelânea. A biomassa seca da serapilheira de cada fração e total foi determinada, assim como os teores de carbono. A mudança do uso do solo no ambiente seco e úmido representou efeitos significativos para o estoque de carbono no solo até 1,0 m de profundidade. A conversão floresta-cultivo agrícola no ambiente úmido altera o teor e estoque de carbono do solo, sobretudo na camada superficial do solo, relacionado principalmente a diminuição do aporte de serapilheira no solo e práticas de cultivo agrícola. A mudança do uso do solo reduziu a taxa de recuperação do carbono das frações ácidos fúlvicos, ácidos húmicos, humina e das substâncias húmicas totais nas camadas superficiais no ambiente seco. A biomassa foliar foi a que contribuiu mais para o total de carbono da serapilheira aportada entre os anos observados no ambiente úmido (~70% do C total aportado). Os maiores aportes de C via serapilheira ocorreram durante o período de limitação hídrica e está relacionado a senescência de folhas das espécies da Caatinga. Os picos de aporte de C via serapilheira na floresta úmida ocorrem durante o inverno e primavera, período mais seco.

Palavras-chave: *pools* de carbono, carbono orgânico do solo, sequestro florestal de carbono, mudança do uso do solo, frações húmicas, carbono oxidável, carbono da serapilheira.

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1 GENERAL INTRODUCTION

Land use changes affect vegetation and soil ecosystems and consequently change the quantity and quality of stored carbon per unit area. The magnitude of the impact of land-use change on carbon sequestration by vegetation and soil in moist tropical forests and dry and seasonally dry tropical forests has not been well explored, especially regarding the responses of links among net primary productivity, quantity and quality of soil carbon.

In general, studies on land use change in these environments suggest that management has major influence on carbon stocks in ecosystem deposits. There is a lack of research that explains the soil-forest relationship in tropical forests, mainly correlating to stocks and carbon levels in plant species, plant litter and soil.

Predicting how the Caatinga vegetation and the Atlantic Forest will behave in the face of predicted climate change contexts is essential to establish accurate management protocols and sustainable conservation strategies for forest ecosystems. Past, present and future carbon stocks in tropical forests are therefore relevant to global carbon budgets.

It is essential to demand greater effort in understanding the capacity of tropical forests to sequestrate or release carbon, as well as the reduction of uncertainties regarding the consequences of the replacement of forest ecosystems for carbon stocks in the scope of climate changes.

Due to the socioeconomic and environmental importance related to the extensive agricultural area of sugarcane in the domain of the Tropical Rainforest, and the agriculture and exploitation of forest resources in the domain of the Tropical Dry Forest, the present work aims to contribute to the knowledge of the effects of changes in land use and management on carbon dynamics.

This work has two hypotheses: 1) The change in use and cover of forest land for agricultural cultivation reduces the stocks, flows and distribution of carbon in reservoirs and decreases the quality of carbon stored in the ecosystem's soil. 2) The magnitude of the impacts of changing land use and forest cover for agricultural cultivation on stocks, flows and carbon distribution in reservoirs is greater in the Tropical Rainforest compared to the Tropical Dry Forest.

The content of this thesis was divided into a general introduction, followed by three chapters and general conclusions.

The chapter I, entitled **STOCK AND CHANGES OF CARBON IN AGRICULTURAL ECOSYSTEMS IN DRY AND HUMID ENVIRONMENTS**, aimed to quantify the carbon stocks in plant biomass, plant litter and soil in forest and agricultural ecosystems in the dry and rainforest environments and to evaluate the effects of land use changes in these deposits within and between these environments.

The chapter II, entitled **SOIL CARBON QUALITY IN AGRICULTURAL AND FOREST ECOSYSTEMS IN DRY AND HUMID ENVIRONMENTS**, aimed to quantify the stocks and quality of soil carbon in forest and agricultural ecosystems in the dry tropical forest and tropical rainforest, and to assess the effects of land use changes in these reservoirs within and between these environments.

Finally, the chapter III, entitled **CARBON FLUX THROUGH LITTERFALL IN A TROPICAL DRY FOREST AND TROPICAL RAINFOREST**, aimed to quantify and compare carbon fluxes through plant litter input in forest ecosystems in dry forest and tropical rainforest.

2 LITERATURE REVIEW

2.1 Carbon stocks and flows in terrestrial ecosystems

In nature, most of the stored carbon (C) is found in geological layers and ocean sediments (99.94%), and the remaining is in the atmosphere, oceans, plants and animals (BERNER; LASAGA 1989). Carbon pools are systems that can store or release C (QIN *et al*., 2013). The main C pools comprise the atmosphere, the lithosphere, the oceans and the terrestrial ecosystems - which include soil, vegetation, animals and microorganisms.

Any movement of C between these pools is called a flow. In an integrated system, C reservoirs are connected by flows to create cycles. Thus, the main carbon pools and flows on Earth comprise the global C cycle.

The main human activities that release carbon into the atmosphere are deforestation, which includes changes in land use, forest or cultural waste burning and fossil fuels burning. Carbon stored in fossil fuels does not naturally participate in flows between carbon pools, only through human action (SCHIMEL, 1995).

In the last centuries, the concentration of C in the atmosphere has increased (~ 370 ppmv), mainly due to the acceleration of industrial activities and agricultural expansion, resulting from deforestation of forest areas (USSIRI; LAL, 2017). This increase in C, mainly in the form of carbon dioxide and other gases, has intensified the greenhouse effect and favoured global warming.

The concentration of carbon in the atmosphere, despite representing a small portion considering the other pools on the planet, is of fundamental importance in the global cycle of this element. Any change in this concentration has significant consequences for the overall flow of the system.

Fixation of carbon dioxide from the atmosphere to another pool can occur through phototrophic and chemolithotrophic organisms. Most organic compounds originate from the photosynthesis of terrestrial vegetables, cyanobacteria and various bacteria. Photosynthetic organisms remove CO_2 from the atmosphere, using water and solar energy to form their structural and functional molecules (DENARDIN *et al*., 2014). Current estimates suggest that photosynthesis removes about 120 Pg C year^{-1} from the atmosphere and 400 - 600 Pg C is stored in plant biomass (Intergovernmental Panel on Climate Change - IPCC, 2007).

Through photosynthesis, bonds are formed between carbon atoms to originate organic molecules. These organic compounds (polysaccharides) can be combined into fats, waxes, hemicellulose, polyphenols, lignin, proteins, sugars, starches and cellulose. Part of these organic materials is temporarily stored as a constituent of biomass. For accumulation of organic compounds to occur, the photosynthesis rate must be higher than the respiratory rate, thus forming biomass.

The carbon dioxide fixed by the plants is then transferred to different C deposits in the biomass. Among various tissues produced by plants, the wood of trees has the capacity to store large amounts of carbon.

According to the IPCC (2007), there are five C deposits in terrestrial ecosystems involving phytomass: aboveground biomass, below-ground biomass, dead litter biomass, wood debris and soil organic matter (SOM). Any land-use change system such as forest degradation and deforestation have direct impact on the storage of C from these deposits in the ecosystem.

Tropical and subtropical forests are considered strategic environments for scientific studies of carbon sequestration. However, even so, they are the ecosystems most threatened by human pressure in the world. Pearson *et al*. (2017) estimated a total of 2.1 Gt CO_2 emitted by degradation of tropical and subtropical forests, including those in Brazil, and approximately 25% of this total is related to deforestation.

Carbon stored in the plant biomass can be returned to the atmosphere as CO_2 through plants respiration. In this process, cells use carbohydrates produced during photosynthesis to obtain energy, which occurs in both light and dark. Respiration returns about half of the carbon that is removed from the atmosphere by photosynthesis (60 Pg C $year^{-1}$) in the form of carbon dioxide (JANZEN, 2004).

Part of the carbon removed by photosynthesis is transferred to the higher animals through the food chain and then integrates its molecules. However, most of these organic materials are added to the soil as plant tissue, including the remains of roots (BRADY; WEIL, 2013).

The contribution of organic residues in the soil corresponds to the production of plant litter, which is one of the main pathways of carbon flow from plant biomass to the soil. An overall contribution of 60 Pg C $year^{-1}$ is estimated through litter (MARTINELLI *et al*., 2009).

Plant litter is one of the most dynamic carbon deposits. This compartment corresponds to the layer of organic residues deposited on the soil surface that accumulates until its fragmentation and decomposition by biotic, physical and chemical processes. (ADUAN; VILELA; KLINK, 2003). The litter consists of leaves, branches, barks, stems, fruits, flowers and parts of animals such as fecal material and other debris. The type of vegetation, the edaphoclimatic characteristics, the topography and the conservation levels will determine the quality and quantity of litter brought to the soil.

Once deposited on or in the soil, organic waste together with animal remains is metabolized by soil organisms, which gradually return C to the atmosphere as carbon dioxide (BRADY; WEIL, 2013) and part of the carbon is temporarily stored in the SOM as humified compounds.

According to Moreira and Siqueira (2006), these compounds are deposited on or in the soil and degraded by organisms that will regenerate CO_2 during respiratory oxidation reactions by using energy. Deposition and subsequent decomposition of phytomass is the main pathway for the transfer of C and nutrients from the plant to the soil (SCHUMACHER *et al*., 2004).

It is estimated that the total amount of carbon accumulated in the world varies between 1500 - 2000 Pg in various organic forms, from freshly fallen litter to much older much humified compounds (AMUNDSON, 2001). On a global scale, soils stock at least twice as much C compared to the atmosphere (TRUMBORE; CAMARGO, 2009), and there are two to three times more C in soils compared to vegetation. About a third of the soil's organic C occurs in forests, another third is in pastures and savannas, and the remaining is in wetlands, cultivated land and other biomes (JANZEN, 2004).

The SOM mass is composed of approximately 58% by C (SILVA; MENDONÇA, 2007). Most soil organisms use organic compounds from SOM as a source of energy and nutrients to generate carbon transformations in the soil, including mineralization, immobilization and formation of humic substances (MOREIRA; SIQUEIRA, 2006).

In terrestrial ecosystems, the TOC stored varies due to edaphoclimatic characteristics, topography, forest typology, conservation status and area usage history. Soil C stocks fluctuate on a local scale due to factors such as topography and land management. On a regional scale, it happens due to the effects of soil source material and underlying geology (TRUMBORE; CAMARGO, 2009).

Tropical forests are known to play an important role in the global C cycle, storing approximately 46% of the world's terrestrial C reserve and approximately 12% of the soil's C reserve, acting as a C reservoir and functioning as a constant sink of atmospheric C (BROWN; LUGO, 1982; SOEPADMO, 1993; VASHUM; JAYAKUMAR, 2012).

Regarding agricultural areas, studies that assess the effects of land use change on COS storage generally find a decrease in stock over time (SCHULZ *et al*., 2016; CONTI *et al*., 2014;

MUÑOZ-ROJAS *et al*., 2012). However, it can also be seen that adequate soil management is one of the main factors for maintaining the COS stock (POEPLAU; DON, 2013; MURTY *et al*., 2002).

2.2 Carbon stocks in the Tropical Dry Forest and Tropical Rainforests

Dry tropical forests (DTF) or seasonally dry tropical forests (SDTF) cover approximately 42% of the area occupied by tropical forests (MEDVIGY *et al*., 2017). Most DTF occur in America (~ 54%) (MILES *et al*., 2006). These forests are among the most threatened ecosystems in the world as a result of intensive human disturbances (HOEKSTRA *et al*., 2005; PORTILLO-QUINTERO; SÁNCHEZ-AZOFEIFA, 2010).

Intensification of the degradation of DTF by human activities reflects negatively in many aspects, mainly in the capture, storage and emissions of carbon (C). Tropical and subtropical forests are considered to be ecosystems of strategic interest for wide-ranging scientific studies, such as the sequestration of C. However, little attention has been given to the potential for C storage in DTF.

In general, the carbon stored in dry forests in aboveground biomass is lower than that reported in humid forests. In the Argentinian Chaco, Conti *et al*. (2014) estimated C stocks in the aboveground biomass of 34.43 Mg C ha^{-1}. Gasparri, Grau and Manghi (2008), also in Argentina, found stocks of aboveground biomass C of 78 Mg ha^{-1} in a similar environment.

An inferior result was found in the Caatinga by Pereira Júnior *et al*. (2016), estimating 19.27 Mg C ha^{-1}. Moura *et al*. (2016) also found stocks of 27 Mg C ha^{-1} in the Brazilian semiarid region. Similarly, Chen, Hutley and Eamus (2003) found a result of 41.20 Mg C ha^{-1} in the Australian savanna.

The global average estimate of COS stock for the 1.0 m surface layer in deciduous tropical forests is 158 Mg ha^{-1} (JOBBÁGY; JACKSON, 2000). Soil C stocks fluctuate on a local scale due to factors such as topography and land management. On a regional scale, it varies due to soil source material and the underlying geology (TRUMBORE; CAMARGO, 2009).

For this reason, C stocks in DTF vary widely across regions. In India, COS stocks are found in DTF between 7.7 and 369.0 Mg ha^{-1} (CHHABRA; PALRIA; DADHWAL, 2003; MOHANRAJ; SARAVANAN; DHANAKUMAR, 2011). Chhabra, Palria and Dadhwal (2003) estimated COS stock ranging from 7.7 to 85.6 Mg ha^{-1} in the first 50 cm of the soil, while in the 0.0 - 1.0 m layer stocks fluctuated between 18.5 and 147.7 Mg ha^{-1}.

Mohanraj, Saravanan and Dhanakumar (2011), also in dry deciduous forest in India, obtained a higher average estimate (246.02 Mg ha^{-1}) in the first 30 cm of the soil. Chaturvedi, Raghubanshi and Singh (2011), assessing organic carbon stocks in five DTF areas in the same country at different levels of anthropic disturbance, found an average of 21.8 Mg ha^{-1}. However, Ahirwal, Maiti and Singh (2017) estimated it to be 30.55 Mg ha^{-1} in dry natural forest in the same country.

In South America, a total of 114 Mg ha^{-1} of C stored in forest in the semi-arid Chaco region of Argentina was observed in the 1.0 m surface layer (VILLARINO *et al*., 2016). In the same region, Conti *et al*. (2014) found lower results, even though they considered the first 200 cm of soil.

The C stored in a Mexican DTF soil was lower than that observed in the Argentine semiarid, varying from 20.1 to 75.2 Mg ha-1 (VARGAS; ALLEN; ALLEN, 2008). Jaramillo *et al*. (2003), in the same country, estimated COS stocks close to that found in the previous study (76.2 Mg ha^{-1}).

In dry tropical forests, Bailis and McCarthy (2011) found COS values stored at a depth of 0 - 30 cm of 67.8 Mg Mg C ha^{-1} in Caatinga, but in a semiarid area with a predominance of mesquites in India they observed stocks of 24 , 9 Mg Mg C ha^{-1}. On the other hand, Correa *et al*. (2009) obtained carbon stocks lower than those observed by previous authors in the Brazilian semiarid with 23.18 Mg Mg C ha^{-1}.

Expanding the scale, it is observed that the variation of carbon in dry areas is more evident. In a dry environment in Argentina, Conti *et al*. (2014) found COS stocks higher than the aforementioned ones, with 73.07 Mg Mg C ha^{-1}. Gandhi *et al*. (2017) found in dry deciduous tropical forest in India stocks ranging between 16 and 47 Mg Mg C ha^{-1}, while Chen, Hutley and Eamus (2003) on savanna in Australia found higher results with 241.50 Mg C ha^{-1}.

On the African continent, specifically in Ethiopia, the estimated average C stock in dry natural forest was 225.03 Mg ha^{-1} in the 0.0 - 1.0 m layer (ASSEFA *et al*., 2017). Feyisa *et al*. (2017) estimated at 50.9 Mg C ha^{-1} stored in the first 30 cm of the soil in a over 30 years old tropical savanna without disturbance located in southern Ethiopia. In Australia, Chen, Hutley and Eamus (2003) verified stocks of C in tropical eucalyptus savannah of 151 Mg ha^{-1}.

In Brazil, Menezes *et al*. (2012) indicated that in the Caatinga soils the carbon stock is 23.68 Mg ha^{-1} on average. Schulz *et al*. (2016) estimated 7.02 and 15.82 Mg ha^{-1} in the 0.0 - 0.05 m and 0.05 - 0.60 m layers, respectively. On the other hand, Moura *et al*. (2016) found superior results for the C stock (30.21 Mg ha^{-1}) in a regeneration area of the Caatinga with approximately 57 years.

Variations in COS stocks can be due to species composition, quality and quantity of organic matter, soil type, texture and soil chemistry (KALIES; HAUBENSAK; FINKRAL, 2016). Gandhi and Sundarapandian (2017) observed a significant positive correlation between COS stocks and some vegetation characteristics such as absolute density, arboreal basal area and richness of herbaceous species, while a significant negative correlation was observed with apparent density and soil pH.

As for the vertical distribution of the COS stock, Jobbágy and Jackson (2000) state that the amount of carbon stored in the first meter is significantly correlated with the climate and soil texture on a global scale, in addition to the greater amount of organic matter. As in other tropical forests, most studies in DTF have found that the largest amounts of C are stored in the superficial layers (SANTOS; LACERDA; ZINN, 2013; GANDHI; SUNDARAPANDIAN, 2017).

The climate can also affect carbon stocks in the soil, especially the humidity provided by gradients of average precipitation. Campo and Merino (2016) revealed an considerable increase in this storage of C in the soil with a decrease in the amount of precipitation: drier environments (~ 600 mm year^{-1}) sequestered twice C in organic layers than the more humid places (~ 1200 mm year^{-1}). In addition, C storage in mineral soil also increased with increasing drought along the gradient (approximately 2.6 times).

Similar results were observed by Cuevas *et al*. (2013). These authors found a substantial reduction in the concentration of C in the soil in mature SDTF with increased annual precipitation. Forest ecosystems located in environments with an average rainfall greater than 1,000 mm year^{-1} obtained only 61% of the COS from forest stands that received less than 550 mm year^{-1}.

The results of these studies demonstrate that the carbon sequestration capacity of soils in dry and seasonally dry forests has not been well explored, especially regarding the responses of links between net primary productivity, the quantity and quality of soil carbon, and the climate.

DTFs are capable of sequestering considerable amounts of C in seasonal environmental conditions of water deficit. The stocks of C in DTF present variations in local, regional and continental scales related to the type of vegetation, characteristics of the soil, the climate and human disturbances.

Tropical forests that are always under humid conditions without no monthly precipitation with less than 100 mm are generally referred to as 'tropical rain forests'. Tropical rainforests are large carbon reservoirs (MALHI *et al*. 1999).

In a tropical rainforest, Razafindrakoto *et al*. (2018) found an aboveground biomass C stock of 30.91 Mg C ha^{-1} in Madagascar. The degradation of a locally similar environment reduced that stock to 8.39 Mg C ha^{-1}. Azian *et al*. (2016) found stocks of 164.76 Mg C ha^{-1} in a protected area of tropical rainforest in Malaysia. Orihuela-Belmonte *et al*. (2013) observed a decrease in the carbon stock in the aboveground living biomass in a secondary forest compared to the forest that was not disturbed in Mexico, respectively 59.29 and 104, 03 Mg C ha^{-1}.

Aboveground biomass C stocks can also vary with topographic and climatic gradients. For example, Selmants *et al*. (2014) observed a variation on C stock in the aboveground living biomass between 97 and 417 Mg C ha^{-1} in humid forest environments with different annual average temperatures in Hawaii. In Atlantic Forest, Magnago *et al*. (2016) found that carbon stocks of tree biomass are negatively impacted by fragmentation through direct links with changes in microclimate and soil conditions.

Regarding carbon stored in litter in a tropical rainforest, Razafindrakoto *et al*. (2018) obtained an average C stock of 2,474 Mg C ha^{-1} in litter in Madagascar, taking into account only the leaf litter. In Hawaii, Selmants *et al*. (2014) observed a stock of C in litter between 2.68 and 4.98 Mg C ha^{-1}.

In Brazil, the Atlantic Forest can have between 7 and 14 Pg C stored in its deposits. Most of the Atlantic Forest carbon stock has been removed in the last 150 years (DEAN, 1996).

Ferez *et al*. (2015) estimated the C stored in litter in the Atlantic Forest as 4 Mg ha^{-1}. In a dry tropical forest, Conti *et al*. (2014) estimated the litter stock in the Argentine Chaco to be 3.98 Mg C ha^{-1}. On the other hand, Gasparri, Grau and Manghi (2008) found 2.30 Mg C ha^{-1} in the litter in similar vegetation in Argentina.

According to the literature, average stocks are found in the first 30 centimetres of soil in natural ecosystems in tropical rainforests, ranging from 18.60 to 194 Mg C ha^{-1}. Gasparri, Grau and Manghi (2008) evaluated the carbon stored in the soil in the Atlantic Forest of Argentina and observed an average COS stock of 54.60 Mg C ha^{-1}. On the other hand, Ferez *et al*. (2015) studying the Atlantic Forest in Brazil found lower stocks (35.50 Mg C ha^{-1}).

2.3 Changes in land use and carbon stocks in the Tropical Dry Forest and Tropical Rainforests

Nutrient cycling in forest ecosystems refers to the rate of minerals absorption by plants, the internal translocation between plant tissues and the transfer of these elements, their accumulation in plant biomass, and their return to the soil, atmosphere and hydrosphere, becoming available for reabsorption (ANDRADE; CABALLERO; FARIA, 1999). Nutrient cycles in agricultural ecosystems differs from natural ecosystems because they are more open. The losses and gains are greater and the trajectories of each nutrient that enters or is removed in the crops constitute a larger and continuous drain in the nutrients' reservoir available to the soil (TIVY, 1987).

Global expansion of agricultural crops has drawn more attention to the potential impacts on the environment resulting from changes in land use. In the past five decades, nutrient cycling in agricultural environments has been rapidly modified by the rapid increase in synthetic fertilizer applications. This is because most of agricultural production systems that depend on fertilizers are designed to optimize productivity in increasingly shorter periods (TULLY; RYALS, 2017).

There is a need for food production to meet the increasing demand generated by the population increase on the planet. Thus, investing in sustainable management practices of natural resources so that they can improve productivity and minimize losses to the environment is essential.

That said, it is essential to understand and study nutrients cycling in natural environments and in areas with agricultural production in order to understand the processes that affect their balance, in order to verify the direction and magnitude of ecosystem responses to anthropogenic disturbances. It is assumed that this knowledge can also be incorporated into environmental planning, which is necessary for the management, conservation and prevention of possible impacts of climate change.

The Atlantic Forest is a complex of ecosystems with great importance for the maintenance of biodiversity, that is, a biodiversity hotspot. It is one of the richest biomes in the world, with high levels of endemism and threats to its integrity (MITTERMEIER *et al*., 2011). Due to intense degradation caused by deforestation since the 16th century, only a small portion of the original cover of the Atlantic Forest remains. These remnants are distributed mainly in small fragments (< 50 ha), distant from each other (RIBEIRO, *et al*., 2009).

One of the main causes of degradation of Atlantic Forest areas is due to changes in land use, which was intensified during the 20th century through the expansion of the sugar cane industry. The ecological consequences of these changes in the landscape and other anthropogenic disturbances are worrying, such as loss of a considerable part of biodiversity and of ecosystem functions (SILVA; TABARELLI, 2000) such as nutrients cycling.

According to data from CONAB (2015), the area of sugarcane cultivation expanded 3.2 Mha between 2005 and 2015 in Brazil, totalling approximately 9.1 Mha. The projection is a further increase in this expansion to supply production demand until 2021. In Northeast Brazil, sugarcane crop planted area was 1,038,627 ha in 2017, representing 9.41% of the total in the country (IBGE, 2017). This increase also reflects an increase in demand for fertilizers. This replacement of forests by agricultural cultivation is negatively reflected in many aspects, mainly in nutrients cycling.

In the Brazilian semiarid region, the Caatinga native vegetation originally used to occupy about one million square kilometres, and almost half of it was deforested according to data from the Brazilian Forest Service - Ministry of the Environment - SFB / MMA (2013). The main causes for degradation of dry Caatinga forests involve deforestation for agricultural production systems such as cuts and burns and firewood production. Often, vegetation is cut in areas that are not suitable for agriculture (ALTHOFF *et al*., 2016). Other activities such as mineral exploration also contribute to the current degradation state of the Caatinga biome.

In addition, the inadequate management of vegetation and soil in the semiarid region has contributed to increasing the region's susceptibility to desertification, which has negative environmental, social and economic consequences for the region. The situation in the Caatinga seems to be even more complex than in the Atlantic Forest region, since the soil in this case can also be completely unprotected and its organic matter exposed to significant losses of nutrients. In all these cases it is important to know how nutrient cycling works in these environments.

Studies on biogeochemical cycles in natural ecosystems are important to better understand the response of vegetation to climate change and anthropogenic disturbances such as deforestation for firewood production, agricultural activities and mineral exploitation. Predicting how the Caatinga vegetation and the Atlantic Forest will behave in the face of predicted climate change contexts is essential to establish accurate management protocols and sustainable conservation strategies for forest ecosystems.

Studies on carbon stocks and flows are important both for preserving natural ecosystems and their sustainability, and for assessing impacts caused to the environment. Understanding these processes in natural ecosystems can provide important information for soil management and to sustain its fertility in agricultural areas.

One consequence of the replacement of forest by agriculture is the disappearance of the litter layer, with a consequent reduction in the abundance and diversity of soil organisms and in the protection of the soil against erosion and other nutrient losses. Moreover, in some agricultural systems such as conventional tillage farmers use bare fallow, changing the carbon input to the soil. In addition to spontaneous weed growth, bare fallow excludes the energy source for the soil biota.

The soil's organic matter is further degraded, and the lack of cover can result in severe erosion and runoff by rain and wind (BOT; BENITES, 2005).

Intensive cultivation of the soil with harrowing and ploughing makes it susceptible to erosive processes as organic matter is lost through increased soil oxidation and compaction and loss of the surface layer, that can be leached more easily thus increasing nutrient outputs of cycles.

Leifeld, Bassin and Fuhrer (2005) found that about 16% of the COS stock in Switzerland has historically been lost due to cultivation, urbanization and deforestation.

Conti *et al*. (2014) observed COS stocks in a potato cultivation area in Argentina of 68.68 Mg C ha^{-1} in the Chaco forest region, representing a reduction of approximately 6% compared to the environment in equilibrium. Poeplau and Don (2013) observed that the balance of the COS stock in land use changes in Europe was positive when considering the change in area from agricultural cultivation to forest.

In an agricultural area in a dry forest region of Argentina, Conti *et al*. (2014) estimated 0.44 Mg C ha^{-1} in potato cultivation biomass aboveground.

Results found by Guo and Gifford (2002) indicate that stocks of soil C decrease after the soil use changes from pasture to agricultural cultivation (-10%), from native forest to agricultural cultivation (-13%), from native forest to harvest (-42%) and from pasture to secondary forest (-59%).

Muñoz-Rojas *et al*. (2012), by studying the impacts of land use changes and land cover on organic carbon stocks in Mediterranean soils between 1956 and 2007, observed that changes resulted in losses of C in all types of soils evaluated. The authors found that forests showed a significant increase (25.4%) in COS compared to other uses.

In Costa Rica, Chacón *et al*. (2015) evaluated the COS stock in four forest types and agricultural systems, including a Pacific Dry Forest environment where between 76–165 Mg C ha^{-1} was estimated. The authors found that land use had significant effects on COS concentrations and stocks only in the dry forest environment.

Rezende (2017) observed a reduction in the COT in a cassava cultivation and in a degraded area of Caatinga of 10 and 21% in relation to the preserved area, respectively. The author attributes this result to the soil preparation that exposed SOM to weathering, to the reduced plant residues due to the low density of vegetation in the degraded area and to the failure to adopt conservationist practices in cassava cultivation.

Bessah *et al*. (2016) found no significant differences for the carbon stock between different types of land use at the three depths assessed, despite areas originally occupied by DTF in Ghana showing the highest C stock values. These authors also related these results to the soil management practices such as cover crops, return of waste compounds to the field, moisture management and tree introduction.

Návar, Estrada-Salvador and Estrada-Castrillón (2010) found that between 1950 to 2000, land use change in dry tropical forest for agriculture in Mexico contributed to carbon emissions of 7.03 (± 4.8) Tg C, of which the permanent biomass was on average 66% and the organic carbon of the soil on average was 34%.

Araújo Filho *et al*. (2018) showed that C stocks and microbiological activity were strongly influenced by the cutting times of a dry Caatinga forest, reflecting significant C losses associated with this type of management. In that study, the average C stock in the depth range from 0 to 20 cm for the most recent cut area was 27.57 Mg ha^{-1}, compared to 45.21 Mg ha^{-1} with undisturbed vegetation. The authors concluded that forest management practices with 15-year cycles are not enough to recover COS. The estimated recovery time for C indicates that it would take at least six decades between cutting cycles to achieve almost stable conditions, similar to forests that have not been cut. Even to achieve 50% recovery, it would take at least 33 years between cut times.

Deterioration of soil quality resulting from successive cultivation can decrease nutrient reserves through harvesting and increase losses due to volatilization, ash burning and production, and soil erosion and leaching depending on the management (FÖLSTER; KHANNA, 1997).

In general, studies on land use changes in these environments suggest that management has greater influence on soil C stocks. There is a lack of research that explains the relationship between soil and forest in DTF, mainly correlating species composition, quality and quantity of litter and soil carbon.

Considering the need for forecasting future climate scenarios, it is essential to demand greater effort in understanding the capacity of tropical forests to sequester or release carbon, as well as improving management to recover soil carbon stocks in these environments.

2.4 Quality of carbon stored in the Tropical Dry Forest and Tropical Rainforests

The entry of carbon into the soil is mainly related to the contribution of plant residues such as aerial parts and roots, release of root exudates, washing of soluble constituents of the plant by rainwater and transformation of these carbonated materials by macro and microorganisms in the soil (MOREIRA; SIQUEIRA, 2006).

In the decomposition of SOM, the large organic molecules are fragmented and transformed into smaller and simpler molecules. Carbon transformations in the soil mainly cover the phases of carbon fixing into carbon dioxide (C-CO_2) in the atmosphere and of regeneration. These phases are regulated by carbon oxidation processes, which regulate CO_2 flows to organic compounds and these to CO_2 and methane (CH_4), determining carbon inputs and outputs of the system (MOREIRA; SIQUEIRA, 2006).

The decomposition process can be characterized by decomposition of hydrosoluble compounds (amino acids, organic acids and sugars), that are readily decomposable and thus characterize the labile carbon which will return to the atmosphere quickly by microbial action. Increase in easily decomposable compounds in the soil stimulates the metabolic activity of soil microorganisms, favouring the release of carbon dioxide through microbial respiration. As microorganisms multiply, there is an increase in microbial biomass that synthesizes new organic compounds outside their cells (BRADY; WEIL, 2013).

The intense microbial activity can even favour the breakdown of more resistant organic matter, a phenomenon called priming effect. In this way, easily decomposable compounds are reduced, leaving the most resistant compounds that require specific organisms to degrade it. Reduction in nutrients supply and in energy causes death to much of the microbial biomass, that is then incorporated to the decomposing SOM and, consequently, causes reduction on microbial activity and C losses (BRADY; WEIL, 2013).

Subsequently, there is the degradation of structural components that are more resistant or recalcitrant and of the new dead biomass, depending on its chemical nature, which can take years (MOREIRA; SIQUEIRA, 2006). Throughout this process, SOM mineralization occurs. The mineralization of SOM involves the action of extracellular enzymes on macromolecules that causes release of low molecular weight substances during decomposition, which are absorbed and metabolized by microbial cells, converting them into inorganic forms. (MOREIRA; SIQUEIRA, 2006).

It is emphasized that when carbon losses are reduced by respiration or by leaching and erosion, the original residual SOM persists, especially as small particles that begin to be stabilized. (SOLLINS; HOMANN; CALDWELL, 1996). The mechanisms of chemical or colloidal, physical and biochemical stabilization prevent the access of microorganisms and their enzymatic systems to SOM.

Physical stabilization comprises the accommodation of residual particles within soil micropores that are too small for most organisms to access (BRADY; WEIL, 2013). This form of stabilization is considered a non-selective protection (CHENU *et al*., 2000), as it can harbour labile SOM compounds inside the microaggregates (EDWARDS; BREMNER, 1967) in inaccessible micropores (LADD; FOSTER; SKJEMSTAD, 1993) or within stable macro-aggregates (ELLIOTT, 1986).

The time that SOM remains physically protected is directly linked to aggregates' stability and their binding agents. Tisdall and Oades (1982) indicate that the macroaggregates stability depends on the action of roots and fungi hyphae. However, in microaggregates binding agents are persistent and include organo-mineral complexes. These agents provide high stability, making them resistant to environmental changes.

Chemical or colloidal protection is understood as the association of carbon present in SOM residues with silt and clay fractions of the soil, culminating in the conversion to humus. Thus, adsorbed SOM is protected from microbial attack and its extracellular enzymes (SOLLINS, HOMANN; CADWELL, 1996). Clays, including layer aluminosilicates, amorphous aluminosilicates, and sesquioxides (oxides, hydroxides, and Al and Fe oxyhydroxides), provide the vast majority of the absorbent surface area in the soil. Clays alter microbial metabolism and the decomposition environment, in addition to binding extracellular enzymes, modifying their activity. They are also related to sorption and aggregation (SOLLINS, HOMANN; CADWELL, 1996).

Humus, a dark coloured and high molecular weight material, is highly resistant to decomposition and may be protected by stable bonds with clay particles, forming clay-organic compounds and constituting the stable soil SOM stock and an important soil carbon reservoir (BRADY; WEIL, 2013; SILVA; MENDONÇA, 2007).

The cycle time of microbial biomass is estimated at 2.5 years for temperate climate and 0.25 years for tropical climate. The labile fraction is cycled in approximately 20 years for temperate climates and 5 years for tropical climates. The cycling of chemically protected organic matter depends on mineralogy and can reach 1000 years, while for physically protected organic matter it depends on soil management (SILVA; MENDONÇA, 2007).

The processes that SOM is subjected to, such as interactions with clays in the soil and microbial digestion, produce more stable organic materials that increase carbon residence time in the soil before it returns to the atmosphere as CO_2 (SILVA; MENDONÇA, 2007). The cycling time in compartments varies from years to millennia, and the control of the compartment size depends on several factors (SILVA; MENDONÇA, 2007).

Humus is formed by humic and non-humic substances. Non-humic substances are less complex and less resistant to microbial action, compared to the humic fraction. Part of the non-humic substances are compounds from plants that have been altered by microbial activity, while another part originates from the synthesis of soil microorganisms. Non-humic substances can reach 10-15% of the total organic carbon in the soil (BRADY; WEIL, 2013; SILVA; MENDONÇA, 2007).

Humic substances, in turn, consist of amorphous humic macromolecules, ranging from yellow to brown, formed from oxidation and subsequent polymerization of OM (STEVENSON, 1994). These make up about 85-90% of total organic carbon of the soil (SILVA; MENDONÇA, 2007).

The formation of these substances occurs through a process called humification. There are at least four main routes by which humic substances can be formed during the decomposition of organic matter, from the classic theory that considers humic substances to be formed from modified lignin to the most accepted theory nowadays, the polyphenol route (Figure 1).

The theory of formation of humic substances (HS) from the reduction of sugars (route 1, FIGURE 1) is probably the oldest, postulated by Maillard in 1916. According to this theory, HS are exclusively products of a chemical reaction between reducing sugars and amino acids (originated from microbial metabolism) that undergo non-enzymatic polymerization (reaction and Maillard), forming nitrogenous polymers (SILVA; MENDONÇA, 2013).

Routes 2 and 3 (FIGURE 1) are the basis of polyphenol theory and are very similar, differing only in the source of polyphenols. On route 2, polyphenols come from carbon sources that do not contain lignin such as cellulose or synthesized by specific microorganisms such as some fungi. Some soil fungi can use simple carbohydrates in their metabolism and then produce aromatic substances, as in the decomposition of cellulose and other organic constituents and synthesis of macromolecules of dark coloured phenols (SILVA; MENDONÇA, 2013).

On route 3, lignin is believed to be degraded by microorganisms, releasing phenolic acids and aldehydes which are converted into quinones by enzymatic action. These quinones polymerize in the presence or absence of amine compounds, originating humic macromolecules.

On route 4, it is proposed that humic substances are exclusively residual products of lignin degradation. In this process, lignin would only be partially degraded by microorganisms, thus integrating HS. Thus, changes in lignin would occur with loss of $–OCH_3$ groups and formation of o-hydroxyphenols, in addition to oxidizing aliphatic chains to form –COOH groups.

As humic substances are considered polymers, the initial product formed through this humification route would be humine, which after oxidation and fragmentation would originate humic acids, which in turn would also undergo additional fragmentation and oxidation of side chains to originate fulvic acids (SILVA; MENDONÇA, 2013).

HS can also differentiate in relation to solubility in aqueous medium. Fulvic acids correspond to the soluble fraction in alkaline and acidic media, while humic acids are soluble in alkaline media and insoluble in acidic media. Humine is insoluble in any pH condition.

As seen earlier, organic carbon in the soil is composed by different types of organic materials with different chemical and physical properties. Soil organic carbon is often divided into relatively labile and stable organic fractions that vary in their vulnerability to decomposition.

The labile organic carbon is decomposed relatively quickly (days to years), that is, it is easily mineralized by the microbiota. This is partly composed of different compartments discussed above such as macro-organic matter, including newly deposited residues and roots (particulate organic matter), C associated with living organisms, remnants of dead organisms (microbial biomass) and non-humic substances in unstable forms (SILVA; MENDONÇA, 2013).

Labile fractions of soil organic carbon serve as an energy source readily available to soil organisms and they significantly increase nutrient cycling in the soil. Labile organic carbon is directly linked to soil quality and it supports the formation of soil aggregates that improve soil structure for better infiltration and water retention (SPACCINI *et al*., 2000).

More stable fractions of organic carbon in the soil take longer to decompose (years, decades, centuries). This includes organic matter in particles of finer size that are physically protected (mineral-protected clay or inserted in soil aggregates) or chemically persistent in the soil.

Small changes in total soil C can hardly be detected in a short-term scale, mainly due to its high natural variability in the soil (ANDRADE; OLIVEIRA; CERRI, 2005). Thus, the quality of soil C, assessed through fractions of soil organic matter that are more sensitive to environmental changes, can be used as an indicator of changes in the dynamics of the organic compartment.

In DTF, studies involving the fractionation of C in SOM are still rare. In most of them, fractionation is used to characterize the effects of land use change or the recovery level of an ecosystem (CAMPANHA *et al*., 2009; ASSIS *et al*., 2010; CUEVAS *et al*., 2013; CONTI *et al*., 2014; FERREIRA *et al*., 2016; AHIRWAL; MAITI; SRIVASTAVA *et al*., 2017; ARAÚJO FILHO *et al*., 2018;).

In Brazilian DTF, a study developed by Araújo *et al*. (2018) can be highlighted. The authors found that microbial biomass carbon (MBC) concentrations were significantly reduced by degradation, demonstrating MBC's sensitivity to changes in the soil caused by cutting the forest. In India, Ahirwal *et al*. (2017) found a 40% increase in MBC between revegetated areas in the DTF region afer 7 and 11 years.

On the other hand, Cuevas *et al*. (2013) evaluated C in SOM fractions in a DTF precipitation gradient in Mexico. MBC varied among the precipitation gradient, with the highest concentrations in the driest region and the lowest concentrations in the soils of the most humid region during the dry season.

Araújo Filho *et al*. (2018) found that the light fraction of organic matter increased with cutting time and was the lowest in the most recently cut area in the Caatinga. Cuevas *et al*. (2003) also found that C concentration in SOM fractions represented between 6 and 12% of the total soil carbon. In addition, the C concentrations in the fractions increased in the following order: C heavy fraction <C intermediate fraction <C light fraction.

This behaviour demonstrates that most of the C is bioavailable, being composed of plant residues from the plant cover which can be lost more easily by decomposition. The carbon in heavier fractions is more stabilized and decomposes more slowly. Similar results are found in studies of carbon fractionation in disturbed DTF environments (CAMPANHA *et al*., 2009; MARTINS *et al*., 2015).

Humus corresponds to the compartment that includes humic and non-humic substances. Non-humic substances can contribute with 10 to 15% of TOC in mineral soils, being composed of carbohydrates, lignins, lipids, organic acids, polyphenols, among others (SILVA; MENDONÇA, 2007).

Campo and Merino (2016) evaluated the quality of SOM in the soil in a DTF precipitation gradient, in relation to characterization of non-humic substances. The authors concluded that increased C storage in the soil in the driest locations was also related to greater chemical recalcitrance of litter related to cellulose and hemicellulose, in addition to the presence of coal in several locations, suggesting an important indirect influence of the climate on C sequestration.

Humic substances (HS), on the other hand, comprise about 85 - 90% of the total TOC. (SILVA; MENDONÇA, 2007). HS are generally amorphous, dark in color and complex. Due to this complexity, this material is highly resistant to microbial attack, taking decades or centuries to decompose (BRADY; WEIL, 2013). For this reason, this compartment consists of a large organic reserve of C in soil.

In a precipitation gradient in the semi-arid region of Chaco in Argentina, Abril, Merlo and Noe (2013) estimated 20% of total SOM represented by humic substances. In general, HS did not demonstrate a pattern for the precipitation gradient evaluated in this study. The authors concluded that in drier areas there was a predominance of SOM fractions that were not humidified, when compared to the more humid places, which represents a risk of C losses under these climatic conditions.

In the Brazilian semiarid region, Assis *et al*. (2010) evaluated C in humic substances (fulvic acids, humic acids and humine) in irrigated fruit crops and in areas of native Caatinga vegetation as a reference. The results showed, in general, a decrease in C stocks of the fulvic acid fraction (CFA) with the cultivations in the superficial layers. The authors related these results to the high lability of this fraction, which favors its use by microbial biomass as a result of the wetter conditions and milder soil temperatures in irrigated crops when compared to the reference ecosystem. In that study, it was also observed that soil management did not affect the content of humic acids in the 0 - 5 cm layer. In addition, it was found that the humine fraction was the one that most contributed to the C stock among the evaluated fractions.

Martins *et al*. (2015) evaluated SOM fractions in soil profiles located in the semiarid region of the north of the State of Minas Gerais. The authors found that the C content in humic fractions also showed a wide variation between the studied horizons, with CFA varying between 0.6 and 3.67 g kg^{-1}, C in the Humic Acid (CHA) fraction from 0.3 to 5 , 8 g kg^{-1} and the C in the Humine fraction (CH) from 3.0 to 40.8 g kg^{-1}, the latter being the predominant fraction, corresponding on average to 65% of the TOC. The authors also found that the CHA/CFA ratios were greater than 1.0 for most of the studied horizons, indicating predominance of humic acids in the different types of soil under the evaluated vegetation, which may demonstrate a more significant conversion of insoluble organic carbon in the soil into soluble fractions.

Similar results are observed by Martins *et al*. (2015) and were verified by Araújo *et al*. (2018) in a Caatinga area managed in different cutting cycles, with humine containing most of the

C stock accumulated in the soil. The authors related this to a possible greater recalcitrance of this fraction in soils which become concentrated in clay, where they form organic mineral complexes.

Rezende (2017) found that land management in a Caatinga environment decreased the CHA levels in the superficial layer in the cassava cultivation and degraded area environments. According to the author, the management that protects the soil cover favors the polymerization of humic substances, resulting in an increase of CHA levels in detriment of carbon in the CFA fulvic acid fraction.

Regarding recovery time of humic fractions in the soil, Araújo *et al*. (2018) found in a Caatinga environment that when vegetation is cut at intervals of 20 years, C concentrations in humic fractions can recover to only about 32% of their original levels. To achieve maximum recovery, an average interval of about 65 years between cuts would be required.

CHAPTER I – STOCK AND CHANGES OF CARBON IN AGRICULTURAL ECOSYSTEMS IN DRY AND HUMID ENVIRONMENTS

ABSTRACT

Changes in land use, especially in tropical forests, is among the main causes of increases in CO_2 emissions to the atmosphere, intensifying the greenhouse effect and contributing to climate change scenarios. In order to obtain a better understanding of C stock and balance and its effects on land use change in tropical forests, the aim of this work was to quantify the C stocks in the biomass, litter and soil reservoirs in forest and agricultural ecosystems in dry and tropical rainforest areas in northeastern Brazil. This study was developed in four different types of forest and agricultural ecosystems, located in two areas originally occupied by Tropical Dry Forest and Tropical Rainforest, in the states of Pernambuco and Paraíba. For this, biomasses of leaves, wood/manioc/stem and all species with the highest absolute density in forest environments and in agricultural crops of cassava and sugarcane were estimated. The accumulated litter biomass in forest environments was also determined. The carbon content and stocks of each compartment were determined by species for each type of land use area. Soil samples from six layers up to 1.0 m deep were collected to determine carbon content and soil density and to estimate the soil's organic carbon stock. The leaf carbon content varied between 44.80 and 45.43% of species in the dry environment, with the highest in *Guapira opposita* and the lowest in *Metrodorea mollis*. The carbon content in the wood or stem in the humid environment varied between 45.17 and 45.68%. Cassava obtained the lowest averages for carbon stock in leaves, in seed and for total stock. In leaves, wood and total stock, the highest carbon stocks were observed in *C. limae* and *M. mollis* species in the dry environment and in *D. guianensis* in the humid environment. Land-use change in the dry environment did not have significant effects on carbon stock in the soil up to 1.0 m depth. Conversion of forest-agricultural cultivation in the humid environment alters carbon content and stock of the soil, especially in the top layer, mainly related to decrease in litter supply in the soil and agricultural cultivation practices. Humid environments store more carbon in the aboveground biomass and in the accumulated litter when compared to dry environments. Changes in land use has been shown to have a negative impact on carbon storage in humid and dry environments.

Keywords: carbon *pools*, soil organic carbon, carbon forest sequestration, land use change, tropical rainforest, tropical dry forest.

1 INTRODUCTION

The replacement of forests by areas of agricultural crops and pasture has been the main reason for the increase in CO_2 release to the atmosphere in recent decades. Net annual CO_2 emissions resulting from land use change due to anthropogenic activities averaged 0.9 ± 0.2 Gt C year^{-1} from 2002 to 2011 (IPCC, 2013).

Tropical and subtropical forests are considered ecosystems of strategic interest for wide-ranging scientific studies such as the sequestration of C. In contradiction, they are the most threatened ecosystems by human actions in the world. Pearson *et al*. (2017) estimated a total of 2.1 Gt CO_2 emitted in 2016 by the degradation of tropical and subtropical forests in 74 countries including Brazil, and approximately 25% of this that is related to deforestation.

In Brazil, the intense forest degradation caused by anthropic disturbances reduced the Atlantic Forest to 16% of its original size, and most of it is now distributed in small fragments (<50 ha) distant from each other (RIBEIRO *et al*., 2009). The Atlantic Forest was greatly impacted by the expansion of sugar cane cultivation in the late 20th century (RIBEIRO *et al*., 2009; COSTA *et al*., 2015). This replacement of forest by agricultural cultivation negatively reflects in many aspects, mainly in capture and emissions of CO_2 and in storage of C.

Magnago *et al*. (2016), studying forest fragmentation and its interference in C stocks, concluded that the C stocks of tree biomass are negatively impacted by fragmentation due to changes in microclimate and soil conditions in forest environments. On the other hand, Oliveira Filho, Pereira and Aquino (2017) demonstrated that the cultivation of sugar cane for nine years, without the practice of straw burning in during pre-harvest, increased the total organic carbon content (TOC) in the superficial layers of the soil.

In the dry tropical forest of Caatinga, natural vegetation has been degraded for many decades by excessive cutting for wood use and/or for subsistence agricultural crops, mainly cassava (MOURA *et al*., 2016). The percentage of tree cover and other vegetation cover in Caatinga was reduced to 16.9% of its original size in 1990, increasing to 46.3% in 2010 according to a study by Beuchle *et al*. (2015).

Deforestation of Caatinga was accentuated in the Brazilian semiarid due to increase in cassava cultivation to meet the demand of small industries producing flour. In the region of Araripe with intense mineral exploration, deforestation in the Caatinga was also accentuated due to the use of wood as an energy source for calcination of mineral gypsum. Plaster mining is a fast-developing economic activity in the region. However, its energy matrix contributes to degradation of vegetation and consequently of the soil. In this case, CO_2 capture and C storage in Caatinga of the Araripe region have been compromised. The soil becomes completely unprotected and its organic matter exposed to significant losses of C. Recovery of C stocks in these soils is difficult and require long-term strategies as long forest management plans.

Recovery of C stocks in deforested Caatinga soils requires at least 60 years, and C sequestration in these forests should require longer periods than in the humid tropical forests (ARAÚJO FILHO *et al*., 2018). According to a study by Althoff *et al*. (2016), if climate changes predictions happen, the biomass of native Caatinga vegetation and the soil TOC stock will decrease throughout this century, even without the loss of vegetation due to cutting.

It is therefore essential to quantify C stocks in biomass, litter and soil in areas of dry tropical forest and tropical rainforest in order to understand the processes that affect their balance, aiming to identify the magnitude of impacts on forest ecosystems and changes land use due to human disturbances, in addition to climate change. It is assumed that this knowledge can also be incorporated into environmental planning and forest management to assist in mitigating these anthropic and/or natural processes.

If a considerable part of the dry or rainforest has been replaced by agricultural crops, the C reservoirs in forests and agricultural areas must be quantified to try to answer the following questions: what are the patterns of C allocation in forests and agricultural crops? Do these C allocation patterns vary between tropical dry and rainforests? What are the variations in C stock among species? What are the effects of changing the vegetation cover on vegetation and soil C reservoirs in dry and humid forest environments, compared to agricultural ecosystems?

To answer these questions, a better understanding of the C stock and balance is necessary, in order to understand and mitigate its negative effects of land use change. Thus, the aim of this study was to quantify C stocks in the biomass, litter and soil reservoirs in forest and agricultural ecosystems in dry and humid tropical forest environments in Northeast Brazil.

2 MATERIAL AND METHODS

2.1 Study area

The study was developed in four different types of forest and agricultural ecosystems, located in two environments originally occupied by dry tropical forest (Caatinga) and tropical rainforest (Atlantic Forest), located in the states of Pernambuco and Paraíba. The first refers to the area covered by the Caatinga dry tropical forest, where a Caatinga forest area and an agricultural area with cassava cultivation were selected, which are equivalent to the types of land uses that are most used in the study region. The second environment is in an area of dense lowland tropical rainforest, where an Atlantic Forest area and an agricultural area with sugarcane cultivation were selected (Figure 1).

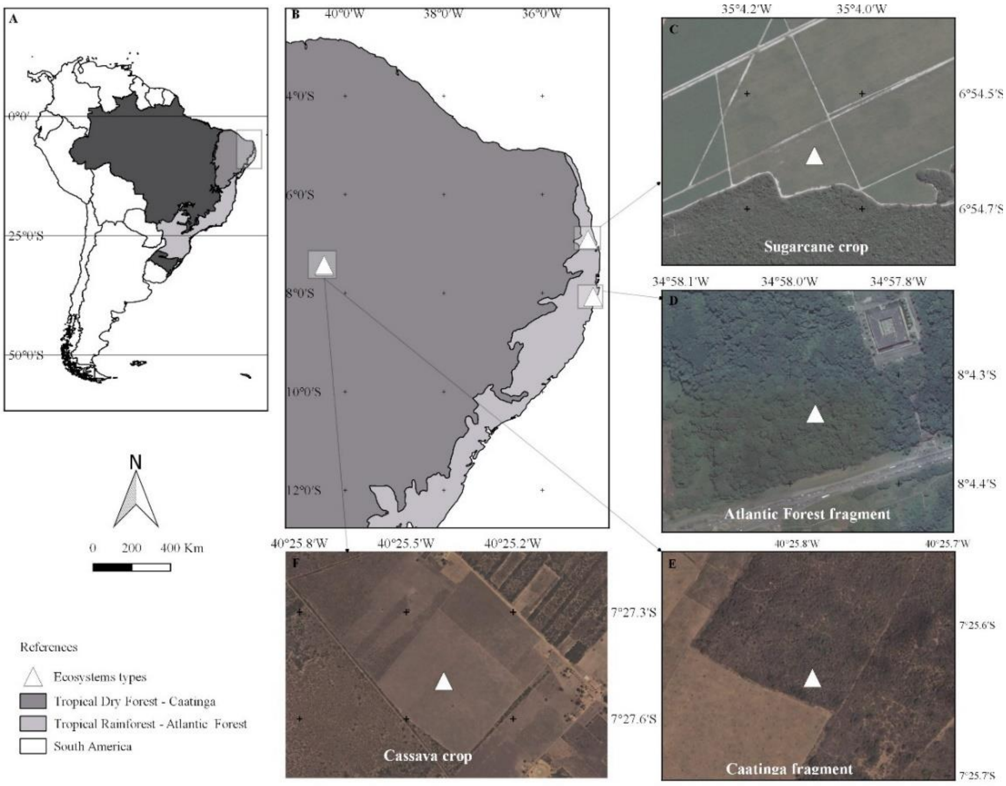

Figure 1 – Study sites location in Tropical Dry Forest and Tropical Rainforest, Northeast, Brazil. A) Brazil in South America; B) Northeast region from Brazil; C) Sugarcane site in Paraiba State, Brazil; D) Atlantic Forest site in Pernambuco State, Brazil; E) Caatinga site in Pernambuco, State; F) Cassava site in Pernambuco State, Brazil.

The edaphoclimatic characterization and geographical location of the study areas are summarized in Table 1.

Table 1 – Study site location and characteristics in Tropical Dry Forest and Tropical Rainforest, Northeast, Brazil

Soil use	Tropical Dry Forest	Cassava	Tropical Rainforest	Sugarcane
Location	Chapada do Araripe, Pernambuco (7°25'S - 40°26'W)	Chapada do Araripe, Pernambuco (7°25'S - 40°26'W)	Recife, Pernambuco (8°04'S - 34°57'W)	Rio Tinto, Paraíba (6°54'S - 35°04'W)
Area size	~13 ha	~31 ha	~28 ha	~12 ha
Altitude	838 m	828 m	38 m	76 m
Topography	Predominantly flat	Predominantly flat	Predominantly flat	Predominantly flat
Climate classification	BSh	BSh	Am	As
	Dry Semi-arid low latitude and altitude [a]	Dry Semi-arid low latitude and altitude [a]	Tropical monsoon [a]	Tropical with dry summer [a]
Precipitation	<700 mm ano^{-1} [b]	<700 mm ano^{-1} [b]	~1500 mm ano^{-1} [b]	~1500 mm ano^{-1} [c]
Temperature	27 °C[b]	27 °C[b]	25.8 °C[b]	26 °C[c]
Forest Domain	Tropical Dry Forest - Caatinga	-	Dense lowland tropica rainforest	-
Plant variety	-	Pernambucana	-	RB92579
Cultivation cycle	-	First cycle[g]	-	First cycle [h]
Absolute density	1294 ind ha^{-1}	6250 ind. ha^{-1}	970 ind ha^{-1}	20416 ind. ha^{-1}
Soil classification	Dystrophic Yellow Latosol (Oxisol)[d]	Dystrophic Yellow Latosol (Oxisol)[d]	Dystrophic Yellow Latosol (Oxisol)[e]	Dystrophic Yellow Argissol[f]

[a]Alvares *et al*. (2014). [b]APAC (2019). [c]AESA (2019) e Francisco e Santos (2017). [d] Agricultural exploration in the area began in 1995 with the removal of native vegetation. The cassava cutting cycle is 18 months. [e] Agricultural exploration has been occurring for at least 50 years with burning straw at harvest. The sugarcane cutting cycle is 12 months.[f] Santos *et al*. (2018).

2.2 Sampling

2.2.1 Agricultural crops

To assess the biomass of sugarcane and cassava plants, a 100 m x 100 m quadrat was launched in the cultivation area, at least 100 m from the edge of the vegetation (Figure 3).

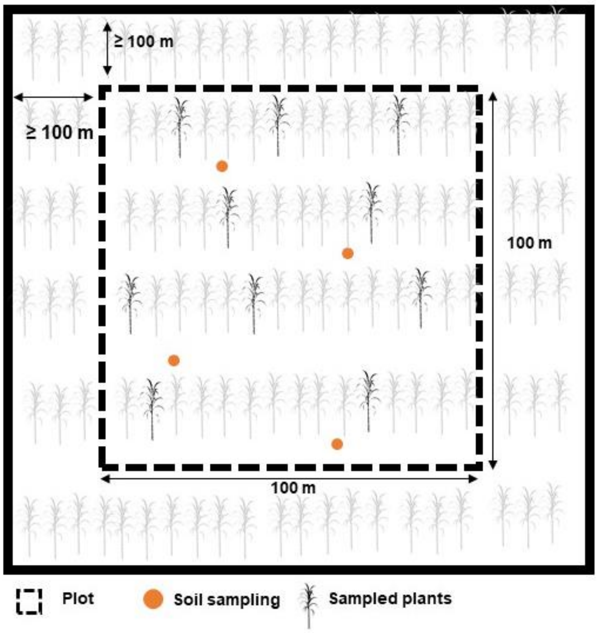

Figure 3 – Plants sampling design for biomass estimation and soil sampling in agricultural sites.

Ten plants were sampled randomly within the quadrat. Sugar cane plants were separated into fractions (pointer + leaves) and stem, being (pointer + leaves) constituted by the cartridge, leaves and sheath. Dry and green leaves were considered from the (+1) leaf and the rest was considered stem. The biomass assessments took place in the 12th month of sugarcane cultivation during the first growing cycle (cane-plant), when the crop yield reached the maximum biomass.

For cassava cultivation, each plant was separated into leaves and manioc, with the leaves component including all green and dry leaves and the manioc fraction including all stems of the plant. Assessments of cassava biomass took place in the 18th month after planting, corresponding to the end of the cultivation cycle, when the productivity of the cultivation reached the maximum biomass.

The wet weight of each ten plants was determined in the field with a digital scale with a precision of two decimal digits. After weighing the compartments in the field, samples of ~

300 g were stored in paper bags for drying in a forced air oven at 65 ºC until constant weight. The dry mass was determined on an analytical balance with an accuracy of 0.01 gram.

The biomass of each fraction (leaves, stems, manioc) and the total biomass per plant were estimated. To extrapolate the dry mass per hectare, the average biomass of sampled plants was multiplied by the number of plants estimated according to the crop spacing.

2.2.2 Forest fragments

In each forest environment, species with the highest absolute density were selected based on floristic and phytosociological survey of adult individuals, which was previously carried out by Espig *et al*. (2008) in the rainforest and by Santos (2018) in the dry forest. In the dry forest, nine species with the highest absolute density were selected (Table 2), representing approximately 87% of the absolute density of the forest fragment evaluated. In the rainforest, ten species with the highest absolute density were selected (Table 2), which represented 58% of the absolute density of the forest fragment.

Table 2 – Absolute density, average height, diameter at breast height and wood basic density in the forest sites

	Species	AD[3]	Ht[4]	DBH[5]	***p*** [6]
Dry forest[1]	*Guapira opposita* (Vell.) Reitz	312	3.97	5.49	0.68
	Croton limae A.P. Gomes. M.F. Sales P.E. Berry	236	4.30	4.11	0.73
	Metrodorea mollis Taub.	232	3.89	4.46	0.82
	Annona leptopetala (R.E.Fr.) H.Rainer	106	4.68	4.69	0.52
	Pilocarpus spicatus A.St.-Hil.	104	3.79	4.05	0.83
	Senegalia langsdorffii (Benth.) Seigler & Ebinger	50	5.64	5.03	1.07
	Zanthoxylum hamadryadicum Pirani	36	4.55	4.81	0.71
	Erythroxylum sp	24	4.07	5.92	0.73
	Byrsonima vacciniifolia A.Juss.	24	4.67	5.83	0.74
Rainforest[2]	*Helicostylis tomentosa* (Poepp & Endl.) J.F.Macbr.	104	13.31	10.89	0.62
	Mabea occidentalis (Benth.) Müll. Arg.	95	9.09	12.32	0.81
	Brosimum guianense (Aubl.) Huber	77	13.88	13.41	0.82
	Parkia pendula (Willd) Benth. ex Walpers	62	12.63	12.00	0.71
	Thyrsodium schomburgkianum Benth.	45	10.46	11.18	0.69
	Protium heptaphyllum (Aubl.) Marchand.	26	11.60	13.54	0.68
	Brosimum conduru Standl	25	10.41	11.16	0.86
	Tapirira guianensis Aubl.	21	27.92	22.10	0.51
	Dialium guianensis (Aublet.) Sandw.	20	19.15	28.46	0.93
	Pouteria grandiflora (A.DC.) Baehni	19	9.04	8.86	0.79

[1]Santos (2018). [2]Espig *et al*. (2008). [3]Absolute density (ind. ha^{-1}). [4]Total height (m). [5]Diameter at breast height (cm). [6]Wood basic density ($g\ cm^{-3}$).

The biomass of leaves, wood and total aerial parts per plant in forest ecosystems were estimated for each species from the averages of wood density (p), diameter at breast height (DBH) and height (Ht) of all individuals of the species selected using the bellow equations (Table 3).

Table 3 – Equations used for tree biomass estimation

		Function	Author
Dry forest	Leaves	$\hat{B}$ = 0.1900 x DBH$^{2.0515}$	Silva and Sampaio (2008)
	Stem (1.1 ≤ DBH ≤ 5.0 cm)	$\hat{B}$ = 0.5737 x DBH$^{1.6847}$	
	Stem (5.0 < DBH ≤ 10.0 cm)	$\hat{B}$ = 0.1331 x DBH$^{1.5784}$	
	Stem (DBH > 10.0 cm)	$\hat{B}$ = 0.0082 x DBH$^{2.8151}$	
Rainforest	Total aboveground biomass	$\hat{B}$ = 0.0673 x (p x DBH^2 x Ht)$^{0.976}$	Chave *et al*. (2014)
	Leaves	5% of total AGB[a]	
	Stem	95% of total AGB[a]	

[a] Aboveground biomass proportion suggested by Chave *et al*. (2014). B: biomass (kg); DBH: Diameter at breast height (cm); *p*: Wood basic density (g cm^{-3}); Ht: Total height (m).

The estimate biomass of leaf, wood and total aerial part for each species per hectare was obtained using the following equation:

$$Ba_{kg\ ha^{-1}} = B_{kg\ ind.^{-1}} \times DA_{ind.\ ha^{-1}} \quad (1)$$

In which Ba: biomass per area; B: average biomass per individual of species; DA: absolute density of species.

2.3 Carbon stocks

2.3.1 Aboveground biomass

2.3.1.1 Agricultural crops

In sugar cane and cassava, fractions of dry biomass were randomly sampled. These materials were ground in a Willey-type mill. Samples were weighed and transferred to porcelain crucibles, and then taken to the analysis of C levels by dry combustion in a equipment by LECO (model C-144) at the BioFix Laboratory of the Federal University of Paraná.

The C stock per plant was calculated by multiplying the average C content by the average dry biomass of each compartment of each individual by species. The C stock per area (hectare) was obtained by multiplying the average C stock of each species by the number of individuals per hectare.

2.3.1.2 Forest fragments

In the forest fragments, 20 plots of 10 m x 25 m (250 m^2) were distributed systematically (Figure 4), from where individuals were selected for sampling. The biomass of leaf and wood compartments of each species was used to determine the C content.

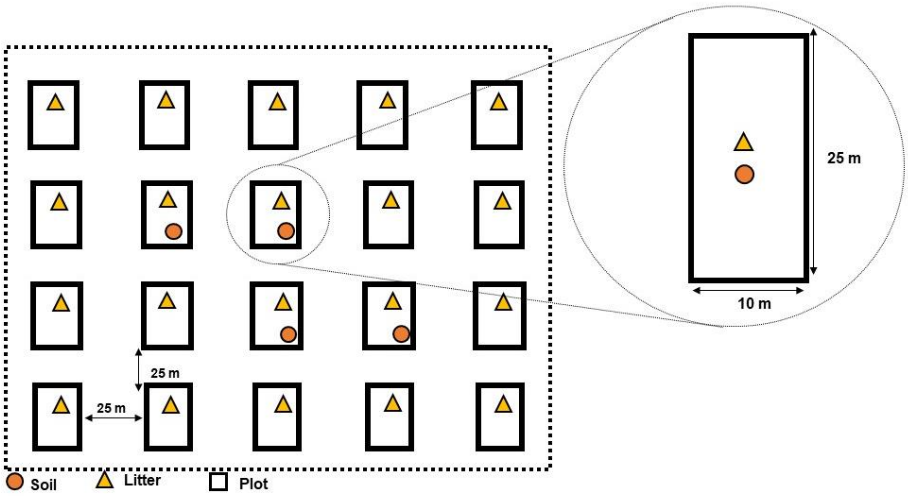

Figure 4 – Biomass, litter and soil sampling design for carbon content determination in forest sites.

To determine the C content in plant biomass in forest ecosystems, four healthy individuals were selected from each species, similar in size and vegetative development. These were selected based on their Ht and DBH values, representing the average of the other individuals. Of these, healthy and freshly ripe leaves located at the four cardinal points (north, south, east and west) of the upper middle third of the treetops were sampled, as well as wood samples using the non-destructive method using an auger and a steel fast drill.

Samples were ground in a Willey-type mill and analysed for C levels by dry combustion. C stock per plant was calculated by multiplying the average C content by the average dry biomass of each compartment of each individual by species. C stock per area (hectare) and per species was obtained by multiplying the average C content of each species by the respective absolute density (ind. ha^{-1}).

2.3.2 Litter deposited and accumulated

The litter accumulated on the soil was determined in forest environments. Harvest in sugar cane cultivation is carried out by straw burning, which does not allow the accumulation of this material on the soil. In cassava cultivation, the culture remains are used as forage in animal feeding, so the organic layer does not remain on the soil. Therefore, it was not possible to evaluate the litter accumulated in agricultural environments.

The litter accumulated in the forest environments was quantified using iron templates measuring 0.5 m x 0.5 m randomly placed in the center of each plot in the forest ecosystems, totalling 20 samples in each environment (Figure 4).

Sampling took place at the beginning of the dry period when most of the senescent materials of the deciduous and semi-deciduous species are brought over the soil in the dry forest. Quantification took place by collecting all plant material circumscribed by the template (Figure 5).

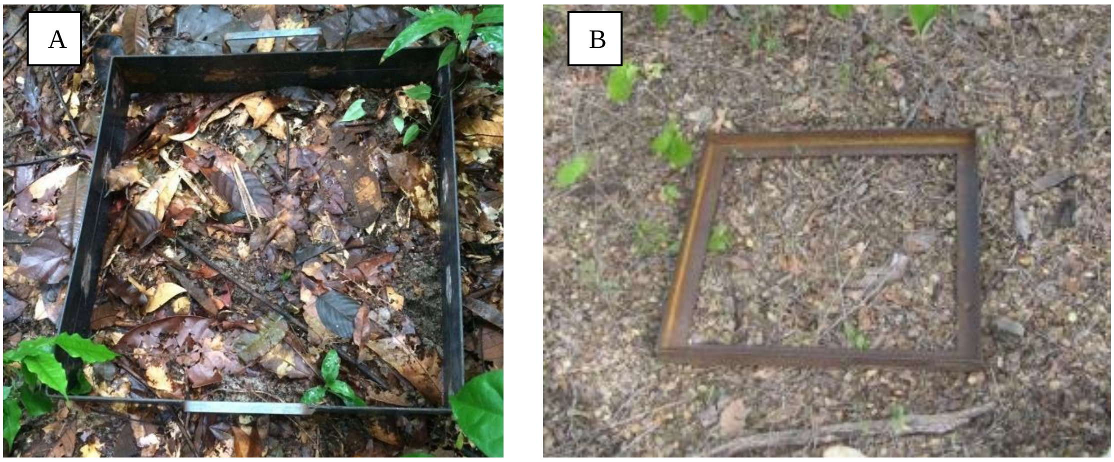

Figure 5 - Iron template used for soil litter accumulation evaluation in the rainforest (A) and dry forest (B).

The material was dried in an oven with forced air circulation at 65 ºC until constant weight, and the dry weight was then determined. After, samples were ground in a Willey-type mill. Ground samples were analysed for C levels by dry combustion. The accumulated litter C stock was estimated by multiplying the average C content and the average litter biomass accumulated in the templates. Subsequently, the template areas were extrapolated to hectare.

2.3.3 Soil carbon stock

Total organic carbon in the soil (TOC) was estimated in soil samples in layers of 0.00 -┤ 0.05; 0.05 -┤ 0.10; 0.10 -┤ 0.20; 0.20 -┤ 0.40; 0.40 -┤ 0.60 and 0.60 -┤ 1.00 m in four trenches randomly arranged in the quadrat demarcated in agricultural cultivation areas (Figure 2) and in four other trenches located in the central plots in forest environments (Figure 3).

Samples were passed through a 60-mesh sieve and weighed in porcelain crucibles and analysed for C levels by dry combustion in LECO equipment (model C-144).

To estimate the carbon stock in each layer, non-deformed samples were collected with volumetric rings with dimensions of 5.0 cm in diameter and 5.0 cm in height in four repetitions per depth. TOC stock in each layer was estimated using the average TOC content and the equivalent mass procedures described by Wendt and Hauser (2013), according to equations 2 and 3:

$$M_{soil} = \frac{M_{sample}}{\pi\left(\frac{D}{2}\right)^2} \; x \; 10000 \qquad (2)$$

In which:

M_{soil} is the mass of soil in each layer (Mg ha^{-1});

M_{sample} is the dry mass of soil sampled in the field in each layer (g) and;

D is the diameter of the soil sampling ring (mm);

$$M_{ETOC} = M_{soil} \; x \; C_{TOC} \qquad (3)$$

In which:

M_{ETOC} is the carbon stock in each layer (kg ha^{-1})

M_{soil} is the mass of soil in each layer (Mg ha^{-1});

C_{TOC} is the carbon content in each layer (g kg^{-1});

The TOC stock (0-1.00 m) was obtained by adding the stocks of each layer of soil. The TOC stocks correction in agricultural areas was carried out by subtracting the estimated carbon stock error acquired by soil compaction in these areas. The estimated carbon stock error in agricultural crops was calculated using equation 4, adapted from Wendt and Hauser (2013).

$$M_{EETOC} = (\rho_{agr} - \rho_{ref}) \times z \times C_{ref} \times 100 \quad (4)$$

In which:

M_{EECOT} is the soil stock error correction in each depth layer (kg ha^{-1})

ρ_{agr} is the soil density in the crop area in each depth layer (g cm^{-3});

ρ_{ref} is the soil density in the reference area (native vegetation) in each depth layer (g cm^{-3});

z is the depth layer thickness (cm);

C_{ref} is the carbon content in each depth layer of the reference area (g kg^{-1});

Therefore, the corrected C stock will be: M_{ECOT} - M_{EECOT}. This procedure corrects the soil C stock when the change in land-use increases the soil density and consequently overestimates the C stock.

2.4 Statistical analysis

Data were tested for normality and homoscedasticity as assumptions required for analysis of variance (ANOVA). For this, the Shapiro-Wilk (SHAPIRO; WILK, 1965) and Levene (BROWN; FORSYTHE, 1974) tests were used, respectively (both at the 5% significance level).

Data from the biomass and carbon stocks of the leaves and wood/manioc/stem compartments and total biomass between land-uses in the dry or humid environment were analysed using a T test at the level of 5% significance with four replications for the forest and ten for agricultural areas.

Data from the C content and stocks of the leaves and wood/manioc/stem compartments between species in the dry or humid environment were analysed using ANOVA, with a F test at the 5% p significance level. When significant, averages were compared using a Scott-Knott test at the level of 5% significance.

Data from the C stock of the total aboveground biomass, litter layer, and soil between the tropical dry forest and tropical rainforest environments were analysed using ANOVA, with a F test at the 5% significance level. When significant, averages were compared using a Scott-Knott test at the level of 5% significance.

3 RESULTS AND DISCUSSION

3.1 Carbon stocks

3.1.1 Dry environment

3.1.1.1 Aboveground biomass

Guapira opposita exhibited the highest leaf, wood and total biomass per hectare among forest species (Table 4).

Table 4 – Leaves, stem and total biomass of the dry forest and cassava by specie

Species	Leaves	Stem	Total
		------------Mg ha^{-1}------------	
Forest species			
Guapira opposita (Vell.) Reitz	4.05	6.13	10.18
Croton limae A.P. Gomes. M.F. Sales P.E. Berry	1.41	2.48	3.89
Metrodorea mollis Taub.	2.67	4.48	7.15
Annona leptopetala (R.E.Fr.) H.Rainer	0.90	1.49	2.39
Pilocarpus spicatus A.St.-Hil.	0.59	1.04	1.63
Senegalia langsdorffii (Benth.) Seigler & Ebinger	1.63	2.58	4.21
Zanthoxylum hamadryadicum Pirani	0.22	0.36	0.58
Erythroxylum sp	0.48	0.59	1.16
Byrsonima vacciniifolia A.Juss.	0.63	0.92	1.55
Total	12.58 a	20.07 a	32.74 a
Crop species			
Manihot esculenta	1.49 b	5.91 b	7.40 b

[1]Different lowercase letters indicate significant difference ($P < 0.05$; T test) in the same column among different land-use sites.

The total biomass and average wood per hectare of forest species (3.64 and 2.23 Mg ha^{-1}) were lower than those of cassava (Table 4).

The leaf, wood/manioc and total biomass compartments per hectare were significantly different between land uses ($p < 0.01$; Table 4). The land-use change between dry forest and cassava cultivation represents a ~ 88% reduction in phytomass ($t = 10.22$; $p < 0.01$), ~ 71% in wood/manioc biomass ($t = 12.65$, $p < 0.01$) and to ~ 77% ($t = 11.40$; $p <0.01$) for total biomass.

The estimated total phytomass for the forest fragment (12.58 Mg ha^{-1}) is within the range observed in the literature for Caatinga environments (SCHACHT *et al*., 1989; COSTA *et al*., 2002; DRUMMOND *et al*., 2008).

The total aboveground biomass estimated in this study (32.74 Mg ha^{-1}) for the dry forest is lower than the range obtained by Becknell, Kucek and Powers (2012) in a literature review of 40 articles on biomass studies in seasonally dry tropical forests (39–334 Mg ha^{-1}). In this study, data were collected from ten studies in South America, where three of them carried out in dry forest in the Brazilian semiarid region. Factors such as soil fertility, climatic conditions, conservation, successional stage, history of use and species composition may explain this divergence.

3.1.1.2 Carbon content

Regarding C content by species, it was found that there was a difference in leaf C content between species. It varied between 448.0 and 454.3 g kg^{-1}, with *Guapira opposita* presenting the highest C content and *Metrodorea mollis* the lowest (Figure 6).

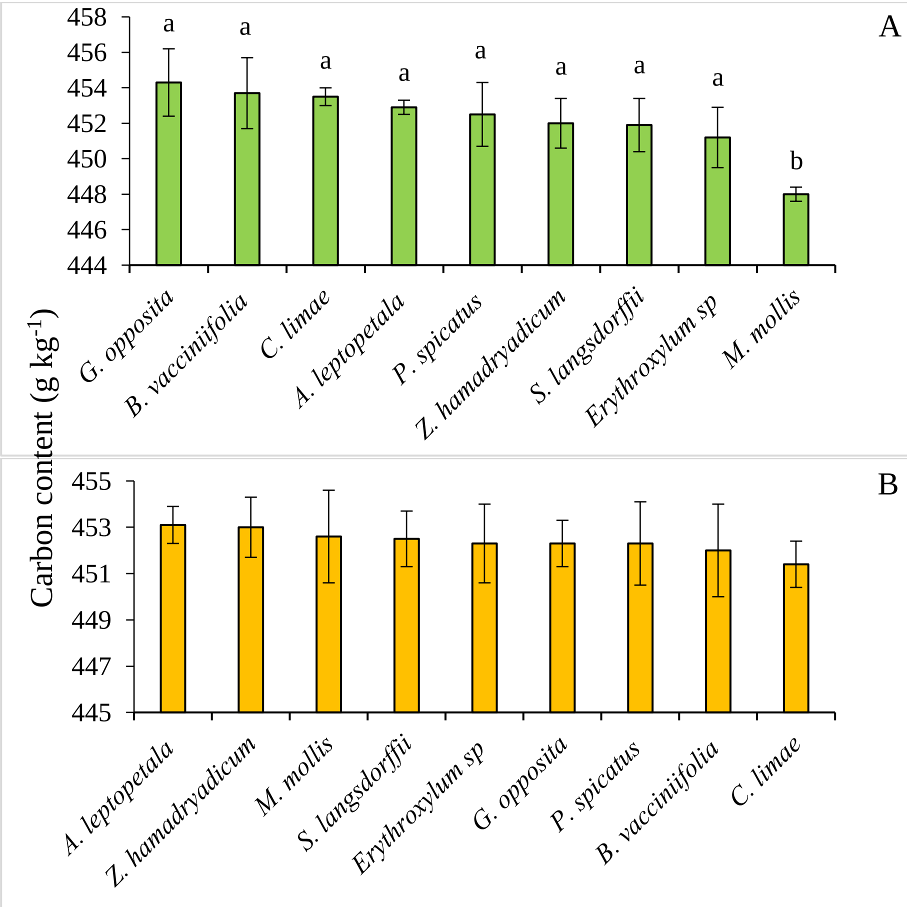

Figure 6 – Species carbon content in leaves (A) and stem (B) in the dry forest site.
[1]Different lowercase letters indicate significant difference ($P < 0.05$; Scott Knott) among different species.

The average levels of C in the leaves of forest species are lower than those verified by Vieira *et al*. (2009) for Caatinga species (473.9 g kg^{-1}). The ten species studied by this author are different from the species in this study, and the different edaphoclimatic conditions in the study area (State of Bahia) may explain the variability of the observed levels.

The IPCC suggests that a fixed value of 50% (500 g kg^{-1}) should be considered for C content in plant tissues (PENMAN *et al*., 2003), which may overestimate the C stocks in dry tropical forests.

C content in wood varied between 451.4 and 453.1 g kg^{-1} (Figure 6). There was no difference in the C content among species. However, in general, the species *Annona leptopetala* tends to have the highest C content, and *Croton limae* the lowest (Figure 6).

These results are lower to those observed by Vieira *et al*. (2009) for stems of ten species of Caatinga, which were different from species evaluated in this study. Carbon fixation in plants varies according to environmental conditions and to intrinsic morphophysiological characteristics. Thus, conditions of the area where individual's occur and the type of species influence the carbon allocation. Plants with similar ecophysiological characteristics are expected to have a similar internal behavior during the carbon allocation process (WRIGHT *et al*., 2006).

3.1.1.3 Carbon stock

Differences were observed in C stock of all compartments between forest species per hectare (Figure 7).

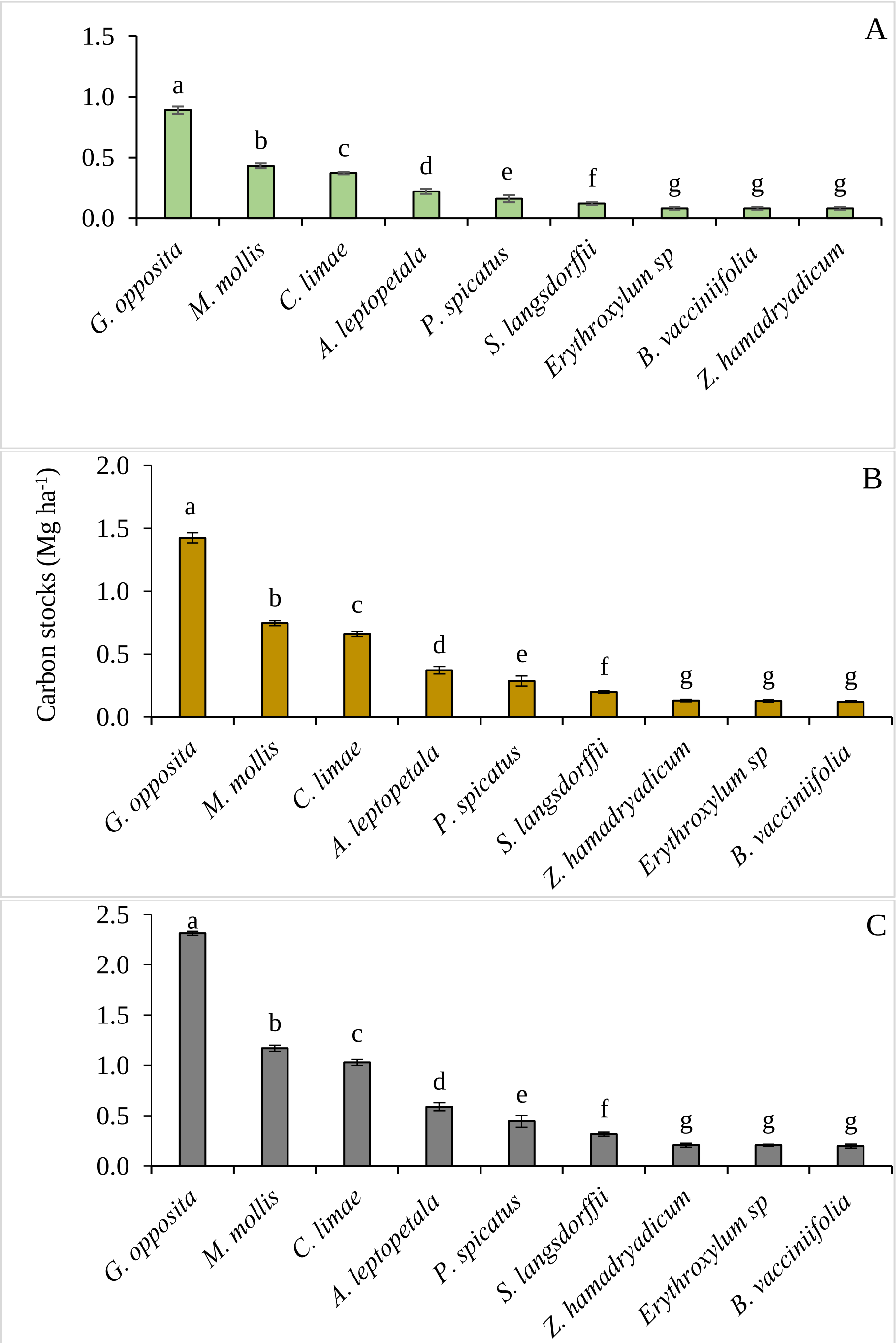

Figure 7 – Carbon stocks by species in leaves (A), stem (B) and total aboveground biomass (C) in the dry forest site.
[1]Different lowercase letters indicate significant difference ($P < 0.05$; Scott Knott) among different species.

G. opposita showed higher C stocks in the aboveground biomass compartments, representing ~ 36% of the total C stock considering all evaluated species.

M. mollis and *C. limae* had the second and third highest C stock in this environment respectively (Figure 7). These results are mainly related to the high densities of these species in the studied dry forest fragment (Table 2).

The total C stock stored by these three species represents 70% of the total carbon. For this reason, *G. opposita*, *M. mollis* and *C. limae* are key species in C sequestration studies in this dry tropical forest ecosystem, and the importance of conserving these species is emphasized by the significant amounts of carbon fixed in their biomass.

C stocks in all aboveground biomass compartments of species in the dry forest were higher than that of cassava cultivation (Figure 8). Reductions in carbon stored in leaf and wood biomass varied between 74 and 80%, respectively (Figure 8). These results demonstrate the negative effects of replacing the dry forest for cultivation of cassava for carbon storage in aboveground biomass in the studied region.

The C stock in the aboveground biomass in the dry tropical forest was 16.41 Mg C ha^{-1}, higher than that of cassava cultivation, which reached 3.34 Mg C ha^{-1}. Conversion from forest to cassava cultivation in the dry tropical forest environment represented a reduction of 80% of total aboveground biomass C stock (Figure 8). It is noteworthy that this decrease represents only the carbon stored by the nine most abundant species in the studied dry forest, so the reduction in carbon in the entire population of the fragment can reach even greater proportions.

Slightly lower carbon stocks than that observed in the studied dry forest fragment was found by Santos *et al*. (2016) in a fragment of regenerated Caatinga after 20 years of total suppression of vegetation in Caicó, Rio Grande do Norte (5.7 Mg ha^{-1}).

On the other hand, a much higher stock was found in the Caatinga by Pereira Júnior *et al*. (2016) (19.27 Mg C ha^{-1}) and Moura *et al*. (2016) (27 Mg C ha^{-1}), also in a Brazilian dry forest.

In other dry forest formations in the world, C stock results have high variability. Greater results than found in this study was reported by Chen, Hutley and Eamus (2003) in Australian dry forest, which they estimated at 41.20 Mg C ha^{-1}.

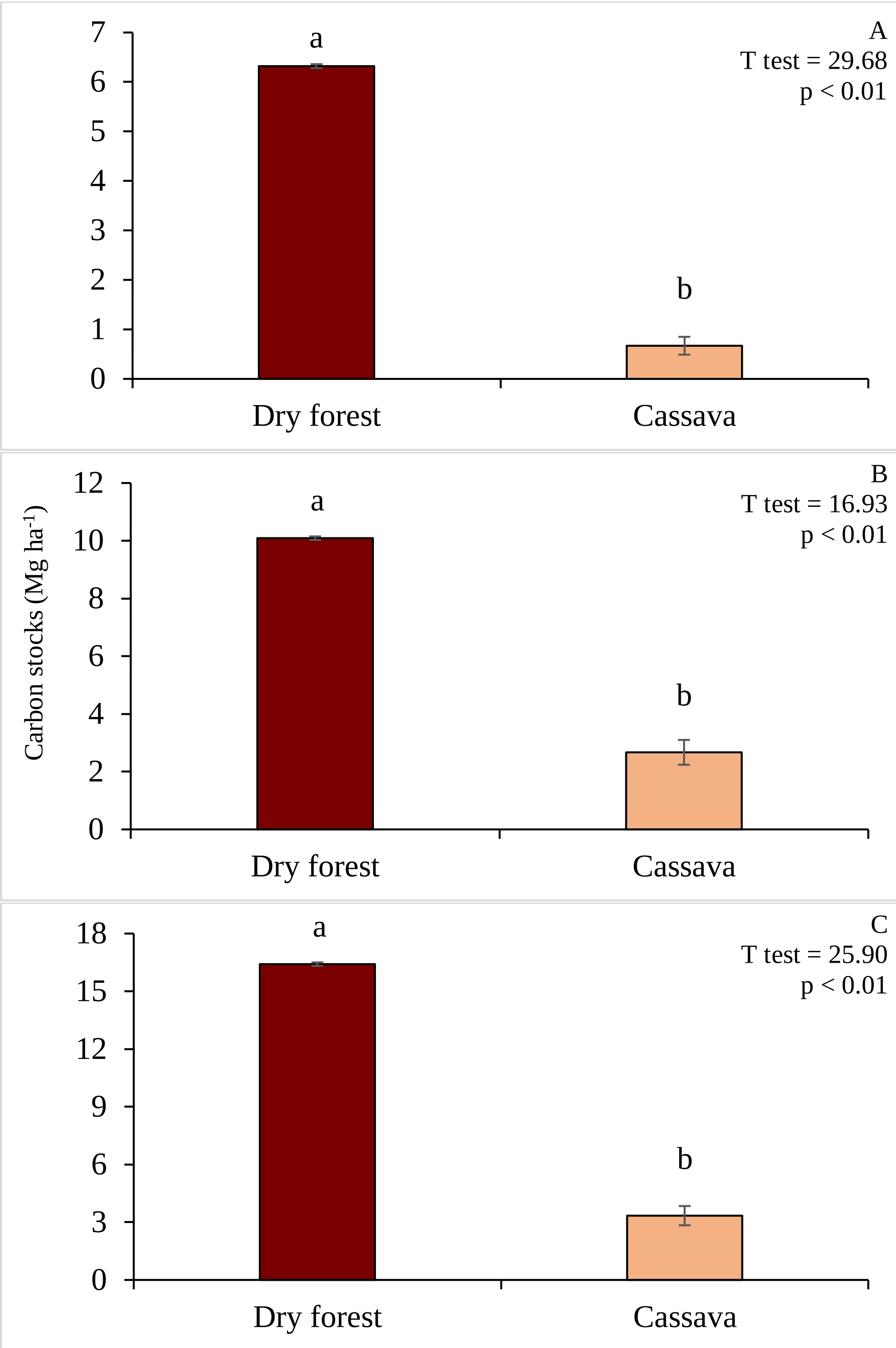

Figure 8 – Carbon stocks in leaves (A), stem (B), and total aboveground biomass (C) in the dry forest and cassava sites.
[1]Different lowercase letters indicate significant difference ($P < 0.01$; T test) among different land-use sites.

Chaturvedi *et al*. (2012) observed lower results than the present study, with C stocks in dry forest at different levels of conservation ranging from 0.6 to 3.6 Mg C ha^{-1}. On the other hand, results verified by Srinivas and Sundarapandian (2018) in young populations of dry forest in India encompass the results of this study (4.68-6.70 Mg C ha^{-1}).

These differences can be related to different characteristics of the vegetation such as size, floristic composition, density, successional stage, edaphoclimatic conditions and intensity of anthropic pressure.

In a dry agricultural area in Argentina, Conti *et al*. (2014) estimated 0.44 Mg ha^{-1} of C stored in aboveground biomass in potato cultivation.

3.1.1.4 Litter accumulated on the forest floor

A consequence of the replacement of the forest by agriculture is the disappearance of the litter layer. The average litter biomass accumulated under the forest floor at the DTF was 5.68 Mg ha^{-1}. The average carbon content observed for this fraction was 453.2 g kg^{-1} (Table 5).

Table 5 – Biomass, carbon content, and carbon stocks in the litter layer of the dry forest site

	Average	Minimum	Maximum
Litter layer biomass (Mg ha^{-1})	5.68 ± 3.65	2.41	18.02
Litter carbon content (g kg^{-1})	453.20 ± 0.17	449.50	455.40
Litter carbon stocks (Mg ha^{-1})	2.58 ± 1.66	1.09	8.18

Lower results were verified by Pereira Júnior *et al*. (2016) in a regenerating dry tropical forest in Brazil. Different successional stages, in addition to factors such as floristic composition, edaphoclimatic conditions and degree of anthropism, may explain the variability of litter biomass.

The carbon stock in the litter was 2.58 Mg ha^{-1}. The result found in this study corroborates the observed in studies in Dry Forests. Solomon *et al*. (2018) found carbon stock in the 2.25 Mg ha^{-1} litter in an area of dense dry tropical forest in Ethiopia.

In a dry tropical forest, Conti *et al*. (2014) estimated the stock in the litter from the Argentine Chaco at 3.98 Mg C ha^{-1}. On the other hand, Gasparri, Grau and Manghi (2008) found 2.30 Mg C ha^{-1} in the litter from a similar vegetation in Argentina. While Motaharfard *et al*. (2019) found that carbon stocks in forest litter from the semi-arid region of Iran ranged between 0.01 and 2.12 Mg ha^{-1}.

3.1.1.5 Soil

The soil density varied between 1.25 and 1.49 g cm^{-3} in the forest fragment, with an average of 1.38 g cm^{-3}, whereas in cassava cultivation it varied from 1.34 to 1.62 g cm^{-3} with an average of 1.51 g cm^{-3}. These results are in agreement with Kiehl (1979), who states that soil density must remain between 1.1 to 1.6 g cm^{-3} in mineral soils, assuming values above 1.6 g cm^{-3} in sandy soils.

Soil density differed between land uses for all evaluated layers, except for the 5-10 cm layer (Table 6). In general, soil densities in cassava cultivation were higher than in the dry forest. Soil compaction in the agricultural area due to the use of machinery for soil preparation can explain these results. In soil compaction, there is an increase in mass per unit volume, resulting in an increase in density and favoring the linear reduction of total porosity and macroporosity and physically degrading the soil (BEUTLER *et al*., 2005).

Average carbon content was not significantly different between different uses of the soil in the evaluated depths (Table 6). However, in general, the carbon content in the layers comprised in the first 20 cm of the soil tends to be higher in the soil under the forest (Table 6).

The carbon content in the cultivated area was higher in the layers between 20 - 40 cm and 40 - 60 cm, (Table 6). These results may be related to the carbon input from the root development of cassava and the release of exudates from the roots.

The carbon content decreased with depth in the forest. This behavior is common under native vegetation, since the contribution of plant residues occurs on the surface where there is a greater concentration of soil organisms that decompose this material, which ensures the continuous incorporation of SOM.

The land-use change did not affect soil carbon stocks in the evaluated layers ($p > 0.05$, Table 6). However, in general, forest carbon stocks tend to be higher than that of cassava in the first 20 cm. However, it is observed that in the 20-40 cm and 40-60 cm layer, carbon stocks in cassava exceed those in the dry forest (Table 6).

Table 6 – Soil density, carbon content, and carbon stocks in the dry forest and cassava sites

Soil depth (cm)	Soil density ($g\ cm^{-3}$)	Carbon content ($g\ kg^{-1}$)	Soil mass ($Mg\ ha^{-1}$)	Soil Carbon stock ($Mg\ ha^{-1}$)	Corrected Soil Carbon stock ($Mg\ ha^{-1}$)	Carbon accumulated ($Mg\ ha^{-1}$)
			Tropical Dry Forest			
0 – 5	1.25 ± 0.09	23.42 ± 5.46	627.35 ± 46.74	14.69 ± 3.48	14.69 ± 3.48	14.69 ± 3.48
5 - 10	1.29 ± 0.07	17.02 ± 1.94	644.47 ± 37.85	10.97 ± 1.06	10.97 ± 1.06	25.66 ± 3.49
10 – 20	1.34 ± 0.03	14.50 ± 3.88	1340.72 ± 33.41	19.44 ± 5.30	19.44 ± 5.30	45.10 ± 6.31
20 – 40	1.40 ± 0.05	10.19 ± 2.33	2794.84 ± 90.03	28.48 ± 6.03	28.48 ± 6.03	73.58 ± 10.15
40 – 60	1.48 ± 0.02	7.88 ± 2.56	2959.88 ± 43.22	23.32 ± 7.60	23.32 ± 7.60	96.91 ± 15.75
60 – 100	1.49 ± 0.02	7.98 ± 0.81	5959.76 ± 98.03	47.56 ± 5.34	47.56 ± 5.34	144.46 ± 20.03
Average	1.38	13.50	2387.84	24.07	24.07	-
			Cassava crop			
0 – 5	1.42 ± 0.03	17.54 ± 2.31	634.99 ± 7.06	11.14 ± 1.29	9.15 ± 1.17	9.15 ± 1.17
5 - 10	1.34 ± 0.01	15.07 ± 1.53	668.73 ± 4.80	10.08 ± 0.97	9.65 ± 0.93	18.80 ± 0.75
10 – 20	1.60 ± 0.03	14.17 ± 1.61	1593.20 ± 26.80	22.58 ± 2.25	18.81 ± 2.19	37.61 ± 2.20
20 – 40	1.62 ± 0.02	12.06 ± 1.92	3234.92 ± 41.16	39.01 ± 6.02	34.53 ± 5.80	72.14 ± 7.54
40 – 60	1.54 ± 0.02	8.19 ± 1.86	3084.88 ± 30.06	25.27 ± 5.54	24.32 ± 5.36	96.46 ± 12.25
60 – 100	1.52 ± 0.07	6.49 ± 1.41	6059.76 ± 285.72	39.33 ± 9.43	38.37 ± 9.42	134.84 ± 20.45
Average	1.51	12.25	2546.08	24.56	22.47	-

[1]Different lowercase letters indicate significant difference ($P < 0.05$; T test) in the same column among different land-use sites.

The carbon stock accumulated in the first 20 cm in the forest environment was 45.10 Mg C ha^{-1} and in the cultivated area it was 37.61 Mg C ha^{-1} (Table 6), which are close to that observed by Araújo Filho *et al*. (2018) in an undisturbed Caatinga area (45.21 Mg ha^{-1}) and less than the results found by Maia *et al*. (2007) in soils cultivated in Ceará (48.37 Mg C ha^{-1}).

Only the carbon accumulated up to the second layer differed significantly between land uses (Table 6), being 27% lower in cassava. According to Oliveira *et al*. (2008), the superficial layers of the soil are the most sensitive to variations in C stock, because the action of microorganisms in the SOM is greater in the superficial layers where there is accumulation of organic material providing ideal habitat and nutritional conditions for the biota .

The carbon stored in the superficial layers of the soil is the most affected by the land-use change (ASSIS *et al*., 2016). These authors, evaluating the changes in the SOM resulting from changes in land use in the Brazilian semiarid region, observed that carbon stocks and levels decreased in the first 15 cm of soil, demonstrating a general tendency to decrease with depth.

Assefa *et al*. (2017) found changes in carbon storage between different land use systems. In this study, forest ecosystems found medium C stocks higher than other uses, following the decreasing order: forest> eucalyptus plantations> pasture> agricultural cultivation.

Studies show that soil carbon stocks in the 0 - 20 cm layer of soil in a dry tropical forest in Brazil vary between 17.84 and 69.16 Mg C ha^{-1} (KAUFFMANN *et al*., 1993; TIESSEN *et al*. , 1998; BERNARDI *et al*., 2007; MAIA *et al*., 2007; AMORIM, 2009; FRACETTO *et al*., 2012; MOREIRA, 2013; AQUINO, 2015; MOURA, 2016; ARAÚJO FILHO *et al*., 2018). Therefore, the results in the present study are within the average found in other studies in Brazilian dry forests.

The carbon stock in the soil considering the first 100 cm was 144.46 and 134.84 Mg C ha^{-1} in the forest and in the area cultivated with cassava, respectively (Table 6). However, there was no significant difference between the land uses for the total C stock in the 100 cm of soil ($p > 0.05$).

Intensive cultivation of the soil with harrowing and ploughing makes the soil susceptible to erosive processes, as organic matter is lost through increased soil oxidation, compaction and consequently the loose surface layer can be leached more easily, increasing the outputs in nutrient cycles (SILVA; MENDONÇA, 2013).

3.1.2 Humid environment

3.1.2.1 Aboveground biomass

The species *D. guianensis* exhibited the highest biomass per hectare considering forest species, representing ~ 28% of the total biomass considering forest species (Table 7). However, individually, the average biomass per hectare of forest species compartments was lower than that of sugarcane (Table 7).

Table 7 – Leaves, stem and total aboveground biomass of the rainforest and sugarcane by specie

Species	Leaves	Stem	Total
Forest species		-----------Mg ha^{-1}-----------	
Helicostylis tomentosa (Poepp & Endl.) J.F.Macbr.	0.82	15.49	16.31
Mabea occidentalis (Benth.) Müll. Arg.	0.36	6.75	7.11
Brosimum guianense (Aubl.) Huber	0.75	14.31	15.06
Parkia pendula (Willd) Benth. ex Walpers	1.15	21.87	23.02
Thyrsodium schomburgkianum Benth.	0.25	4.77	5.03
Dialium guianensis (Aublet.) Sandw.	1.73	32.95	34.69
Pouteria grandiflora (A.DC.) Baehni	0.08	1.58	1.67
Tapirira guianensis Aubl.	0.64	12.14	12.78
Protium heptaphyllum (Aubl.) Marchand.	0.25	4.79	5.04
Brosimum conduru Standl	0.15	2.80	2.95
Total	6.18 b	117.45 a	123.66 a
Crop species			
Saccharum officinarum	23.89 a	87.79 b	111.68 b

[1]Different lowercase letters indicate significant difference ($P < 0.05$; T test) in the same column among different land-use sites.

This result can be explained by the difference between the absolute density of forest species (between 25 and 104 ind. ha^{-1}) compared to sugarcane (20416 ind. ha^{-1}).

There was a statistical difference in leaf biomass per hectare between the rainforest and the area cultivated with sugarcane ($t = 7.94$; $p < 0.01$; Table 7), with the highest leaf biomass per hectare in sugarcane. For the wood/stem biomass, the rainforest exhibited 34% higher biomass when compared to cultivation ($t = 8.01$; $p < 0.01$). On the other hand, changes in land use represented 10% reduction in total biomass per hectare ($t = 9.88$; $p < 0.01$).

The total biomass of the rainforest considering the nine species with the highest density in the fragment was 123.66 Mg ha^{-1}. This result is within the range found in the literature for estimating biomass in forest fragments at different levels of conservation and phytophysiognomy of the Atlantic Forest (BURGER, 2005; ROLIM *et al*., 2005; LIMA *et al*., 2006; CUNHA *et al*., 2009). It is worth mentioning that this value represents only 58% of the individuals existing in the fragment, thus when considering all individuals this estimate would be much higher.

The results of biomass per hectare of leaves and stem compartments are similar to those found by De Oliveira, Braga and Santos (2014) in a study of biomass production in irrigated sugarcane in the São Francisco Valley. These results corroborate with Trivelin *et al*. (1996), that indicate that the amount of straw in crops without burning varies from 10 to 30 t ha^{-1}.

3.1.2.2 Carbon content

The carbon contentin leaves and wood varied between species, with *B. guianense* presenting the highest average leaf content (456.7 g kg^{-1}) and *M. occidentalis*, the lowest (452.0 g kg^{-1}, Figure 9).

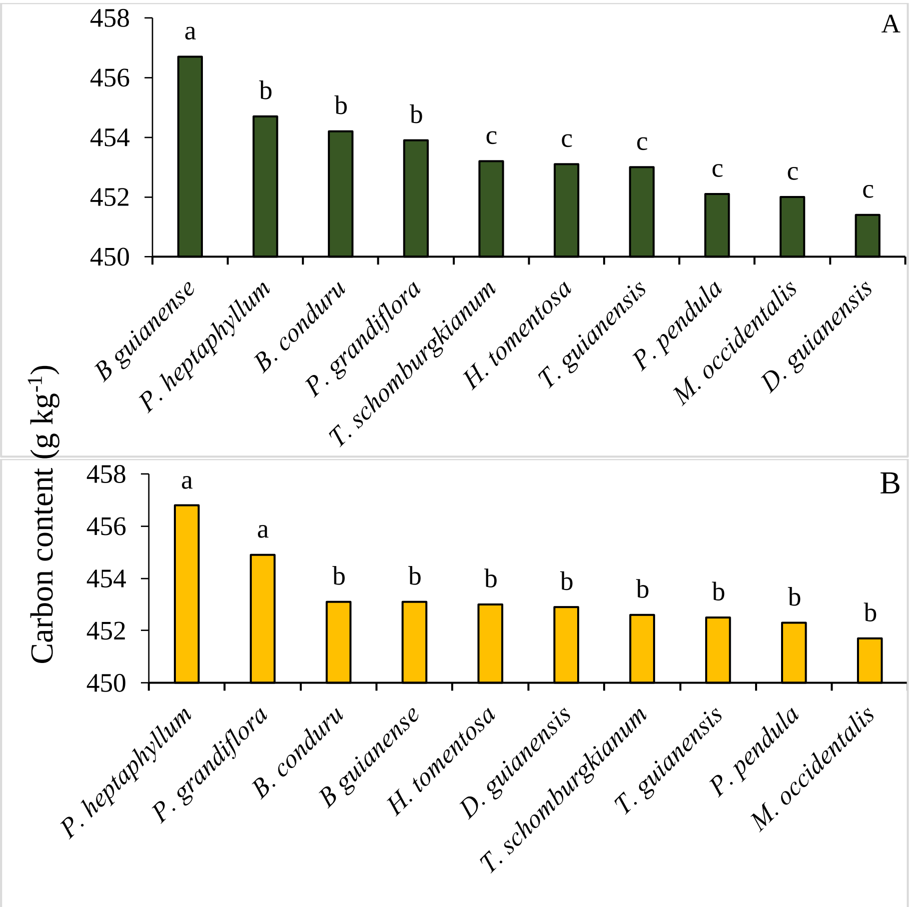

Figure 9 – Species carbon content in leaves (A) and stem (B) in the rainforest site.
[1]Different lowercase letters indicate significant difference ($P < 0.05$; Scott Knott) among different species.

The carbon content in wood varied between 451.7 and 456.8 g kg^{-1}. *P. heptaphyllum* and *M. occidentalis* had the highest and lowest levels, respectively. According to Hoppe (2003), different concentrations of carbon are related to soil conditions and the capacity that each plant must fix this component through the biochemical cycle.

Watzlawick *et al*. (2012) and Watzlawick *et al*. (2014) observed lower average carbon contentin tree species in Mixed Ombrophilous Forest than this study. Mello Cunha *et al*. (2009) found an average of 443 g kg^{-1} of carbon content in leaves and 453 g kg^{-1} in branches of species from the Atlantic Forest in Rio de Janeiro. Results similar to this study were found by Vieira *et al*. (2011) in Atlantic Forest in Rio de Janeiro, with values ranging between 450 and 459 g kg^{-1}. The species evaluated by these authors are different from the species in this study, and the different edaphoclimatic and morphophysiological conditions may explain the different levels observed.

3.1.2.3 Carbon stock

Carbon stocks in the leaf, wood and total compartments varied significantly among species. For leaves, wood and total C stocks, the largest carbon stock per plant was observed in *D. guianensis* (Figure 10).

The group formed by *D. guianensis*, *P. pendula*, *H. tomentosa*, *B. guianense* and *T. guianensis* represents the species that store more carbon in the studied area, equivalent to 82% of the carbon in the aboveground biomass in the ten species with higher density in the studied fragment. The results of carbon content and stocks by species indicate that those that fix more carbon in their biomass and can be recommended in studies for carbon sequestration and should be prioritized in conservation studies.

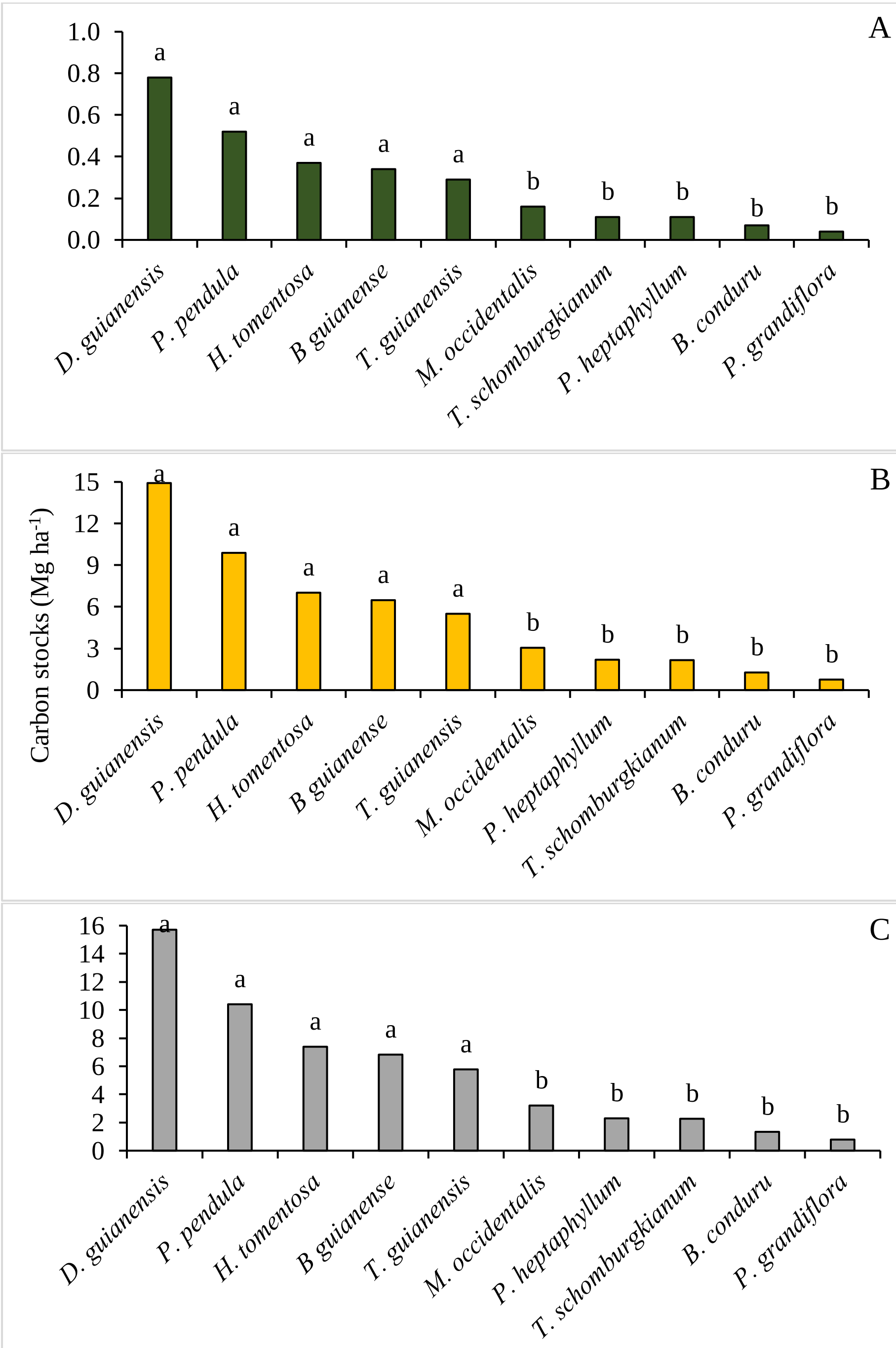

Figure 10 – Carbon stocks by species in leaves (A), stem (B) and total aboveground biomass (C) in the rainforest site.
[1]Different lowercase letters indicate significant difference ($P < 0.05$; Scott Knott) among different species.

Sugarcane obtained the highest averages for the carbon stock in the leaves, having approximately 3.5 times more carbon stored in the leaf biomass than in the forest fragment (Figure 11).

On the other hand, for the wood/stem and total compartments, the carbon stock in the forest was higher ($p < 0.01$, Figure 11). The carbon reduction of these fractions represents 32% considering the carbon stored in the wood.

The average carbon stock in the aboveground biomass in the rainforest considering the ten species with highest density was 61.59 Mg C ha^{-1}, higher than that of the area cultivated with sugarcane, which obtained 50.54 Mg C ha^{-1}. The land-use change from the rainforest to sugarcane would represent a ~18% reduction in total carbon stock of the aboveground biomass. These results demonstrate that the land-use change can significantly affect the aboveground biomass carbon stocks in the studied Tropical Rain Forest (Figure 11).

Ferez *et al*. (2015) observed carbon stock in the aboveground biomass in a remnant of mature Atlantic Forest of 148.70 Mg C ha^{-1}. Vieira *et al*. (2011) found carbon stocks in aboveground biomass ranging from 94.28 to 126.72 Mg C ha^{-1} in coastal Atlantic Forest in São Paulo.

These differences may be related to the different conservation status of the forest and topographic and climatic gradients that have a direct influence on the aboveground biomass carbon stocks.

In a tropical rainforest, Razafindrakoto *et al*. (2018) found an aboveground biomass C stock of 30.91 Mg C ha^{-1} in Madagascar, and the degradation of a locally similar environment reduced that stock to 8.39 Mg C ha^{-1}. Azian *et al*. (2016) found stocks of 164.76 Mg C ha^{-1} in a protected area of tropical rainforest in Malaysia. Orihuela-Belmonte *et al*. (2013) observed a decrease in the carbon stock in the aboveground living biomass in a secondary forest compared to a forest that was not disturbed in Mexico, with 59.29 and 104, 03 Mg C ha^{-1} respectively.

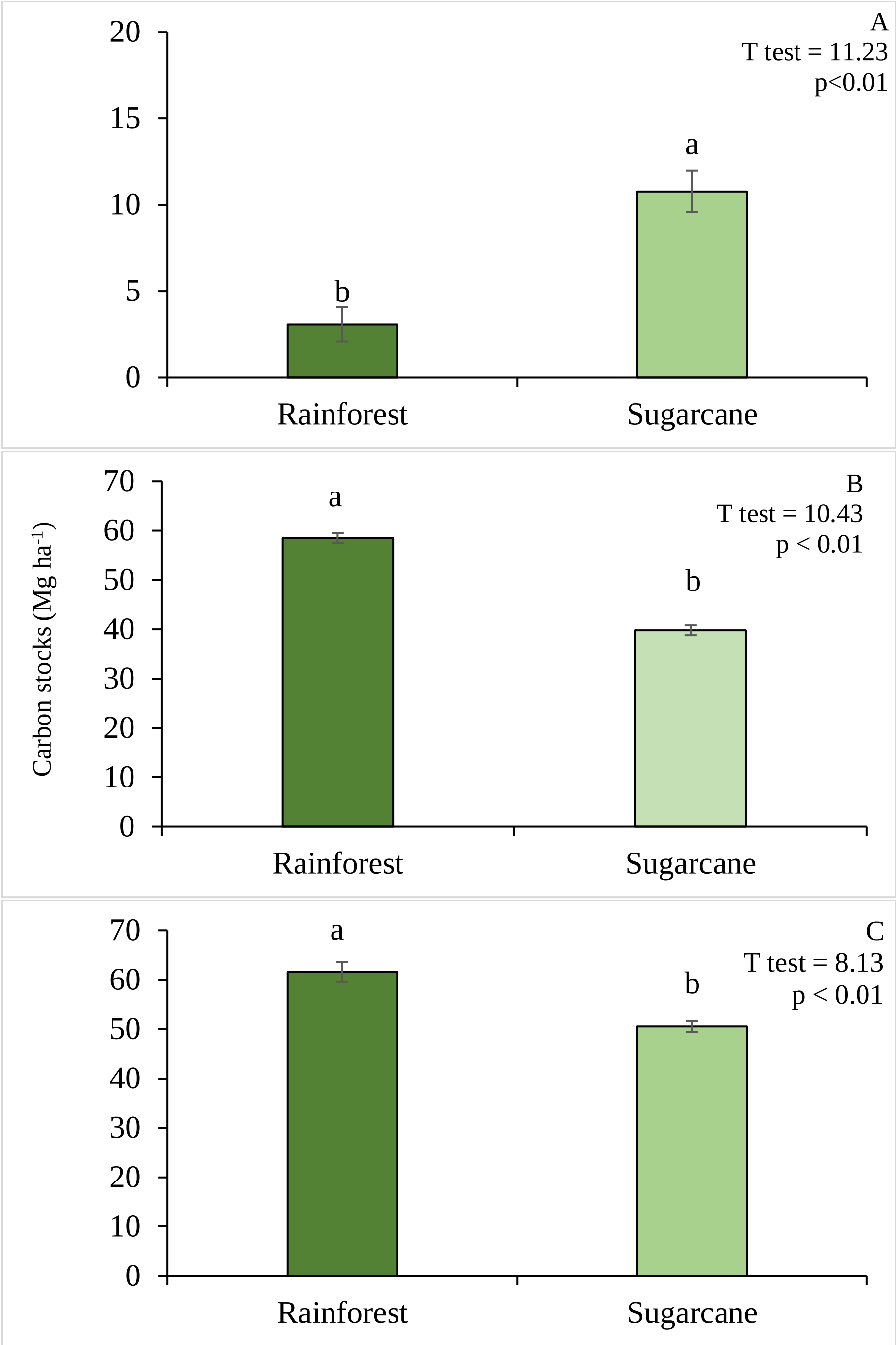

Figure 11 – Carbon stocks in leaves (A), stem (B), and total aboveground biomass (C) in the rainforest and sugarcane sites.
[1]Different lowercase letters indicate significant difference ($P < 0.01$; T test) among different land-use sites.

3.1.2.4 Litter accumulated on the forest floor

The average litter biomass accumulated under the forest floor in the TRF was 10.74 Mg ha^{-1}. The average carbon content observed for this fraction was 453.2 g kg^{-1} (Table 5). The carbon stored in the litter biomass accumulated on the rainforest floor contributed less than 1.5% to the total carbon stock of the ecosystem (Table 8).

Table 8 – Biomass, carbon content, and carbon stocks in the litter layer of the rainforest site

	Average	Minimum	Maximum
Litter layer biomass (Mg ha^{-1})	10.74 ± 3.78	3.84	17.68
Litter carbon content (g kg^{-1})	456.90 ± 0.42	450.50	464.20
Litter carbon stocks (Mg ha^{-1})	4.91 ± 1.74	1.77	8.19

The carbon stored in this compartment was an average of 4.91 Mg C ha^{-1}. This result is in line with values found in the literature for the Brazilian Atlantic Forest. Ferez *et al*. (2015) estimated the carbon stored in litter in the Atlantic Forest at 4.00 Mg ha^{-1}. Meanwhile, Vieira *et al*. (2011) observed a variation of 2.64 and 4.00 Mg C ha^{-1} in an altitudinal gradient of an ombrophilous forest in São Paulo.

Lower results were observed by Doetterl *et al*. (2015) in tropical lowland rainforest in Africa, with average litter biomass between 4.8 - 4.9 Mg ha^{-1} with carbon stocks between 1.8 - 2.0 Mg C ha^{-1}.

3.1.2.5 Soil

Soil density was significantly different between the forest and the cultivated area in all evaluated layers, with the highest estimated densities for the agricultural area (Table 9). The average density for the forest was 1.47 g cm^{-3}, while in sugarcane the estimated average soil density was 1.71 g cm^{-3}.

The use and management systems of an area have a great influence on the physical quality of the soil, especially in superficial layers where soil compaction is more intensified, resulting in the degradation of the physical quality of the soil (ARAÚJO; GOEDERT; LACERDA, 2007).

Table 9 – Soil density, carbon content, and carbon stocks in the rainforest and sugarcane sites

Depth	Soil density ($g\ cm^{-3}$)	Carbon content ($g\ kg^{-1}$)	Soil mass (g)	Carbon stocks ($Mg\ ha^{-1}$)	Corrected C stocks ($Mg\ ha^{-1}$)	Carbon accumulation ($Mg\ ha^{-1}$)
			Tropical Rainforest			
0 – 5	1.27 ± 0.01	19.58 ± 2.07	707.86 ± 15.54	13.85 ± 1.40	13.85 ± 1.40	13.85 ± 1.40
5 - 10	1.28 ± 0.02	16.38 ± 3.32	638.60 ± 1.71	10.46 ± 2.14	10.46 ± 2.14	24.31 ± 3.27
10 – 20	1.49 ± 0.01	13.45 ± 3.33	1488.97 ± 1.18	20.03 ± 4.92	20.03 ± 4.92	44.34 ± 8.16
20 – 40	1.58 ± 0.01	11.19 ± 5.50	3164.86 ± 19.11	35.41 ± 17.46	35.41 ± 17.46	79.75 ± 24.32
40 – 60	1.57 ± 0.04	9.69 ± 4.54	3129.87 ± 87.12	30.33 ± 14.62	30.33 ± 14.62	110.08 ± 38.86
60 – 100	1.65 ± 0.03	6.88 ± 2.36	6599.85 ± 138.55	45.41 ± 29.69	45.41 ± 29.69	155.49 ± 67.99
Average	1.47	12.86	2636.02	25.92	25.92	-
			Sugarcane crop			
0 – 5	1.60 ± 0.01	12.01 ± 1.42	845.96 ± 1.15	10.16 ± 1.21	7.27 ± 0.95	7.27 ± 0.95
5 - 10	1.69 ± 0.01	12.16 ± 0.97	842.48 ± 0.65	10.24 ± 0.82	6.89 ± 1.23	14.16 ± 1.33
10 – 20	1.79 ± 0.03	9.94 ± 1.91	1782.96 ± 8.91	17.72 ± 3.37	13.67 ± 3.48	27.83 ± 3.38
20 – 40	1.77 ± 0.02	8.27 ± 2.46	3539.90 ± 36.56	29.27 ± 8.44	25.18 ± 9.17	53.01 ± 10.00
40 – 60	1.75 ± 0.05	7.15 ± 0.95	3489.89 ± 101.29	24.95 ± 3.40	21.67 ± 3.02	74.68 ± 10.46
60 – 100	1.72 ± 0.01	7.41 ± 0.68	6869.88 ± 20.17	50.91 ± 4.57	49.00 ± 4.57	123.68 ± 14.43
Average	1.72	9.49	2895.20	23.88	20.61	-

[1]Different lowercase letters indicate significant difference ($P < 0.05$; T test) in the same column among different land-use sites.

The average carbon content in the soil had a decreasing vertical distribution in the forest (Table 9). In the first 5 cm, the carbon content in the forest was higher than that of sugar cane cultivation ($p < 0.05$; Table 9). In general, carbon content up to 60 cm deep was higher in the rainforest compared to the cultivation of sugarcane (Table 9).

This condition is probably due to high deposition of litter, and in the sugarcane evaluated there is straw burning before manual harvesting, which further contributes to the reduction of the soil's carbon content, especially in the superficial layers.

The first 40 cm of soil depth accounted for ~51 and 43% of the total soil carbon stock in the rainforest and sugarcane cultivation, respectively (Table 9). Comparing the two land uses, a greater accumulated carbon stock was found in the rainforest up to 20 cm deep ($p < 0.05$, Table 9).

After 20 cm of depth, the accumulated carbon stock does not differ between land uses (Table 9), however, the rainforest has higher stocks than sugarcane. Reduction of carbon stocks after land-use change, especially in the superficial layers, is mainly associated with changes in the local microclimate that favor the mineralization of organic compounds and with decrease in the deposition of organic residues, which occurs in natural vegetation. The use of fire further also contributes to these reductions.

According to Guimarães *et al*. (2018), land-use change to sugarcane decreases the content and the stabilization of carbon in superficial layers of the soil. These authors observed a 65% decrease in the carbon stored in the soil after changing its use from native Cerrado vegetation to burning sugarcane.

In general, C stocks in the rainforest tend to be higher than that of sugar cane up to 60 cm. In the 60-100 cm layer, the carbon stock of the cultivated area exceeds that of the rainforest (Table 9).

According to Conti *et al*. (2014), the process of carbon reduction through forest removal, whether through forest management or simple deforestation, is usually accompanied by the direct loss of carbon from the soil surface. This is due to reduced physical protection and increased soil temperature in the short term, as well as reduced litter accumulation in the long term. For Ferreira *et al*. (2016), lower COS stocks in lands cultivated in agriculture can be explained by inadequate soil management.

In general, studies that assess the effects of land use change on COS storage show a decrease in stock over time (SCHULZ *et al*., 2016; CONTI *et al*., 2014; MUÑOZ-ROJAS *et al*., 2012). However, it also turns out that adequate soil management is one of the main factors for maintaining the COS stock (POEPLAU; DON, 2013; MURTY *et al*., 2002).

3.2 Distribution of total carbon deposits in dry and humid environments

Total carbon stocks ranged from ~138 - 222 Mg C ha^{-1} between forest and agricultural environments (Figure 12). The total carbon stocks in the environments followed the following order: rainforest > sugarcane > dry forest > cassava (Figure 12).

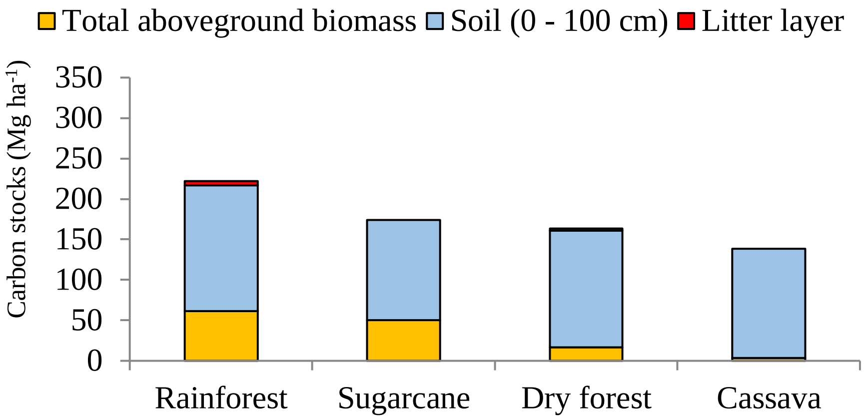

Figure 12 – Carbon stocks proportion distribution in the study sites.

The rainforest stores 40% more carbon than the dry forest (Figure 12), while the area cultivated with sugar cane stores 26% more carbon than the area cultivated with cassava (Table 10). The results indicate that the studied humid environments store more carbon than the dry environments, and that changes in land use reduces the total carbon stocks of ecosystems in dry and humid environments.

Regarding the carbon stored in the aboveground biomass, there were differences between environments (Table 10), with the rainforest having the largest stock, followed by the area cultivated with sugarcane.

Table 10 – Total aboveground biomass, litter layer, soil and total ecosystem carbon stocks in the study sites

	Dry forest	Cassava	Rainforest	Sugarcane
	--------------------------------------Mg ha^{-1}			--------------------------------------
Total aboveground biomass	16.41±2.32 c[1]	3.34±0.62 d	61.59±5.87 a	50.54±2.11 b
Litter layer	2.58 ± 1.66 b[2]	-	4.91 ± 1.74 a	-
Soil (0 – 100 cm)	144.46±20.03[1]	134.84±20.45	155.49±68.00	123.68±14.44
Total ecosystem	163.45	138.18	221.99	174.22

[1]Different lowercase letters indicate significant difference ($P < 0.05$; Scott Knott) in the same layer among different land-use sites.

The rainforest stored about 3.8 times more carbon in the aboveground biomass compared to the dry forest. While in agricultural crops, the carbon stored in the cassava area represents ~15 times less aboveground biomass C stock than sugarcane (Table 10). In general, the dry environment stores 82% less carbon than the humid environment.

For litter accumulated on the forest floor, it was found that in the rainforest litter stores 90% more carbon than the dry forest (Table 10). These results are related to the increase in biomass in tropical forests along the precipitation gradients (MALHI *et al*., 2006). In very humid forests, nutrients and light are limiting factors for growth and storage of carbon in biomass (CLEVELAND *et al*., 2011), while dry forests have less nutrient leaching and frequent periods of water restriction, with intense and prolonged constraints on growth (EAMUS, 1999) and consequently on primary productivity and carbon storage.

Carbon deposits in the soil were the largest compartments in all environments, ranging from ~123 - 156 Mg C ha^{-1}. There was no significant difference for soil carbon stock between environments. However, the environments under forests reached the highest carbon stocks in the soil (Table 10).

The global average estimate of COS stock for the 1.0 m surface layer in deciduous tropical forests is 158 Mg ha^{-1} (JOBBÁGY; JACKSON, 2000). Soil C stocks fluctuate on a local scale due to factors such as topography and land management, already on a regional scale, due to the effect of the soil source material and the underlying geology (TRUMBORE; CAMARGO, 2009).

The soil carbon constituted the highest percentage of the total carbon of the evaluated areas, representing on average 82% (Figure 13). In general, in dry environments 93% of the ecosystem's carbon is stored in the soil on average. However, in the humid environment this proportion is reduced to 71% (Figure 13).

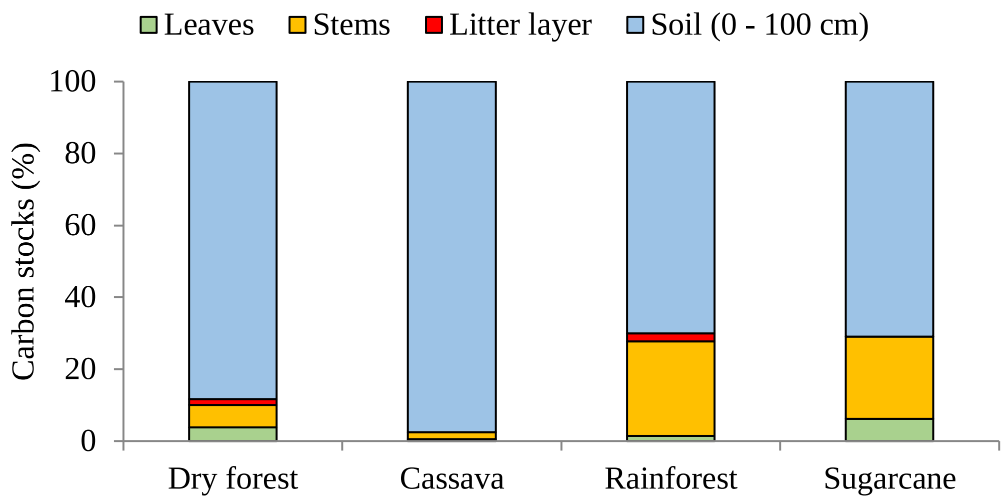

Figure 13 – Relative carbon distribution in the study sites.

The biomass of wood, manioc or stem was the second compartment that most stores carbon in the studied ecosystems (Figure 16). Meanwhile, leaf biomass contributed less than 4% to the total carbon stock in dry environments, while in humid environments the proportion varied between 1 - 7%. In the rainforest, approximately 27% of the total carbon is stored in the aboveground biomass (Figure 13).

3.4 Losses of carbon stocks in forest-agriculture conversion in dry and humid environments

The previous results demonstrated that the replacement of a forest by agricultural areas in environments of Tropical Dry and Tropical Rainforest has a direct impact on carbon storage in the evaluated C deposits. In general, there is a reduction in carbon stocks, resulting in a deficit in these environments which contributes to increases in C concentrations in the atmosphere.

In the conversion of a rainforest to a sugar cane cultivation, there is a decrease of ~18% of carbon stock considering the aboveground biomass. Considering the change from dry forest to cassava, reduction in carbon stock is ~ 80% (Figure 14).

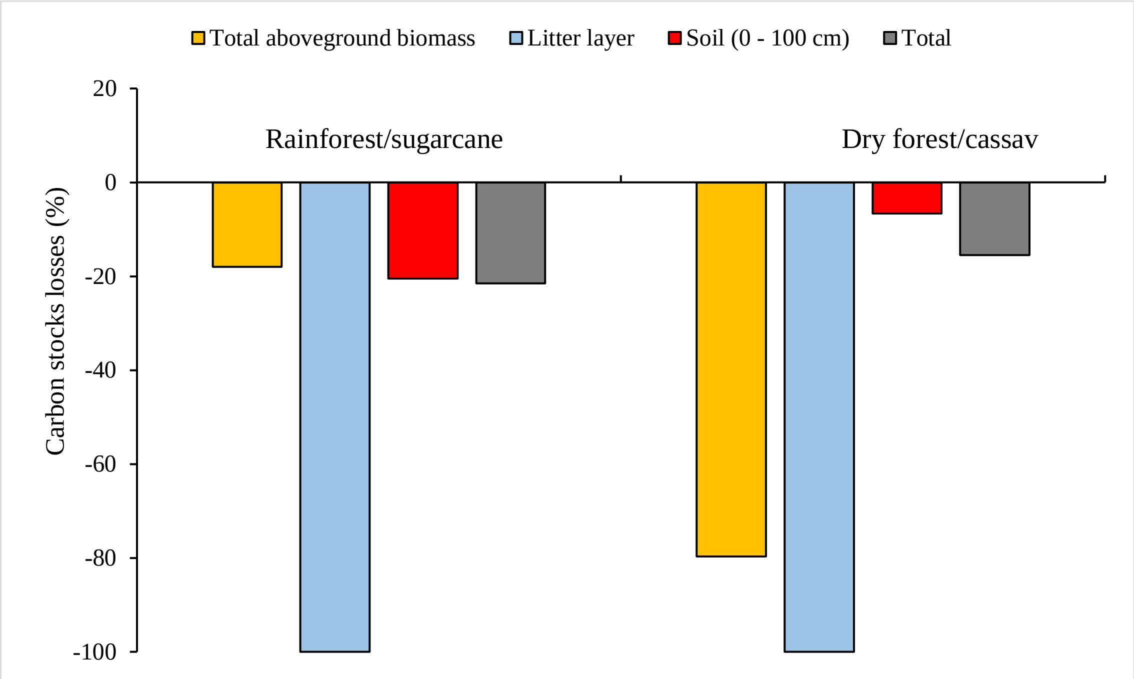

Figure 14 – Relative carbon stocks losses in carbon deposits by land-use change in the dry and rainforest ecosystems.

The replacement of a forest by agriculture reduces the supply of organic residues in the soil, consequently inducing the disappearance of the organic layer, which is one of the main pathways of the carbon flux from plant biomass to the soil.

In addition, in the agricultural areas evaluated, there is no incorporation of harvest residues into the soil. In sugarcane, waste is burned during harvest. In cassava, the residues are used to feed goats. In both environments evaluated, the carbon losses from the deposit of the litter layer with conversion to agricultural activity were 100% (Figure 14).

Considering the carbon stocks in the soil, there is a ~21% reduction in the change from rainforest to sugarcane. On the other hand, the substitution of dry forest for the cultivation of cassava promoted a decrease of ~7% in the carbon stock in the soil.

Finally, the total carbon stock of carbon in forest ecosystems is in general reduced (Figure 14). In the TRF, there is a loss of ~22% of the carbon stored in the forest/agriculture conversion. While in DTF, the proportion is lower, with about 16% of carbon loss (Figure 14).

4 CONCLUSIONS

The species *G. opposita*, *M. mollis* and *C. limae* in the studied dry forest are key species in C sequestration studies and should be considered when planning conservation studies and carbon sequestration programs and policies.

The aboveground and litter biomass carbon stocks are most affected by the land-use change in the dry environment than in the humid environment.

In the rainforest, the species *D. guianensis*, *P. pendula*, *H. tomentosa*, *B. guianense* and *T. guianensis* store more carbon in their biomass aboveground and can be recommended in studies for carbon sequestration, and also should be prioritized in studies conservation.

The land-use change caused a reduction in the carbon stock in the soil up to 1.0 m deep in the dry and humid environments.

The conversion of forest to agricultural cultivation in the humid environment alters the carbon content and stock of the soil, especially in the top layers, mainly related to decrease in litter supply and to agricultural cultivation practices.

The biomass compartments of wood/manioc/stem and soil are the main carbon reservoirs in dry and humid environments.

The land-use change (forest to agriculture) has been shown to have a negative impact on carbon storage in humid and dry environments, promoting a massive reduction in stored carbon.

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CHAPTER II – SOIL CARBON QUALITY IN AGRICULTURAL AND FOREST ECOSYSTEMS IN A DRY AND HUMID ENVIRONMENT

ABSTRACT

Land-use change affects soil C content and stocks, significantly altering the dynamics of soil organic matter. Small changes in the total soil C can be hardly detectable in the short term, consequently, so it is essential to evaluate the soil C quality through the soil organic matter (SOM), fractions that are more sensitive to environmental changes. To obtain a better understanding of the C stock and quality and its effects on land-use change of tropical forests in Northeast Brazil, the aimed of this study was to quantify the soil C stocks and quality in forestry and agricultural ecosystems of dry and humid environments and evaluate the effects of land-use changes in their C reservoirs. The study was developed in four different forest and agricultural environments, located in sites originally occupied by the Tropical Dry Forest and Tropical Rain Forest, Pernambuco and Paraíba States, Brazil. We collected soil samples in the 0.00 - 0.05 m; 0.05 - 0.10 m; 0.10 - 0.20 m layers. The total soil C contents, humic substances carbon (fulvic acids, humic acids, and humin), labile carbon and oxidizable carbon were estimated. We calculated the carbon stocks, as well as the carbon recovery rate, carbon accumulation, and carbon depletion. In the FTS, there was a reduction of 25% and 11% of the COT under cassava cultivation in layers 0 - 5 cm and 5 - 10 cm respectively. The levels of C-HU were higher than the levels of C-AF and C-AH in the dry environment. In the 0-5 cm layer, the change in land-use reduced the COT stock by ~ 60%. The TOC stock accumulated in the 20 cm of soil ranged between ~ 37.61 and 45.10 Mg ha^{-1} between the uses of the soil in the dry environment. The land-use change reduced the total organic carbon content of the soil by ~ 39% in the first 5 cm in the humid environment. In the 10-20 cm layer, a 50% increase in carbon content in this fraction was observed in sugarcane. The relations between labile carbon and recalcitrant carbon were higher in the soil under cassava cultivation. The F1 fraction in the rainforest was 80% higher than in the sugarcane in the 0-5 cm layer and 74% higher in the 5-10 cm layer. The non-labile carbon was 48 and 58% higher in the soil under rainforest in layers 0-5 cm and 10-20 cm. The land-use change promoted the reduction of non-labile carbon stocks in the evaluated layers. The land-use change reduced the carbon recovery rate of fulvic acids, humic acids, humin, and total humic substances in the surface layers of the dry environment. The land-use change reduced the carbon recovery rate of non-humic substances in the surface layer. The carbon depletion rate in humid environment was higher in the surface layers.

Keywords: humic fractions, oxidable carbon, labile carbon, soil carbon sequestration, land use change, croplands, Atlantic forest, Caatinga

1 INTRODUCTION

Tropical forests are considered strategic environments for studies on carbon sequestration. Contrastingly, they are the most threatened ecosystems by human pressure in the world. In the last decades, the replacement of forests by areas of agricultural crops and pasture has been the main reason for the acceleration of the global release of carbon dioxide to the atmosphere (USSIRI; LAL, 2017).

In Brazil, the Atlantic Forest and the Caatinga have been intensively degraded through agricultural expansion. In the rainforest, changes in land use intensified during the 20th century through the expansion of the sugarcane industry, and ecological consequences of these changes such as considerable loss of biodiversity and ecosystem functioning such as carbon sequestration are worrying (SILVA; TABARELLI, 2000).

In the dry forest, almost half of the original Caatinga area was deforested, according to data from the Brazilian Forest Service - Ministry of the Environment - SFB/MMA (2013). The main causes of this degradation involve deforestation for agricultural production systems and firewood extraction. The situation in the Caatinga seems to be even more complex than in the Atlantic Forest region, since the soil in this case can also be completely unprotected and its organic matter exposed to significant carbon losses.

Changes in land use affect stocks and content of carbon in the soil, significantly altering the dynamics of SOM. Studies that assess the effects of land use change on COS storage normally find a decrease in stock over time (SCHULZ *et al*., 2016; CONTI *et al*., 2014; MUÑOZ-ROJAS *et al*., 2012).

The losses of C are promoted by revolving the soil, changes in temperature, humidity and aeration, aggregates breakdown, decrease in input and fractionation of vegetal residues and soil exposure that directly affects the quantity and activity of soil microorganisms and consequently the decomposition of SOM (BOT; BENITES, 2005). In general, studies on land use changes in these environments suggest that management has a greater influence on soil C stocks (POEPLAU; DON, 2013; MURTY *et al*., 2002).

Small changes in the total soil C can hardly be detected in the short term, mainly due to its high natural variability in the soil (ANDRADE; OLIVEIRA; CERRI, 2005). The quality of soil C, assessed through fractions of soil organic matter that are more sensitive to environmental changes, can be used as an indicator of changes in the dynamics of the organic compartment.

The C fractions used as indicators of changes in the quality of SOM include relatively labile organic and stable fractions that vary in their vulnerability to decomposition, including: labile carbon, fulvic acids, humic acids and humine.

The labile fractions of soil organic carbon serve as a source of energy readily available to soil organisms. The more stable fractions of organic carbon in the soil take longer to decompose (years, decades, centuries). This stable fraction includes organic matter in particles of finer size that is physically protected (mineral-protected clay or inserted in soil aggregates) or chemically persistent in the soil.

Quantification and continuous monitoring of changes in flows and stocks of total carbon and their fractions in the Tropical Dry Forest and Tropical Rainforest are essential to elucidate the effects of changes in land use on the functioning of ecosystems and to limit emissions of greenhouse gases. Thus, the aim of the present study was to quantify the stocks and quality of carbon in the soil in forest and agricultural ecosystems in dry and humid environments and to evaluate the effects of changes in land use in these reservoirs in these environments.

2 MATERIAL AND METHODS

2.1 Study area

The study was developed in four different types of forest and agricultural ecosystems, located in two environments originally occupied by the Dry Tropical Forest and Tropical Rainforest, located in the states of Pernambuco and Paraíba. The first refers to the area covered by the Caatinga dry tropical forest, where a Caatinga forest ecosystem and an agricultural area with cassava cultivation were selected, which are equivalent to the most common types of land use in the study region. The second environment relates to the domain area of the dense lowland tropical rainforest, where an Atlantic Forest ecosystem and an agricultural area with sugarcane cultivation were selected (Figure 1).

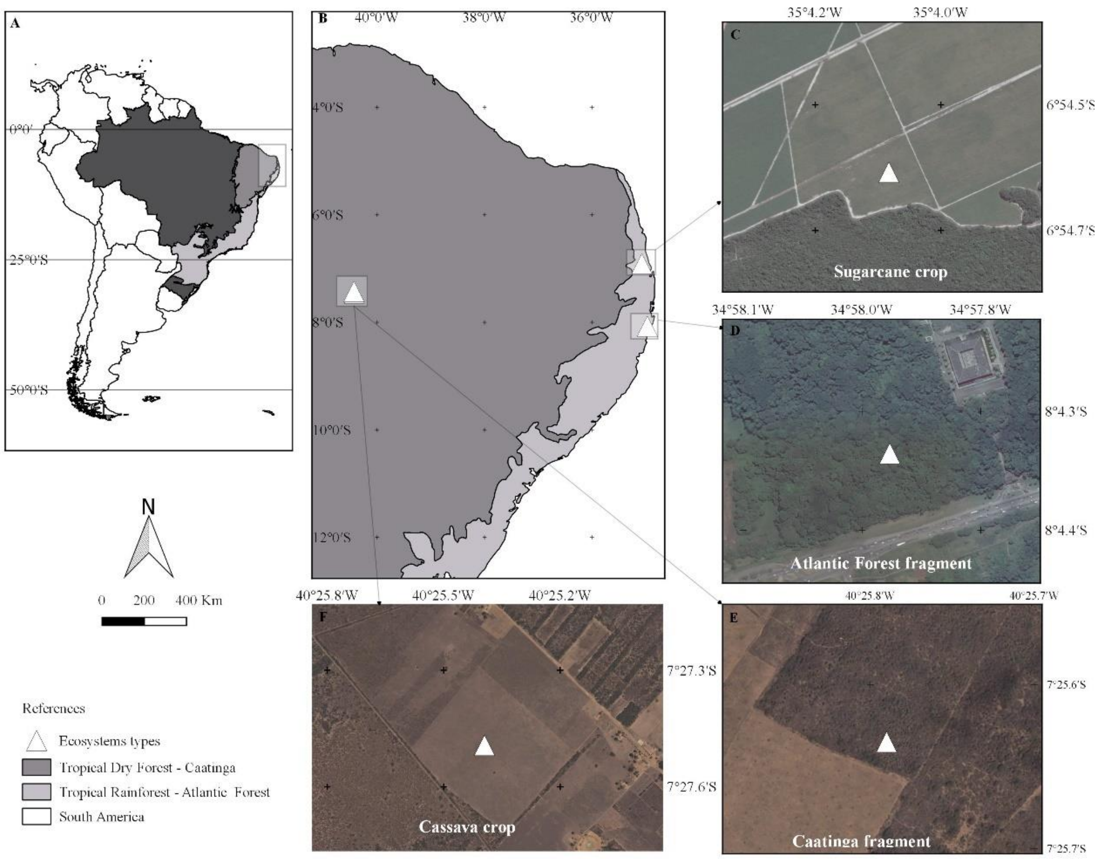

Figure 1 - Study sites location in Tropical Dry Forest and Tropical Rainforest, Northeast, Brazil.

The edaphoclimatic characterization and geographical location of the study areas are summarized in Table 1.

Table 1 – Study site location and characteristics in Tropical Dry Forest and Tropical Rainforest, Northeast, Brazil

Soil use	Tropical dry forest	Cassava	Tropical rainforest	Sugarcane
Location	Chapada do Araripe, Pernambuco	Chapada do Araripe, Pernambuco	Recife, Pernambuco	Rio Tinto, Paraíba
	(7°25'S - 40°26'W)	(7°25'S - 40°26'W)	(8°04'S - 34°57'W)	(6°54'S - 35°04'W)
Area size	~13 há	~31 ha	~28 ha	~12 ha
Altitude	838 m	828 m	38 m	76 m
Topography	Predominantly flat	Predominantly flat	Predominantly flat	Predominantly flat
Climate classification	BSh	BSh	Am	As
	Dry Semi-arid low latitude and altitude [a]	Dry Semi-arid low latitude and altitude [a]	Tropical monsoon [a]	Tropical with dry summer [a]
Precipitation	<700 mm ano^{-1} [b]	<700 mm ano^{-1} [b]	~1500 mm ano^{-1} [b]	~1500 mm ano^{-1} [c]
Temperature	27 °C[b]	27 °C [b]	25.8 °C [b]	26 °C [c]
Forest Domain	Tropical Dry Forest - Caatinga	-	Dense lowland tropica rainforest	-
Plant variety	-	Pernambucana	-	RB92579
Cultivation cycle	-	First cycle d	-	First cycle e
Absolute density	1294 ind ha^{-1}	6250 ind. ha^{-1}	970 ind ha^{-1}	20416 ind. ha^{-1}
Soil classification	Dystrophic Yellow Latosol (Oxisol) [f]	Dystrophic Yellow Latosol (Oxisol) [f]	Dystrophic Yellow Latosol (Oxisol) [f]	Dystrophic Yellow Argissol (Oxisol - Kandic) [f]

[a]Alvares *et al*. (2014); [b]APAC (2019); [c]AESA (2019) and Francisco and Santos (2017); [d]Agricultural exploration in the area began in 1995 with the removal of native vegetation. The cassava cutting cycle is 18 months. [e]Agricultural exploration has been occurring for at least 50 years with burning straw at harvest. The sugarcane cutting cycle is 12 months; [f] Santos *et al*. (2018) and Soil Survey Staff (2014)

2.2 Sampling

In the forest fragments, four central plots of the 20 plots of 10 m x 25 m (250 m^2) were selected, as used in a phytosociological survey by Santos (2018) (Figure 2), where four trenches with dimensions 1.0 m x 1.0 m x 1.0 m were open for collecting soil samples.

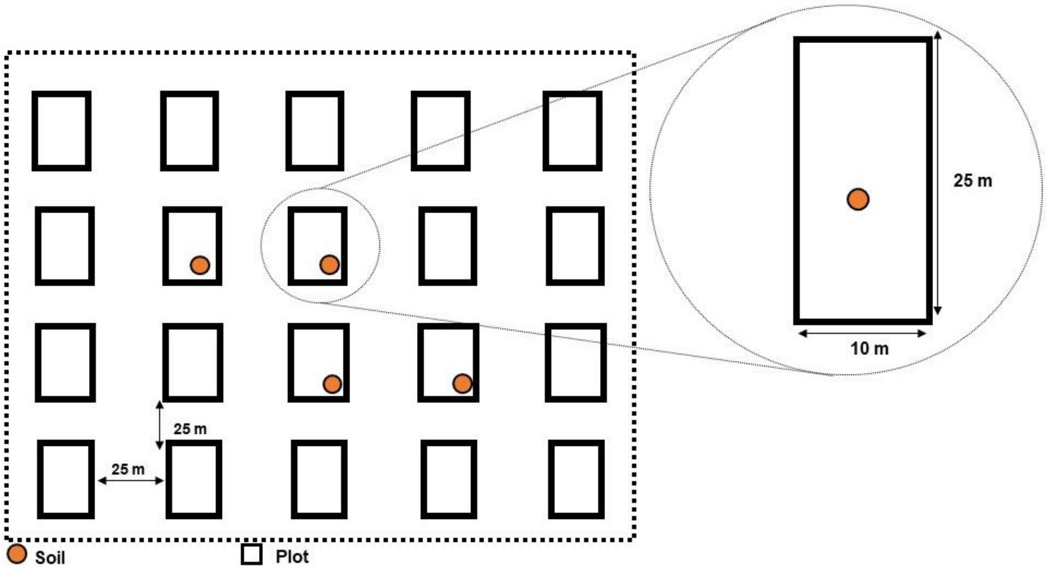

Figure 2 – Soil sampling design for carbon content determination in forest sites.

In agricultural ecosystems, a polygon with an area of 1.0 ha was designed, where four trenches were randomly opened with dimensions 1.0 m x 1.0 m and 1.0 m for collection of soil samples (Figure 3).

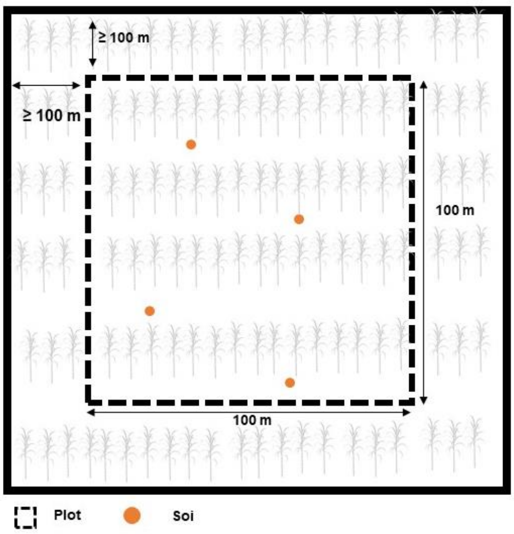

Figure 3 – Soil sampling design for carbon content determination in agricultural sites.

In each trench, approximately 500g of simple deformed soil samples were collected in the layers between 0.00 -| 0.05; 0.05 -| 0.10; 0.10 -| 0.20 m in March 2017 for determination of total organic carbon, carbon of humic substances, labile carbon and oxidizable fractions of carbon, with 4 repetitions per layer, totalling 12 samples per area.

2.3 Carbon content determinations

2.3.1 TOC

Deformed samples were air dried, ground and passed through a 2.00 mm mesh sieve to obtain the air-dried fine soil (ADFS). Analysis of the TOC content was carried out by dry combustion in a LECO equipment (model C-144) at the Biofix Laboratory at the Federal University of Paraná.

2.3.2 Carbon in humic substances

For chemical fractionation of the soil organic matter, a differential solubility technique was used (SWIFT, 1996), obtaining the fractions of fulvic acids (C-FA), humic acids (C-HA) and humine (C-HU). After separating the fractions, the organic carbon content of each fraction was estimated by wet oxidation with sulfuric acid by the method of Yeomans and Bremner (1988).

2.3.3 Fractions of oxidizable carbon

The levels of oxidizable carbon were obtained using different concentrations of H_2SO_4 according to the method adapted by Chan, Bowman and Oates (2001) for the separation of TOC into four oxidizable fractions: very labile carbon (F1), labile carbon (F2), less labile carbon (F3) and non-labile carbon (F4). The levels of organic carbon were quantified by wet oxidation with sulfuric acid in the presence of potassium dichromate without external heating, according to Yeomans and Bremner (1988).

Fractions of oxidizable carbon were estimated using 2.5, 5.0 and 10 mL of concentrated sulfuric acid resulting in three proportions of acid-aqueous solution: 0.25:1.0; 0.50:1.0 and 1.0:1.0; corresponding to 3, 6 and 9 mol L^{-1} H_2SO_4, respectively. The amount of organic C determined using the previous concentrations allowed the separation of oxidizable C in the four fractions of decreasing oxidability: fraction 1 (F1, oxidizable organic carbon under < 3 mol L^{-1} H_2SO_4); fraction

2 (F2, difference between organic carbon extracted in 6 and 3 mol L^{-1} H_2SO_4; fraction 3 (F3, difference between organic carbon extracted in 9 and 6 mol L^{-1} H_2SO_4); and fraction 4 (F4, organic carbon residual after reaction of oxidizable carbon and 9 mol L^{-1} H_2SO_4).

The relationship between the distribution of labile fractions and recalcitrant fractions (F1+F2)/(F3 + F4) was calculated.

2.3.4 Labile carbon

The content of carbon oxidizable by potassium permanganate was determined by oxidation with $KMnO_4$ 0.033 mol L^{-1} solution according to the method proposed by Blair *et al*. (1995) and adapted by Shang and Tiessen (1997).

The content of carbon oxidizable by potassium permanganate was considered as the labile carbon content (LC), while the non-labile carbon content (NLC) was calculated by the difference between the TOC content and the labile carbon content. The ratio between labile carbon and non-labile carbon (LC/NLC), the proportion of labile carbon and total organic carbon (LC/TOC) and non-labile carbon and total organic carbon (NLC/TOC) were calculated.

2.4 Carbon stocks

To determine the total soil carbon stock or soil carbon fractions in each layer, undisturbed samples were collected with volumetric rings with dimensions of 5.0 cm in diameter and 5.0 cm in height in four repetitions per depth. The TOC stock or soil carbon fractions in each layer was estimated using the total carbon content, and the carbon content of each fraction and the equivalent mass procedures described by Wendt and Hauser (2013), according to equation 1 and 2:

$$M_{soil_{(DL)}} = \frac{M_{sample_{(DL)}}}{\pi\left(\frac{D}{2}\right)^2} \; x \; 10000 \qquad (1)$$

In which:

$M_{soil(DL)}$ is the mass of soil in each layer (Mg ha^{-1});

$M_{sample(DL)}$ is dry mass of soil sampled in the field in each layer (g) and;

D is the diameter of the soil sampling ring (mm);

$$M_{OC_{(DL)}} = M_{soil_{(DL)}}\ x\ C_{OC_{(DL)}} \quad (2)$$

In which:

$M_{OC(DL)}$ is the carbon stock in each layer (kg ha^{-1})

$M_{soil(DL)}$ is the mass of soil in each layer (Mg ha^{-1});

$C_{OC(DL)}$ is the carbon content in each layer (g);

The TOC stock or soil carbon fractions (0-20 cm) was obtained by adding the stocks of each layer of soil. The correction of TOC stocks or of your fractions in agricultural areas was carried out by subtracting the estimated carbon stock error (M_{EECOT}) acquired by the increased in the soil density by the soil compaction in these areas. The M_{EECOT} in agricultural crops was calculated using equation 3, adapted from Wendt and Hauser (2013).

$$M_{EECOT} = (\rho_{agr} - \rho_{ref}) \times z \times C_{ref} \times 100 \quad (3)$$

In which:

M_{EECOT} is the correction of the carbon stock in each layer (kg ha^{-1})

ρ_{agr} is the density of the soil in the agricultural area (g cm^{-3});

ρ_{ref} is the density of the soil in the reference area (g cm^{-3});

z is the thickness of the soil layer (cm);

C_{ref} is the carbon content in each layer of the reference area (g kg^{-1});

Therefore, the corrected C stock will be: M_{ECOT} - M_{EECOT}. This procedure corrects the soil C stock when the change in land-use increases the soil density and consequently overestimates the C stock.

2.5 Carbon recovery rate

The TOC or C fractions recovery rate was calculated according to equation 4, adapted from De Oliveira Ferreira *et al*. (2018):

$$CR(\%) = \frac{ECOT_{agricultural}}{ECOT_{reference}} \times 100 \qquad (4)$$

In which:

CR = Carbon Recovery;

$ECOT_{agricultural}$ = Soil Carbon Stock in Sugarcane or Cassava (Mg ha^{-1});

$ECOT_{reference}$ = Soil Carbon Stock in native vegetation in Tropical Dry Forest or Tropical Rain Forest (Mg ha^{-1}).

2.6 Carbon accumulation/depletion rate

The C depletion/accumulation rate was calculated according to equation 5, adapted from Oliveira Bordonal *et al*. (2017):

$$DR = ECOT_{agricultural} - \frac{ECOT_{reference}}{crop\ time} \qquad (5)$$

In which:

DR = Carbon Depletion/Accumulation Rate;

$ECOT_{agricultural}$= Soil Carbon Stock in Sugarcane or Cassava (Mg ha^{-1});

$ECOT_{reference}$ = Soil Carbon Stock in native vegetation in Tropical Dry Forest or Tropical Rain Forest (Mg ha^{-1});

2.6 Statistical analysis

As assumptions required for analysis of variance (ANOVA), data were tested for normality and homoscedasticity using Shapiro-Wilk (SHAPIRO; WILK, 1965) and Levene (BROWN; FORSYTRE, 1974) tests, respectively (both at the 5% probability level).

Contents and stocks of total organic carbon, carbon of humic, fulvic and humine acid fractions; carbon from humic substances; carbon ratio of humic acid fraction and carbon of fulvic acid fraction and; carbon ratio of humic substances and total organic carbon were compared in each soil layer between land uses in the dry and humid environments by analysis of variance (ANOVA) using the F test at the 5% probability level.

Carbon contents of oxidizable carbon of each fraction, labile carbon and non-labile carbon were compared in each soil layer between the uses of the soil in the dry and humid environments through analysis of variance (ANOVA) using a F test at the level 5% probability.

The stocks of labile and non-labile carbon were compared in each soil layer between land uses in the dry and humid environments by analysis of variance (ANOVA) using a F test at the 5% probability level.

3 RESULTS AND DISCUSSION

3.1 Dry environment

3.1.1 Labile carbon and fractions of oxidizable carbon

The most labile fractions (C-F1 and C-F2) in the dry forest soil when together represent ~40, 62 and 48% of TOC in the 0-5 cm, 5-10 cm and 10-20 cm layers, respectively. In the soil under cassava crop, they represent 54, 86 and 57% of TOC in the 0-5 cm, 5-10 cm and 10-20 cm layers, respectively (Table 2). The soil under cassava crop showed less TOC and more labile C, however, this lability did not differ from the more labile fractions of the soil under dry forest, because the continuous supply of litter contributed to the accumulation of C of the most labile fractions.

In the dry forest, the less labile fractions (C-F3 and C-F4) together represent ~60, 38 and 52% of the TOC in the 0-5 cm, 5-10 cm and 10-20 cm layers, respectively. In the soil under cassava crop, they represent 46, 14 and 43% of TOC in layers 0-5 cm, 5-10 cm and 10-20 cm, respectively (Table 2). The substitution of dry forest for cassava cultivation favored the decrease of C levels of the most recalcitrant fractions, reducing carbon quality in the soil.

The land-use change from dry forest to cassava cultivation affected the recalcitrance of C. The C less or non-labile (C-F3 and C-F4) of the soil under forest was 43 and 68% higher than C less or non-labile soil under cassava cultivation in 0-5 cm and 5-10 cm layers, respectively (Table 2). This demonstrated greater stability of soil C in the forest compared to soil C under cassava cultivation. Therefore, the soil C under Caatinga showed labile fractions that did not differ from the soil C under cassava, but also showed non-labile C fractions, which allow greater sustainability to the ecosystem due to the stability of C.

The relationships between labile carbon and recalcitrant carbon (C-F1+C-F2)/(C-F3+C-F4) were higher in the soil under cassava cultivation (Table 2), indicating a predominance of labile carbon fractions to the detriment of more stable fractions compared to the dry forest. These results suggest that land-use change promoted a reduction in accumulation of more recalcitrant carbon, thus interfering with the quality of carbon stored in the soil.

Table 2 - Oxidizable carbon fractions, labile carbon and non-labile carbon in layers 0 - 5 cm, 5 - 10 cm and 10 - 20 cm in soils under tropical dry forest and cassava crop

Site	TOC	C-F1 + C-F2	C-F3 + C-F4	(C-F1+C-F2)/(C-F3+C-F4)	LC	NLC	LC/NLC	LC/TOC	NLC/TOC
	--------------g kg^{-1}------------				--------------g kg^{-1}------------				
------0 – 5 cm------									
TDF	23.42 ± 5.46	9.26 ± 4.16	14.15 ± 3.76 a	0.65	3.06 ± 0.81 b	15.92 ± 4.40 a	0.19 ± 0.06 a	0.13 ± 0.03 b	0.68 ± 0.03 a
MN	17.54 ± 2.31	9.53 ± 2.87	8.01 ± 2.29 b	1.19	6.70 ± 1.32 a	4.69 ± 0.92 b	1.43 ± 0.43 b	0.38 ± 0.03 a	0.27 ± 0.06 b
Average	20.48 ± 7.26	8.52 ± 4.47	11.08 ± 3.99		4.88 ± 1.90	10.31 ± 5.40	0.81 ± 0.52	0.26 ± 0.05	0.48 ± 0.08
F value	3.93^{ns}	1.29^{ns}	19.25*		22.23*	29.71*	35.50*	84.90*	15.80*
------5 – 10 cm------									
TDF	17.02 ± 1.94	10.61 ± 3.44	6.42 ± 2.21 a	1.65	3.96 ± 0.62 b	11.49 ± 0.24 a	0.34 ± 0.12 b	0.23 ± 0.06 b	0.68 ± 0.06
MN	15.07 ± 1.53	13.01 ± 4.11	2.06 ± 1.91 b	6.32	7.01 ± 0.91 a	10.78 ± 0.50 b	0.65 ± 0.11 a	0.47 ± 0.04 a	0.72 ± 0.03
Average	16.04 ± 3.03	11.81 ± 4.33	4.24 ± 2.35		5.48 ± 1.30	11.14 ± 0.61	0.50 ± 0.19	0.35 ± 0.09	0.70 ± 0.09
F value	2.47^{ns}	1.18^{ns}	10.87^{*}		32.96*	74.31***	14.18*	40.93***	0.94^{ns}
------10 – 20 cm------									
TDF	14.50 ±3.88	6.99 ± 2.51	7.51 ± 1.96	0.93	6.14 ± 1.92	9.97 ± 0.52	0.62 ± 0.17	0.42 ± 0.06 a	0.69 ± 0.05 a
MN	14.17 ±1.61	8.09 ± 5.02	6.08 ± 2.59	1.33	3.80 ± 0.51	9.99 ± 0.31	0.38 ± 0.28	0.27 ± 0.04 b	0.38 ± 0.03 b
Average	14.33 ± 5.14	7.54 ± 5.33	6.80 ± 2.88		4.97 ± 2.24	0.98 ± 0.80	0.50 ± 0.31	0.34 ± 0.09	0.54 ± 0.14
F value	0.03^{ns}	0.89^{ns}	1.26^{ns}		5.82^{ns}	0.01^{ns}	0.15^{ns}	18.27**	10.79*

TDF: Tropical Dry Forest; MN: Cassava crop; C-F1: Very labile carbon; C-F2: moderately labile carbon; C-F3: less labile carbon; C-F4: Carbon slightly labile; LC: labile carbon; NLC: Non-labile carbon; (C-F1 + C-F2) / (C-F3 + C-F4): Fractions easily oxidizable / fractions more resistant to oxidation. Means represented by the same letter per soil layer between areas do not differ by the F test at 5% significance. *, ** and *** significant at 5, 1 and 0.1% significance. ns not significant.

The ratio of labile carbon and total organic carbon (LC/TOC) was higher in the area cultivated with cassava compared to the forest in the surface layers (Table 2). The proportion of recalcitrant carbon (NLC /TOC) was higher in the forest in 0-5 cm and 10-20 cm layers and it did not differ of the soil under cassava cultivation in 5-10 cm layer (Table 2).

The carbon in the more recalcitrant fractions is more stabilized and decomposes more slowly. Similar results are found in studies of carbon fractionation in disturbed area in tropical dry forest (CAMPANHA *et al*., 2009; MARTINS *et al*., 2015).

When assessing the C lability through the stock, considering the equivalent soil mass corrected by the soil density, it was observed that the land-use change altered the accumulated stock of labile C up to 10 cm in soil depth (Table 3) , favoring the storage of more labile C in the soil (Table 3). The labile carbon was a sensitive indicator to the land-use change. The accumulated labile carbon was reduced by 52 and 48%, respectively in the 0-5 cm and 0-10 cm layers (Table 3), when the dry forest was substituted by the cassava cultivation. The produced litter in the dry forest interfered with the C lability only in the very superficial layer because at 20 cm of soil depth, the accumulated labile C was no longer different from the soil under cassava cultivation.

Table 3 – Accumulated stocks of labile and non-labile carbon up to 20 cm deep in soils under tropical dry tropical forest and cassava crop

Soil depth	TOC	Soil density	Soil mass	LC	NLC
(cm)	-----Mg ha^{-1}----	---g cm^{-3}---	---Mg ha^{-1}---	-----------------Mg ha^{-1}-----------------	
			Tropical Dry Forest		
0 – 5	14.69 ± 3.48	1.25 ± 0.09	627.35 ± 46.74	4.00 ± 0.56	9.94 ± 2.48
5 - 10	25.66 ± 3.49	1.29 ± 0.07	644.47 ± 37.85	8.58 ± 0.94	17.30 ± 3.22
10 – 20	45.10 ± 6.31	1.34 ± 0.03	1340.72 ± 33.41	12.76 ± 2.61	30.17 ± 10.28
			Cassava crop		
0 – 5	9.15 ± 1.17	1.42 ± 0.03	634.99 ± 7.06	1.93 ± 0.78	2.96 ± 0.60
5 - 10	18.80 ± 0.75	1.34 ± 0.01	668.73 ± 4.80	4.49 ± 0.67	3.39 ± 0.79
10 – 20	37.61 ± 2.20	1.60 ± 0.03	1593.20 ± 26.80	13.03 ± 1.39	16.69 ± 5.85

TOC: Total organic carbon; LC: labile carbon; NLC: Non-labile carbon.

The forest-agriculture conversion reduced the stock of non-labile carbon by ~70% in the surface layer (Table 3). These results are related to the low supply of organic residues in the agricultural environment that reduces the supply of organic matter readily available for degradation by soil microbiota.

Revolving of the soil by harrowing promotes soil aeration and the breakdown of aggregates, increasing the oxidation of SOM and the degradation of more recalcitrant compounds that were physically and chemically protected. Reducing the quality of C stored in the soil by decreasing the accumulation of less labile carbon fractions in the soil promoted by land-use change has implications for long-term carbon sequestration.

The largest stocks of labile carbon in the forest are mainly related to the fact that labile carbon is formed from different compartments of macrorganic matter, including freshly deposited waste and roots, C of microbial biomass, non-humic substances in unstabilized forms (SILVA; MENDONÇA, 2013).

Labile carbon is found in water-soluble compounds such as amino acids and sugars that are readily decomposable by microbial activity (BRADY; WEIL, 2013). This carbon returns to the atmosphere quickly, since it decomposes relatively fast (days to years) in tropical forests (SILVA; MENDONÇA, 2007).

Non-labile carbon is associated with more recalcitrant and stabilized compounds, taking longer time to decompose. For this reason, non-labile carbon is an important carbon reservoir in the soil and any change in that storage has effects on long-term carbon storage.

3.1.2 Total carbon and carbon from humic soil fractions

The land-use change changed the total organic carbon (TOC) content in the 0 - 5 cm and 5 - 10 cm layers in the dry environment (Table 4). Compared with forest ecosystems, agricultural cultivation in the soil promoted a decrease in TOC in these layers. There was a 25% and 11% reduction in TOC under cassava cultivation, respectively in the 0 - 5 cm and 5 - 10 cm layers, compared to the adjacent forest ecosystem (Table 4). In the 10 - 20 cm layer, there was no difference in TOC levels between land uses. The distribution of TOC content in the soil profile in the cultivation area demonstrated a pattern like that observed in dry forest, with the highest concentrations of TOC in the superficial layers (Table 4).

Table 4 - Total organic carbon and humic fractions of organic matter in 0 - 5 cm, 5 - 10 cm and 10 - 20 cm layers in soils under tropical dry forest and cassava crop

Sites	TOC	C-HA	C-FA	C-HU	C-HS	C-HA/C-FA	(C-HA+C-FA)/TOC	C-HS/TOC
				g kg^{-1}				
				0 – 5 cm				
TDF	23.42 ± 5.47 a	3.37 ± 0.25	5.05 ± 0.40	5.41 ± 0.20 a	13.83 ± 2.16 a	0.68 ± 0.19	0.37 ± 0.14	0.59 ± 0.21
MN	17.55 ± 2.31 b	1.88 ± 0.46	3.13 ± 1.47	2.83 ± 1.72 b	7.84 ± 2.17 b	0.60 ± 0.13	0.26 ± 0.06	0.45 ± 0.20
Average	18.14 ± 6.75	2.62 ± 0.55	3.18 ± 1.19	4.12 ± 1.71	10.84 ± 2.61	0.64 ± 0.31	0.31 ± 0.23	0.52 ± 0.38
F value	8.75*	1.72^{ns}	2.33^{ns}	66.11*	9.49*	0.002^{ns}	1.49^{ns}	4.59^{ns}
				5 – 10 cm				
TDF	17.02 ± 1.94 a	1.80 ± 0.62	1.78 ± 0.56	2.89 ± 0.85	6.47 ± 0.06 b	1.01 ± 0.21 a	0.21 ± 0.05 b	0.38 ± 0.04 b
MN	15.07 ± 1.53 b	1.22 ± 0.96	3.33 ± 1.85	4.07 ± 2.16	8.62 ± 0.15 a	0.37 ± 0.15 b	0.30 ± 0.15 a	0.57 ± 0.06 a
Average	15.16 ± 4.47	1.51 ± 0.69	2.55 ± 2.56	3.48 ± 1.66	7.54 ± 0.90	0.69 ± 0.32	0.26 ± 0.20	0.48 ± 0.38
F value	4.10*	1.03^{ns}	2.59^{ns}	1.03^{ns}	7.04*	4.55*	0.76*	23.39*
				10 – 20 cm				
TDF	14.50 ± 3.88	1.10 ± 0.26 a	2.71 ± 1.26	2.97 ± 0.15	6.78 ± 0.23	0.41 ± 0.19	0.26 ± 0.05	0.47 ± 0.17
MN	14.17 ± 1.61	0.58 ± 0.32 b	2.98 ± 1.13	3.49 ± 0.21	7.05 ± 0.19	0.19 ± 0.18	0.26 ± 0.07	0.50 ± 0.16
Average	13.01 ± 5.96	0.83 ± 0.51	3.08 ± 1.81	3.23 ± 0.31	6.91 ± 0.54	0.30 ± 0.32	0.26 ± 0.12	0.49 ± 0.55
F value	2.18^{ns}	6.14*	0.10^{ns}	2.63^{ns}	0.03^{ns}	2.75^{ns}	0.06^{ns}	0.05^{ns}

TDF: Tropical Dry forest; MN: Cassava crop; TOC: Total organic carbon; C-HA: Carbon of the humic acid fraction; C-FA: Carbon of the fulvic acid fraction; C-HU: Carbon from the humine fraction; C-HS: Carbon from humic substances; C-HA / C-FA: Carbon ratio of the humic acids and fulvic acids fraction; C-HS / TOC: Carbon ratio of humic substances and total organic carbon. Means represented by the same letter in the column per soil layer between the areas do not differ by the F test at 5% probability. * Significant at 5% significance by the F test. ^{Ns} Not significant.

The entry of carbon into the soil is mainly related to the contribution and decomposition of plant residues. The litterfall is one of the main pathways of the carbon flow from plant biomass to the soil. The higher values observed in the dry forest when compared to agricultural cultivation may be related to the continuous amount of litter deposited on the forest floor and the higher concentration of roots on the surface (TORRES *et al*., 2014), to the detriment of removing crop residues in the cassava areas. The residues from the cassava harvest are used to feed goats, a common practice in the region.

In addition, the change in soil temperature and humidity in revolved soils without adopting conservation practices and the lower input of plant residues makes the conditions favourable for the decline of soil organic matter (LOSS *et al*., 2009).

The C-HA fractions differed between environments only in the 10 - 20 cm layer, with higher C-HA levels in the forest. Soil under cassava cultivation obtained C-HA content in the 10 - 20 cm layer 47% lower than that of the dry forest. In general, C-HA levels in superficial layers tend to be higher in the dry forest (Table 4).

The maintenance of soil cover favours the polymerization of humic substances, which results in higher levels of C-HA (GUARESCHI *et al*., 2013). In addition, the land-use change favoured the reduction of the supply of vegetable residues to the soil, favouring the lower accumulation of C-HA in the agricultural area (CAMPOS *et al*., 2013).

No significant differences were found for C-FA levels between the land uses. However, it is observed that agricultural environments tend to exhibit higher C-FA levels in the subsurface layers compared to the forest ecosystem (Table 4). In the superficial layer, the dry forest exhibited a higher C-FA content (Table 4).

In the superficial layer, there is greater activity of the soil biota acting on the degradation of organic compounds, because this layer is directly linked to accumulation of litter and higher concentration of roots. Higher soil microbial activity in this layer in the forest favours the highest concentration of fulvic acids. In the subsurface layers, a possible explanation for the lower levels of C-FA in cassava is related to soil revolving, which favours microbial activity and decomposition of the SOM. The fulvic acid fraction has high mobility in the soil profile compared to other fractions. For this reason, an increase in this fraction is observed in the forest in the 10-20 cm layer compared to the 5-10 cm layer (Table 4).

C-HU contents were, in general, higher than C-FA and C-HA contents (Table 4). This is related to the greater stability of this fraction, that has a higher degree of connection with colloids in the complex form of the soil and the size of the molecules, making them more resistant to degradation (ROSSI *et al*., 2011, SANTOS *et al*., 2013).

In contrast, although C-HU represents most part of humic substances, low levels of humine (< 27%) were observed in the different land uses, since the C-HU fraction represented on average 23, 17 and 20% of the TOC at depths 0 - 5 cm, 5 - 10 cm and 10 - 20 cm, respectively in the dry forest. In the soil under cassava cultivation, this fraction represented 16, 27 and 25% TOC at depths of 0 - 5 cm, 5 - 10 cm and 10 - 20 cm, respectively in cassava (Table 4). According to Sousa *et al*. (2012), this low level of humification is typical of semiarid regions, since water restriction reduces microbial activity.

The dry forest had a higher C-HU content in the surface layer (Table 4). The humine fraction is more stable than the FA and HA fractions because it has a higher molecular mass, being more difficult to mineralize, translocate to the subsurface layers or polymerize in depth, increasing its contents on the surface (VALLADARES *et al*., 2011).

The land-use change altered the carbon content of humic substances in the 0 - 5 cm and 5 - 10 cm layers (Table 4). Higher carbon content in humic substances was found in the TDF in the 0 - 5 cm layer and a reduction of 51% of C-HS in the subsurface layer (Table 4). In the 5 - 10 cm layer a higher C-HS content was found in the soil under cassava cultivation (Table 4). There was no significant difference for the C-HA/C-FA ratio between land uses in layers 0-5 cm and 10-20 cm. The C-HA/C-FA ratio was, in general, less than 1.0 (Table 4).

The C-HA/C-FA ratio demonstrate the dynamics of formation of fulvic and humic acids, indicating the quality of the humus, with smaller values indicating predominance of fulvic acid fractions, that is, soils with evolved SOM decomposition (CUNHA *et al*., 2005; SANTANA *et al*., 2011). Ratios above 1.0 are explained by soil and climate conditions, where polymerization and condensation processes are favourable (VALLADARES *et al*., 2007).

The C-HA/C-FA ratio was greater than 1.0 in the 5-10 cm layer in the forest, different from cassava (Table 4), demonstrating the predominance of humic acids and the greater stability of SOM in the forest. Higher C-HA/C-FA ratios indicate higher carbon stability, which favours carbon sequestration. In this sense, the higher values of the C-HA/C-FA ratio found in the dry forest indicate that the land-use change reduced the stability of the C stored in the soil in the form of humic acids. In the 0-5 cm and 5-10 cm layer, the average C-HA/C-FA ratio was higher than 0.66, which according to Santos *et al*. (2013) is an average value for Caatinga soils.

The C-HA+C-FA/TOC ratio showed a significant difference between land uses only in the 5-10 cm layer (Table 4). There was no significant difference for the C-HS/TOC ratio between soil uses in layers 0 - 5 cm and 10 - 20 cm, with the highest value found in cassava soil (Table 4). The C-HS/TOC ratio indicates the state of SOM humification. According to Labrador-Moreno (1996), this index varies between 65 and 92%. In this study, all values for this ratio were less than 65% (35 - 61%), indicating a low degree of humification, independent of land use. In dry environments, water restriction is so intense that the decomposition state of MOS is little affected by the land-use change. Even in forest areas, humification is reduced by the lack of humidity and high temperatures, which are unpleasant to microbial activity.

The stock of TOC accumulated in the 20 cm of soil varied between ~ 37.61 and 45.10 Mg ha^{-1} between the land uses (Table 5). These results are related to reduction in organic inputs in the agricultural environment, since crop residues are not incorporated into the soil in this area, reducing the supply of organic material for decomposition by soil biota and consequently the carbon stored in the soil, especially in the surface layer, where TOC was reduced by 25% (Table 5).

On the other hand, when comparing land uses in relation to the TOC stock in the first 10 cm of soil, there is a ~27% reduction in cassava soil cultivation (Table 5). These results indicate that changes in land use negatively impacts the TOC stock, especially in the superficial layers. This is related to a decrease in the amount of waste and to soil revolving, which increases the oxidation of SOM in agricultural soils, reducing TOC stock.

Accumulated carbon stocks of the fulvic acid fractions did not differentiate between land uses in the evaluated layers (Table 5). In contrast, the carbon stock in the humic acid fraction accumulated in the first 20 cm of soil was twice as high in soil under forest (Table 5). The carbon stored as humine was affected by the land-use change, representing a 60% reduction in forest/agriculture conversion. These results demonstrate that the humic acid and humine fractions were the most sensitive to the land-use change. The humine fraction is characterized by high development and resistance to microbial degradation, which is intensely linked to soil minerals (SPARKS, 2001), thus promoting long-term carbon storage.

Carbon stored in the most stable fractions remains stored in the soil for a longer time since its decomposition takes longer (years, decades, centuries). Thus, changes in carbon stocks of the most stable fractions are not beneficial for soil carbon storage.

Considering the accumulated carbon stock of humic substances, there were significant decreases in the change of forest to cassava cultivation in the 0-5 cm and 5-10 cm layers (Table 5), representing reductions of 65 and 33% of carbon, respectively.

Table 5 - Accumulated stocks of total carbon, carbon of fulvic acids, humic acids, humine and humic substances up to 20 cm deep in soils under Tropical Dry Forest and cassava crop

Soil depth	Soil density	Soil mass	TOC	C-FA	C-HA	C-HU	C-HS
(cm)	---g cm^{-3}---	----Mg ha^{-1}---	--Mg ha^{-1}--				
			Tropical Dry Forest				
0 – 5	1.25 ±0.09 b	627.35 ±46.74	14.69 ± 3.48	3.19 ± 1.51	2.15 ± 1.48	3.39 ± 0.16 a	8.73 ± 2.91 a
5 - 10	1.29 ±0.07	644.47 ±37.85	25.66 ± 3.49 a	4.35 ± 1.35	3.32 ± 1.51	5.24 ± 0.50	12.90 ± 2.78 a
10 – 20	1.34 ±0.03 b	1340.72 ±33.41	45.10 ±6.31	7.97 ± 1.45	4.79 ± 1.48 a	9.19 ± 2.17	21.95 ± 3.68
			Cassava crop				
0 – 5	1.42 ±0.03 a	634.99 ±7.06	9.15 ±1.17	1.55 ± 0.79	0.90 ± 0.09	1.34 ± 0.40 b	3.07 ± 1.59 b
5 - 10	1.34 ±0.01	668.73 ±4.80	18.80 ±0.75 b	3.74 ± 1.07	1.69 ± 0.67	3.98 ± 1.69	8.68 ± 2.00 b
10 – 20	1.60 ±0.03 a	1593.20 ±26.80	37.61 ±2.20	7.78 ± 1.33	2.33 ± 0.90 b	8.76 ± 2.52	18.14 ± 1.46

TOC: Total organic carbon; C-HA: Carbon of the humic acid fraction; C-FA: Carbon of the fulvic acid fraction; C-HU: Carbon from the humine fraction; C-HS: Carbon from humic substances; C-HA / C-FA: Carbon ratio of the humic acids and fulvic acids fraction; C-HS / TOC: Carbon ratio of humic substances and total organic carbon. Means represented by the same letter in the column per soil layer between the areas do not differ by the F test at 5% significance.

In general, a predominance of humine fraction was found compared to other humic fractions Table 5). These results corroborate the values found by Santos *et al*. (2019) in a study on fractions of soil organic carbon and humic substances in different land uses in Caatinga in Pernambuco.

The proportions of carbon in humic substances fractions followed the order: humic acids (C-HA) < fulvic acids (C-FA) < humine (C-HU). High values found for the C-HU fraction may be related to their larger molecules size and its greater stability when compared to the other fractions (FONTANA *et al*., 2006).

Due to its greater resistance to degradation and a higher proportion of stored carbon when compared to other humic fractions, humine is the most important carbon reservoir in the soil. Any change in carbon stored in this fraction caused by the land-use change will negatively impact the carbon sequestration by the soil in the ecosystem.

Most studies about changes in carbon fractions through land use change in forest areas indicate a reduction in carbon stocks of soil humic substances in agricultural crops (CAMPANHA *et al*., 2009; MARINHO *et al*., 2016; SALES *et al*., 2017). As these studies report, this is due to reduction in carbon input by biomass through agricultural harvest and to greater carbon losses due to fragmentation of aggregates, oxidation of carbon by soil preparation (harrowing and ploughing), waste burning, water erosion and pasture (ISLAM; WEIL, 2000). However, the type of management can influence the direction and magnitude of changes in these stocks, and can often favour the increase of total carbon in the soil or of carbon fractions, especially in the superficial layers of the soil (BARRETO *et al*., 2008; AMARAL *et al*., 2015; OLIVEIRA FILHO; PEREIRA; AQUINO, 2017).

In a dry Caatinga forest, Marinho *et al*. (2016) observed higher carbon losses in the most recalcitrant fractions of humic substances in areas of conventional crops compared to the native vegetation of Caatinga. Similar results were found by Sales *et al*. (2017) for humic substances, in which the C-FA and C-HU of soils under different cultivation systems were lower than those in the soil under Caatinga.

On the other hand, Silva (2012) found that the use of different organic compounds increases the stock of the humine fraction at depth 0-5 cm, when compared to the caatinga reference area. Amaral *et al*. (2015) observed that the soil under mango cultivation in the semiarid region showed higher C stocks in the fractions of fulvic acids, humic acids and humines and in humic substances, when compared to the soil under native Caatinga in the 0-10 cm deep layer. These authors explained the results found due to the greater supply of waste in mango plantations and to irrigation, which favours microbial activity. Corroborating with these authors, Ferreira (2014) found that agricultural use of the soil provided greater HS formation than in soil under native forest, mainly in grape and corn cultivation systems, where more than 50% of C was in the form of HS. This is due to the organic fertilizer used. According to the author, conversion of semiarid soils into agricultural use will alter carbon distribution among humic fractions, mainly favouring the dynamics of humic acid formation, which, due to their higher carbon content, suggest greater potential for carbon accumulation in the soil.

Martins *et al*. (2015) observed that forest areas in the Caatinga used as a reference had low C content in the different carbon fractions. Although humic substances are more stable under changes resulting from handling operations, non-humic substances (also called light fraction) accumulated, probably due to recalcitrant compounds in the source material of the applied organic compounds.

3.2 Humid environment

3.2.1 Labile carbon and fractions of oxidizable carbon

The uses of the soil in the humid environment showed significant differences for less labile C oxidizable fractions (C-F3 + C-F4) (Table 6). The soil under tropical rainforest (Atlantic forest) showed higher contents of the high recalcitrance fractions compared to the sugarcane cultivation (Table 6). The most labile fractions (C-F1 and C-F2) did not differ between different land uses, by this method of assessing the lability of C, despite the higher values of labile C presented by the soil under forest. The continuous deposition and accumulation of plant biomass residues in the soil under forest favored the highest C concentrations of the most labile fractions, increasing the supply of C readily available for degradation by soil biota.

The more labile fractions C-F1 and C-F2 together represent ~48, 46 and 41% of TOC in layers 0-5 cm, 5-10 cm and 10-20 cm, respectively. In sugarcane, they represent 57, 50 and 64% of TOC in the 0-5 cm, 5-10 cm and 10-20 cm layers, respectively (Table 6). The soil under sugarcane cultivation showed less C, but for the most part it was in labile form. Sugarcane renews most of its root system between crops, favoring the continuous supply of C in the soil.

The less labile fractions (C-F3 and C-F4) together represent ~52, 54 and 59% of the TOC in the 0-5 cm, 5-10 cm and 10-20 cm layers, respectively. In sugarcane, on the other hand, they reach 43, 50 and 36% of TOC in layers 0-5 cm, 5-10 cm and 10-20 cm, respectively (Table 6).

Table 6 – Oxidizable carbon fractions, labile carbon and non-labile carbon in layers 0 - 5 cm, 5 - 10 cm and 10 - 20 cm in soils under tropical rain forest and sugarcane crop

Site	TOC	C-F1 + C-F2	C-F3 + C-F4	(C-F1+C-F2)/(C-F3+C-F4)	LC	NLC	LC/NLC	LC/TOC	NLC/TOC
	----------g kg^{-1}----------				----------g kg^{-1}----------				
				0 – 5 cm					
TRF	19.58 ± 2.07 a	9.47 ± 4.99	10.11 ± 1.21 a	0.94	2.59 ± 0.50 b	12.52 ± 1.91 a	0.21 ± 0.03 b	0.13 ± 0.02 b	0.64 ± 0.03 a
CA	12.01 ± 1.42 b	6.84 ± 1.90	5.17 ± 1.09 b	1.32	3.56 ± 0.90 a	4.14 ± 0.32 b	0.86 ± 0.17 a	0.30 ± 0.03 a	0.34 ± 0.04 b
Average	15.79 ± 3.06	8.16 ± 6.89	7.64 ± 1.33		3.08 ± 0.90	8.33 ± 2.33	0.54 ± 0.21	0.22 ± 0.03	0.49 ± 0.06
F value	36.46^{**}	1.21^{ns}	16.21^{*}		6.64^{*}	76.39^{*}	59.86^{*}	47.10^{*}	51.56^{*}
				5 – 10 cm					
TRF	16.38 ± 3.32	7.51 ± 1.77	8.87 ± 1.58	0.85	2.38 ± 0.31 b	13.68 ± 3.20 a	0.17 ± 0.03 b	0.15 ± 0.03 b	0.84 ± 0.03 a
CA	12.16 ± 0.97	6.02 ± 1.81	6.14 ± 1.87	0.98	3.59 ± 0.40 a	4.40 ± 0.71 b	0.82 ± 0.20 a	0.30 ± 0.07 a	0.36 ± 0.06 b
Average	14.27 ± 4.23	6.77 ± 1.99	7.51 ± 1.99		2.99 ± 0.60	9.04 ± 2.52	0.50 ± 0.25	0.23 ± 0.09	0.60 ± 0.08
F value	5.95^{ns}	0.98^{ns}	0.89^{ns}		21.16^{*}	30.10^{*}	40.58^{*}	49.16^{*}	94.10^{*}
				10 – 20 cm					
TRF	13.45 ± 3.33	5.48 ± 1.40	7.97 ± 1.30 a	0.69	1.52 ± 0.41	10.70 ± 2.51 a	0.14 ± 0.01 b	0.11 ± 0.01 b	0.80 ± 0.02 a
CA	9.94 ± 1.91	6.33 ± 0.91	3.61 ± 0.58 b	1.75	1.75 ± 0.52	3.90 ± 0.90 b	0.45 ± 0.16 a	0.18 ± 0.04 a	0.39 ± 0.05 b
Average	11.69 ± 4.69	5.91 ± 1.89	5.79 ± 1.87		1.64 ± 0.83	7.30 ± 0.33	0.30 ± 0.20	0.15 ± 0.05	0.60 ± 0.06
F value	3.35^{ns}	0.21^{ns}	15.41^{*}		0.42^{ns}	26.04^{*}	15.99^{*}	9.14^{*}	83.20^{*}

TRF: Tropical Rain Forest; CA: sugarcane crop; C-F1: Very labile carbon; C-F2: moderately labile carbon; C-F3: less labile carbon; C-F4: Carbon slightly labile; LC: labile carbon; NLC: Non-labile carbon; (C-F1 + C-F2) / (C-F3 + C-F4): Fractions easily oxidizable / fractions more resistant to oxidation. Means represented by the same letter per soil layer between areas do not differ by the F test at 5% probability. *, ** and *** significant at 5, 1 and 0.1% probability. ^{ns} not significant.

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The substitution of the rainforest for sugarcane cultivation favored the decrease of the levels of C of the most recalcitrant fractions, reducing the soil carbon quality. The land-use change in the humid environment has altered the quality of carbon especially in the surface layer, promoting a reduction in the accumulation of compounds with more recalcitrant C. According to Cerri (1986), with a replacement of a natural ecosystem by a cultivation system with intensive management such as sugarcane, the C stock is substantially reduced, mainly by reducing the supply of organic material in the soil.

When oxidizable C was evaluated by the potassium permanganate method, the labile carbon was higher in the soil under sugarcane cultivation in the surface layers (0-5 cm and 5-10 cm) (Table 6), ratifying that the lower soil TOC contents in sugarcane was in a condition of greater lability. Even the continuous litterfall deposition that contributes to the renewal of the C of compounds more easily degraded by soil biota in the soil under forest, has not overcome the continuous renewal of the root system of sugarcane.

On the other hand, the forest-agriculture conversion had effects on the non-labile C content in all soil layers. The non-labile carbon was on average 66% higher in the soil under forest (Table 6), demonstrating greater carbon stability in the forest compared to agricultural cultivation.

The proportions of labile C and recalcitrant non-labile C showed, on average, 46% of the soil carbon content in the forest is readily available for degradation by soil microorganisms, while in sugarcane is 56%. These results have implications for carbon sequestration in the humid environment, since a higher proportion of labile carbon changes the amounts of C stored in long term scales. The non-labile C represented between 64 and 84% of the TOC in the soil under forest, showing that the conservation of these environments is very important in the storage of soil C.

The stocks of labile carbon differed between soil uses up to 10 cm soil deep (Table 7), showing that sugarcane cultivation stored more labile C in the superficial layers. In the humid forest, favorable conditions for microorganism's performance with the continuous supply of fresh C, humidity and temperature probably promotes faster consumption of labile carbon from the mineral surface layer of the soil. On the other hand, the land-use change reduced the stocks of non-labile C in the soil cultivated with sugarcane. The reduction in the C quality stored in the soil by decreasing the accumulation of less labile fractions of C in the soil promoted by the land-use change has implications for long-term C sequestration. The forest-agriculture conversion in the humid environment reduced the non-labile carbon stock by ~ 82% considering the first 20 cm of soil (Table 7).

Table 7 – Accumulated stocks of labile and non-labile carbon up to 20 cm deep in soils under tropical rain forest and sugarcane crop

Soil depth (cm)	TOC	Soil density ---g cm^{-3}---	Soil mass ---Mg ha^{-1}---	LC	NLC
				-----------------Mg ha^{-1}-----------------	
			Tropical Rainforest		
0 – 5 cm	13.85 ± 1.40	1.27 ±0.01 b	707.86 ±15.54	1.83 ± 0.31 b	8.84 ± 1.17 a
0 - 10 cm	24.31 ± 3.27	1.28 ±0.02 b	638.60 ± 1.71	3.36 ± 0.46 b	17.38 ± 3.10 a
0 – 20 cm	44.34 ± 8.16	1.49 ±0.01 b	1488.97 ± 1.18	5.63 ± 1.07	33.31 ± 6.68 a
			Sugarcane crop		
0 – 5 cm	7.27 ± 0.95	1.60 ±0.01 a	845.96 ±1.15	2.59 ± 0.48 a	1.44 ± 0.19 b
0 - 10 cm	14.16 ± 1.33	1.69 ±0.01 a	842.48 ± 0.65	5.12 ± 0.69 a	2.40 ± 1.01 b
0 – 20 cm	27.83 ± 3.38	1.79 ±0.03 a	1782.96 ± 8.91	7.78 ± 1.54	6.15 ± 2.06 b

TOC: Total organic carbon; LC: labile carbon; NLC: Non-labile carbon. Means represented by the same letter per layer of soil between the areas do not differ by the F test at 5% probability.

3.2.2 Total carbon and carbon from humic soil fractions

Changes in land use reduced the TOC content of the soil in the first 5 cm, representing a ~39% decrease when converting to sugarcane (Table 8). At the other depths, no significant differences were found for the TOC content between land uses. However, the rainforest showed more TOC compared to the agricultural area (Table 8). This result demonstrates that the topsoil is the most altered by the land-use change in this environment.

The conversion of rainforest to sugarcane affects the input of carbon through litterfall in the soil, since cultivation of sugar cane is carried out by burning waste before harvest, which has an impact on carbon storage, especially in the topsoil. Decrease in soil cover has a direct impact on the maintenance of soil temperature and humidity, essential factors for microbial activity. In addition, fire decreases microbial activity.

On the other hand, no significant differences were found between the levels of TOC in the 5-10 cm and 10-20 cm layers (Table 8). Sugarcane through its root system may have provided a large amount of C in the subsurface layers.

The carbon content of the humic acid fraction was not influenced by the land-use change in the first 10 cm of the soil (Table 8). However, in the 10-20 cm layer, a 50% increase in the carbon content in this fraction was observed in sugarcane (Table 8).

Carbon content in the fulvic acid fraction did not change with land-use change regardless of the evaluated soil layer (Table 8). However, higher values of this fraction were found in the sugarcane area, especially in the first 10 cm of soil.

Table 8 - Total organic carbon and humic fractions of organic matter in layers 0 - 5 cm, 5 - 10 cm and 10 - 20 cm in soils under tropical rainforest and sugarcane crop

Site	TOC	C-HA	C-FA	C-HU	C-HS	C-HA/C-FA	(C-HA+C-FA)/TOC	C-HS/TOC
				g kg^{-1}				
				0 – 5 cm				
TRF	19.58 ± 2.07 a	1.12 ± 0.46	1.33 ± 0.47	3.40 ± 0.60	5.85 ± 2.03	0.84 ± 0.09	0.13 ± 0.05 b	0.30 ± 0.13 b
CA	12.01 ± 1.42 b	2.02 ± 0.68	2.64 ± 0.57	4.41 ± 0.82	9.07 ± 1.34	0.77 ± 0.21	0.39 ± 0.09 a	0.76 ± 0.18 a
Average	15.79 ± 3.06	1.57 ± 1.00	3.18 ± 1.19	3.91 ± 1.71	7.46 ± 2.61	0.80 ± 0.29	0.26 ± 0.18	0.53 ± 0.38
F value	36.46^{*}	4.81^{ns}	1.40^{ns}	0.65^{ns}	0.34^{ns}	0.59^{ns}	2.04^{*}	4.91^{*}
				5 – 10 cm				
TRF	16.38 ± 3.32	2.59 ± 1.14	3.42 ± 0.91	5.89 ± 2.38	11.90 ± 0.82	0.76 ± 0.38	0.37 ± 0.09	0.73 ± 0.32
CA	12.16 ± 0.97	1.40 ± 1.08	3.98 ± 1.18	4.49 ± 2.13	9.87 ± 0.17	0.35 ± 0.15	0.44 ± 0.12	0.81 ± 0.14
Average	14.27 ± 4.23	1.75 ± 0.69	3.13 ± 2.56	5.19 ± 1.66	10.89 ± 0.90	0.55 ± 0.49	0.40 ± 0.18	0.77 ± 0.38
F value	4.10^{ns}	0.51^{ns}	0.56^{ns}	0.33^{ns}	0.23^{ns}	0.66^{ns}	0.94^{ns}	0.57^{ns}
				10 – 20 cm				
TRF	13.45 ± 3.33	1.33 ± 0.47 b	3.42 ± 1.68	3.97 ± 1.62	8.72 ± 0.38	0.39 ± 0.24	0.35 ± 0.17	0.65 ± 0.18
CA	9.94 ± 1.91	2.64 ± 0.57 a	3.20 ± 1.21	3.03 ± 1.36	8.87 ± 0.18	0.83 ± 0.17	0.59 ± 0.19	0.89 ± 0.44
Average	11.69 ± 4.69	1.99 ± 0.90	3.08 ± 1.81	3.50 ± 1.22	8.80 ± 0.54	0.61 ± 0.29	0.47 ± 0.31	0.77 ± 0.55
F value	3.35^{ns}	12.66^{*}	0.05^{ns}	0.27^{ns}	0.05^{ns}	0.68^{ns}	1.60^{ns}	1.72^{ns}

TRF: Tropical Rainforest; CA: sugarcane crop; TOC: Total organic carbon; C-HA: Carbon of the humic acid fraction; C-FA: Carbon of the fulvic acid fraction; C-HU: Carbon from the humine fraction; C-HS: Carbon from humic substances; C-HA / C-FA: Carbon ratio of the humic acids and fulvic acids fraction; C-HS / TOC: Carbon ratio of humic substances and total organic carbon. Means represented by the same letter in the column per soil layer between the areas do not differ by the F test at 5% probability. * Significant at 5% probability by the F test. ^{Ns} Not significant.

In general, the C-FA levels showed an increase in depth in different soil uses (Table 8). This is related to lower stability of the AF fraction and high mobility in the soil profile, accumulating in depth (LEITE *et al*., 2003).

Considering the first 20 cm of soil, sugarcane showed higher levels of C-HA (6.06 g kg^{-1}), compared to the humid forest (5.05 g kg^{-1}). C stocks in areas cultivated with sugar cane are influenced by the application of mineral and organic fertilizers (GALDOS *et al*., 2009) such as the application of vinasse and filter cake. The history of soil management in the sugarcane area evaluated reports the use of filter cake in the years prior to this research. Thus, these results may be related to the increase in carbon stocks compared to areas that do not receive fertilization and, consequently, have a greater potential for carbon sequestration (RESCK *et al*., 2008).

C-HU contents were not influenced by land-use change in the evaluated layers (Table 8). In general, higher values of C-HU were found in comparison with the other humic fractions in the evaluated areas. This behaviour indicates a possible more advanced degree of humification of the soil's organic matter, since the humine fraction has greater stability and is more resistant to degradation by the soil's biota due to complexation with metal ions and/or clay-minerals (BARRETO *et al*., 2008), becoming a long-term carbon deposit.

Higher C-FA contents compared to C-HA values in both land uses were observed (Table 8). Higher C-HA values are consequence of intense humification and faster mineralization rate of organic residues in the soil (CUNHA *et al*., 2007).

There was no significant difference between the levels of C in humic substances in the land uses (Table 8). For the C-HA/C-FA ratio, land-use change affected the degree of humification of the organic matter in the 0-5 cm layer (Table 8), with higher values observed in sugarcane. In general, the C-HA/C-FA ratio was less than 1.0 (Table 8), indicating greater loss or less synthesis and accumulation of the more stable fraction (C-HA) (BONIFÁCIO *et al*., 2006).

In relation to accumulated C stocks, the land-use change affected the TOC stock in the 0-5 cm layer in the humid environment (Table 9), representing a ~ 40% reduction in C when there was sugarcane cultivation.

C-FA stocks have not been altered by the land-use change (Table 9). Considering the first 20 cm of soil, it was observed that the sugarcane area had 38% more C stored in the C-HA fraction when compared to the humid forest (Table 9). A possible explanation for these results is related to the higher speed of SOM decomposition when the sugarcane is burned during the harvest. Even though the area under forest has a continuous supply of litter and favourable conditions for microbial activity such as temperature and humidity, which favors the decomposition of the SOM, the burning of sugarcane residues is an instant C loss and much faster than decomposition in the forest area. Thus, SOM is more decomposed, favoring the accumulation of more stable fractions, to the detriment of fractions of lower molecular weight and more vulnerable to decomposition.

In general, most studies about changes in carbon fractions through land use change in areas under forest indicate a reduction in the carbon stocks of soil humic substances in agricultural crops (LEITE *et al*., 2003; LIMA *et al*., 2008; FONTANA *et al*., 2011; MACHADO *et al*., 2014; BALDOTTO *et al*., 2015).

The land use change for sugarcane promoted a reduction of 11% in the TOC stock in the first 20 cm of the soil. However, the conversion of the rainforest to sugarcane in the C-AH, C-AF and C-HU fractions of humic substances showed an increase of 57, 30 and 13%, respectively (Table 9).

Machado *et al*. (2014) observed that levels of C-FA, C-HA and C-HU were significantly higher in the native forest system when compared to coffee cultivations systems at a depth of 0-0.05 m. Baldotto *et al*. (2015) found that, compared to continuous cultivation or pasture monoculture, the native forest had higher carbon stocks that were more stable and less soluble, with more aromatic and hydrophobic forms (higher HA/FA ratio).

Leite *et al*. (2003) found a decrease in the values of humic substances in cultivated areas with mineral and organic fertilization in Minas Gerais, with greater values in areas with mineral fertilization, mostly C-HA and C-HU. Similar results were found by Fontana *et al*. (2011) under study in areas of banana and cassava cultivation compared to native forest with reductions in the levels of C-FA and C-HA.

Pessoa (2011) found that the levels of fulvic acids, humic acids and humine were similar in areas of native forest and capoeira, but higher than those in areas of pasture and agricultural cultivation. Lima *et al*. (2008) obtained higher stocks of C in the fractions of fulvic acids and humic acids in the soil under forest compared to those under pasture and planting of eucalyptus, indicating that management practices influence this reduction. Barreto *et al*. (2008) demonstrated higher carbon stocks in the fulvic acid and humine fractions in a pasture area, in comparison with the Atlantic Forest. Fontana *et al*. (2010), on the other hand, did not observe significant changes in carbon stocks in the humic fractions in pasture soil, sugar cane and native forest. A similar result was obtained by Miranda *et al*. (2007) for HS in different vegetation cover and Atlantic forest.

Table 9 - Accumulated stocks of total carbon, carbon of fulvic acids, humic acids, humine and humic substances up to 20 cm deep in soils under dry tropical forest and agricultural cultivation of sugarcane

Soil depth (cm)	Soil density ---g cm^{-3}---	Soil mass ----Mg ha^{-1}---	TOC	C-FA	C-HA	C-HU	C-HS
			Mg ha^{-1}				
Tropical Rainforest							
0 – 5	1.27 ±0.01 b	707.86 ±15.54	13.85±1.40 a	2.33 ± 1.06	0.80 ± 0.33	2.40 ± 1.19	5.53 ± 2.23
5 - 10	1.28 ±0.02 b	638.60 ± 1.71	24.31±3.27 a	4.52 ± 0.83	2.45 ± 1.69	6.16 ± 2.37	13.13 ± 3.53
10 – 20	1.49 ±0.01 b	1488.97 ± 1.18	44.34±8.16 a	9.62 ± 3.01	4.43 ± 2.15	12.07 ± 7.65	26.11 ± 8.86
Sugarcane crop							
0 – 5	1.60 ±0.01 a	845.96 ±1.15	7.27±0.95 b	1.48 ± 0.48	1.53 ± 0.53	3.17 ± 1.46	6.17 ± 0.85
5 - 10	1.69 ±0.01 a	842.48 ± 0.65	14.16±1.33 b	4.12 ± 1.37	2.37 ± 1.42	5.74 ± 1.38	12.04 ± 1.38
10 – 20	1.79 ±0.03 a	1782.96 ± 8.91	27.83±3.38 b	7.86 ± 3.21	4.94 ± 3.16	9.06 ± 1.02	22.63 ± 4.56

TOC: Total organic carbon; C-HA: Carbon of the humic acid fraction; C-FA: Carbon of the fulvic acid fraction; C-HU: Carbon from the humine fraction; C-HS: Carbon from humic substances; C-HA / C-FA: Carbon ratio of the humic acids and fulvic acids fraction; C-HS / TOC: Carbon ratio of humic substances and total organic carbon. Means represented by the same letter in the column per soil layer between the areas do not differ by the F test at 5% probability.

Ribas *et al*. (2008) studied the distribution of organic fractions in areas of native forest, marginal vegetation, pasture and sugarcane, noting that in areas with sugarcane and pasture the most reactive fraction (fulvic acids and humic acids) represents less than 20% of carbon, most of which corresponds to the inert fraction (humine). In the native forest area, the most reactive fraction is equivalent to more than 40% of carbon.

Humic substances and their fractions were not changed by converting the forest to agricultural area (Table 9). The proportions of the humic fractions of the SOM considering the 20 cm depth was C-HU > C-FA > C-HA in both soil uses (Table 9). It was found that 59% of the total carbon is stored up to 20 cm deep in the forest as humic substances. In sugar cane, 81% of the total carbon is stored as humic substances (Table 9).

In general, carbon proportions of fulvic acid, humic acid and humine fractions are lower in the forest area (22, 10 and 27% of the TOC under forest and 28, 18 and 33% of the TOC in sugarcane). These results may be related to deterioration of the stability of organic C by continuous supply of fresh C, which is an essential source of energy for soil microorganisms in the forest, especially in the superficial layers. The compounds readily available for decomposition are a source of energy for microbial activity, and the acquisition of energy through degradation of more recalcitrant compounds is not enough for the decomposition of more stabilized organic matter (FONTAINE *et al*., 2007). As in sugarcane the supply of fresh C is reduced and the situation is intensified by the fire which further reduces the input of fresh SOM, there is a greater accumulation of humid substances.

3.3 Carbon recovery and depletion rate

3.3.1 Dry environment

Considering carbon stocks in the dry forest as a reference, the percentage of total soil carbon (TOC) not recovered after the land-use change for cassava cultivation in the dry environment at 20 cm depth was 17% (Table 10). There was a very significant loss of C-HA and non-labile C and no change or loss of labile C.

Carbon depletion rate when switching from dry forest to cassava cultivation was negative for all fractions of carbon and TOC, except for labile carbon (Table 10). Positive values indicate accumulation of C stock in the soil and negative values suggest depletion of C stock in the soil.

Table 10 – Carbon recovery and accumulation/depletion rate up to 20 cm soil depth after land-use change in dry environment

	Carbon recovery rate %	Carbon accumulation/depletion rate Mg ha^{-1} year^{-1}
	------------------------ 0- 20 cm	------------------------
TOC	83	-0.25
C-FA	98	-0.01
C-HA	49	-0.08
C-HU	95	-0.01
C-HS	83	-0.13
C_{labile}	102	0.01
$C_{non\text{-}labile}$	55	-0.45

TOC: total organic carbon; C-HA: Carbon of the humic acid fraction; C-FA: Carbon of the fulvic acid fraction; C-HU: Carbon from the humine fraction; C-HS: Carbon from humic substances; Labile: Labile carbon; Non-labile: Non-labile carbon.

Labile carbon consists of the organic compounds easily mineralized by soil biota and are the main constituents of newly deposited waste in the soil. Labile organic carbon is decomposed relatively quickly (days to years). In agricultural crops, non-incorporation of vegetable residues in the soil reduces C input, reducing C stocks, especially of the more labile fractions that are quickly degraded.

The conversion of forest to cassava depleted TOC stocks in the 0-20 cm layer at an average of 0.25 Mg C ha^{-1} year^{-1} (Table 11), considering the 30 years of cultivation, carbon loss was on average 7.5 Mg C ha^{-1}. The depletion of non-labile C was very significant, showing the impact that cassava cultivation had on the sustainability of soil C dynamics.

Recovery of C stocks in the deforested Caatinga soils requires at least 60 years and the sequestration of C in these forests should require longer periods than in tropical rainforests. (ARAÚJO FILHO *et al*., 2018).

3.3.2 Humid environment

On average, 65% of carbon stored in TOC, C-FA, C-HU, C-HS and NLC were recovered after land-use change in the dry environment (Table 11).

Table 11 – Carbon recovery and depletion rate up to 20 cm soil depth after land-use change in humid environment

	Carbon recovery rate %	Carbon accumulation/depletion rate Mg ha^{-1} $year^{-1}$
	------------------------ 0- 20 cm	------------------------
TOC	63	-0.55
C-FA	82	-0.06
C-HA	112	0.02
C-HU	75	-0.10
C-HS	87	-0.12
C_{labile}	138	0.07
$C_{non\text{-}labile}$	18	-0.91

TOC: total organic carbon; C-HA: Carbon of the humic acid fraction; C-FA: Carbon of the fulvic acid fraction; C-HU: Carbon from the humine fraction; C-HS: Carbon from humic substances; Labile: Labile carbon; Non-labile: Non-labile carbon.

Considering the carbon stocks of the rainforest as a reference, the percentage of total soil carbon (TOC) not recovered after the change of land use to cultivate sugarcane in the 20 cm depth was 37% (Table 11).

The lowest carbon recovery was observed for non-labile carbon (Table 11), with a carbon loss of 82%. On the other hand, the carbon of the humic acid and labile carbon fractions were not lost, but exceeded the values found in the reference area (Table 11).

The rate of carbon depletion in the change from the rainforest to sugarcane is negative for TOC, C-FA, C-HU, C-HS and NLC (Table 11). For labile C and the C-HA, it was positive (Table 11). The conversion of forest to sugarcane depleted the TOC stocks in the 0-20 cm layer at an average of 0.55 Mg C ha^{-1} (Table 11). Considering the 30 years of cultivation, the reduction of stocks carbon content would be an average of 16.55 Mg C ha^{-1}.

4 CONCLUSIONS

The land-use change reduced the content and stock of total organic carbon in the surface layers of dry and humid environments.

The C-FA fraction was not a sensitive indicator of land-use change in the dry environment.

The land-use change altered the carbon content of humic substances in superficial layers in the dry environment.

The quality of the humification given by the C-HA/C-FA ratio was not affected by land-use change in the dry environment. In general, the uses of soil in the dry environment show low quality of humification.

The fractions C-FA, C-HU and C-HS were not sensitive indicators of the land-use change in the humid environment.

The quality of humification was affected by the land-use change in the humid environment. In general, the uses of the soil in the humid environment show low quality of humification.

The land-use change in the humid environment has altered carbon quality, especially in the surface layer, promoting a reduction in the accumulation of compounds with more recalcitrant C.

The land-use change reduced the carbon recovery rate from fractions of fulvic acids, humic acids, humine and total humic substances in the surface layers in the dry environment.

The land-use change reduced the carbon recovery rate from non-humic substances in the surface layer. The carbon depletion rate with land-use change in the humid environment is higher in the surface layers.

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CHAPTER III – CARBON FLUX THROUGH LITTERFALL IN A TROPICAL DRY FOREST AND TROPICAL RAINFOREST

ABSTRACT

The plant litter input to the soil is one of the main pathways of the carbon flow from plant biomass to the soil. Tropical forests are known to play an important role in the global C cycle. However, carbon dynamics in response to climatic conditions and seasonal fluctuations in litter have not been well explored in these environments and there is little information on the annual carbon flow. Thus, the objective of this work was to quantify and evaluate the seasonal variation on carbon flows through litter input in the forest ecosystems of Dry Tropical Forest and Tropical Rainforest. The study was developed in forest fragments located in Pernambuco. The contribution of litter was evaluated using 20 collectors of 1.0 m^2, installed in the center of the plots. The material deposited in the collectors was collected at 15; 30; 45; 90; 135; 180; 225; 270 and 315 days after its installation in April 2017 and the collection cycle was repeated the following year (April/2018), totaling 18 collections per area. The contributed litter was divided into leaves, branches+bark and miscellaneous. The dry litter biomass of each fraction and total was determined, as well as the carbon content. Leaf biomass contributed the most to the litter content, varying between 82.12 and 82.28% between years, and exhibited the same time trend as the total litter. Production peaks were observed for the litter fractions at days 45 of each year, corresponding to May 2018 and May 2017, which may be associated with the lower precipitations and beginning of water stress in this period in that region. Considering total litter, there was an increase of 34% on deposited litter and of 33% in total C contributed through litter in the drier year (2018/19). In the humid environment, leaf biomass contributed the most (~70%) to the total carbon of the litter in the observed years. The largest contributions of C through litter occurred during the period of water limitation and is related to leaf senescence in Caatinga species. Peaks of C input through litter in the humid forest occur during winter and spring, the driest period. A 30% reduction in total rainfall over the years did not change the pattern and seasonal amount of litter and carbon deposition in the rainforest.

Keywords: carbon pool, litter carbon, soil carbon, forest carbon sequestration, croplands, Atlantic forest, Caatinga.

1 INTRODUCTION

The contribution of plant litter to the soil is one of the main pathways of the carbon flow from plant biomass to the soil. Litter is a significant proportion of the forest's carbon reservoirs. Globally, a contribution of 60 Pg C year^{-1} is estimated through plant litter (MARTINELLI *et al*., 2009).

This compartment corresponds to the layer of organic residues deposited on the soil surface that accumulates until its fragmentation and decomposition by biotic, physical and chemical processes (ADUAN; VILELA; KLINK, 2003). Litter is one of the most dynamic carbon deposits, and climatic conditions significantly influence the amount and quality of litter deposited.

Climate variations such as rainier or drier years, forest type, species composition, topography and conservation levels will influence the quality and quantity of litter deposited in the soil and consequently alter the carbon flows in these ecosystems. The dynamics of litter influences carbon cycling in terrestrial ecosystems due to seasonal differences in the quantity, type and quality of the material that reaches the forest floor during the year and between years (PRESCOTT, 2002).

Tropical forests are known to play an important role in the global C cycle. However, carbon dynamics in response to climatic conditions and seasonal fluctuations in litter have not been well explored in these environments and there is little information on the annual carbon flow in these ecosystems.

The Atlantic Forest is a complex of ecosystems of great importance for the maintenance of biodiversity, i.e. it is a biodiversity hotspot, with one of the richest species in the world, with high levels of endemism but that also faces high threats to its integrity (MITTERMEIER *et al*., 2011). Due to intense degradation caused by deforestation since the 16th century, only a small portion of the original cover of the Atlantic Forest still exists. These remnants are distributed mainly in small fragments (< 50 ha), often distant from each other (RIBEIRO, *et al*., 2009).

In the Brazilian semiarid region, caatinga vegetation occupies an area of approximately 845,000 km², which represents around 10% of Brazil's territory (BRAZIL/MMA, 2019). The main causes of the degradation of dry Caatinga forests involve deforestation for agricultural production systems such as cutting and burning agricultural practices and firewood production. In addition, the inadequate management of vegetation and soil in the semiarid region has contributed to increasing the region's susceptibility to desertification, which has negative environmental, social and economic consequences for the region.

In dry forests, the carbon stored in litter is normally lower than that reported for humid forests. In Caatinga, studies show that the annual carbon flux of litter can vary between 0.91 and 2.62 Mg C ha^{-1} $year^{-1}$ (AMORIM *et al*., 2014; PEREIRA JÚNIOR *et al*., 2016; MOURA *et al*., 2016). In the Atlantic Forest, the C fluxes found oscillate between 0.70 and 5.82 Mg C ha-1 $year^{-1}$ (SANQUETTA *et al*., 2014; TORRES *et al*., 2014; DINIZ *et al*., 2015; FEREZ *et al*., 2015).

The litter production in the Caatinga can reach its peak at the beginning of the dry season and be minimal during the wettest period (MOURA *et al*., 2016; HOLANDA *et al*., 2017; BRASIL *et al*., 2017; FERREIRA *et al* ., 2018; SILVA *et al*., 2019). In the Atlantic Forest, on the other hand, there is no severe drought period and, therefore, the highest rates of litter deposition are usually verified during the rainy season (PEREIRA; ESPÍNDULA JÚNIOR, 2009; MENEZES *et al*., 2010; BIANCHIN *et al*. , 2016; CAMARA *et al*., 2018).

Some studies have demonstrated different seasonal patterns for litter production in these ecosystems, with litter production peaks during the driest period in the humid tropical forest (ESPIG *et al*., 2009) and during the longer rainy period in the seasonally dry forest (SILVA *et al*., 2019).

Studies on carbon stocks and flows are important for preserving natural ecosystems and their sustainability and for assessing impacts caused to the environment. Understanding these processes in natural ecosystems can provide important information to better understand the vegetation's response to climate change and anthropogenic disturbances. Predicting how the Caatinga and the Atlantic Forest vegetations will behave in the face of predicted climate change contexts is essential to establish accurate management protocols and sustainable conservation strategies for these forest ecosystems.

Thus, the aim of the present study was to quantify and evaluate the seasonal variation of carbon flux via litter input as a function of the seasonal variation of rainfall and temperature in forest ecosystems in Tropical Dry Forest and Tropical Rainforest.

2 MATERIAL AND METHODS

2.1 Study area

The study was developed in two forest fragments, located in two environments originally occupied by the Dry Tropical Forest and Tropical Rainforest, located in the state of Pernambuco. The first refers to the area covered by the Caatinga dry tropical forest, where a Caatinga forest ecosystem and an agricultural area with cassava cultivation were selected, which are equivalent to the most common types of land uses in the study region. The second environment relates to the domain area of the dense lowland tropical rainforest, where an Atlantic Forest ecosystem and an agricultural area with sugarcane cultivation were selected (Figure 1).

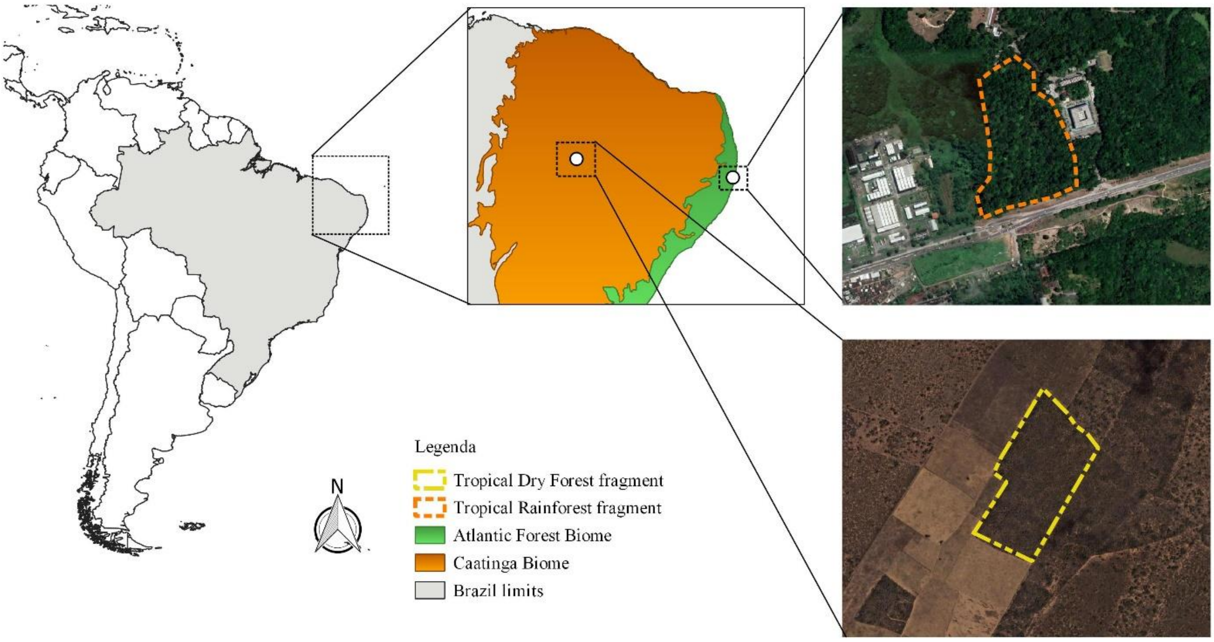

Figure 1 - Study sites location in Tropical Dry Forest and Tropical Rainforest, Northeast, Brazil.

The edaphoclimatic characterization and geographical location of the study areas are summarized in Table 1.

Table 1 - Location and characteristics of the areas in the dry and humid environment

	Tropical Dry Forest	Tropical Rainforest
Location	Chapada do Araripe, Pernambuco (7°25'S - 40°26'W)	Recife, Pernambuco (8°04'S - 34°57'W)
Area size	~13 ha	~28 ha
Altitude	838 m	38 m
Topography	Predominantly flat	Predominantly flat
Climate classification	BSh Dry Semi-arid low latitude and altitude [a]	Am Tropical monsoon [a]
Precipitation	<700 mm ano^{-1} [b]	~1500 mm ano^{-1} [b]
Temperature	27 °C[b]	25.8 °C [b]
Forest Domain	Tropical Dry Forest - Caatinga	Dense lowland tropical rainforest – Atlantic forest
Soil Classification	Dystrophic Yellow Latosol (Oxisol)[d]	Dystrophic Yellow Latosol (Oxisol)[d]
Absolute density	1294 ind ha^{-1}	970 ind ha^{-1}
Number of species	29	107
Highest absolute density species	*Guapira opposita (*Vell.) Reitz	*Helicostylis tomentosa (Poepp & Endl.) J.F.Macbr.*
	Croton limae A.P. Gomes, M.F. Sales P.E. Berry	*Mabea occidentalis (Benth.) Müll. Arg.*
	Metrodorea mollis Taub.	*Brosimum guianense (Aubl.) Huber*
	*Annona leptopetala (*R.E.Fr.) H.Rainer	*Parkia pendula (Willd) Benth. ex Walpers*
	Pilocarpus spicatus A.St.-Hil.	*Thyrsodium schomburgkianum Benth.*
	Senegalia langsdorffii (Benth.) Seigler & Ebinger	*Protium heptaphyllum (Aubl.) Marchand.*
	Zanthoxylum hamadryadicum Pirani	*Brosimum conduru Standl*
	Erythroxylum sp	*Tapirira guianensis* Aubl.
	Byrsonima vacciniifolia A.Juss.	*Dialium guianensis* (Aublet.) Sandw.

[a]Alvares *et al*. (2014); [b]APAC (2019); [c]Santos *et al*. (2018); [d]Densidade absoluta; [e]Santos (2018); [e]Espig *et al*. (2008).

The total precipitation for the evaluation period was 1,244.7 mm, ~ 576.6 mm in the first year (April/2017 to March/2018) and 668.10 mm in the second year (April/2018 to March/2019) in the dry forest. In the first year, the dry period started in May/2017 and continued until December/2017. In the second year, the water restriction period started in May/2018 and extended until November/2018 (Figure 2).

In the rainforest, the total precipitation recorded for the evaluation years was 3,935.0 mm, ~ 2,354.4 mm for the first and ~ 1,580.6 mm in the second year, respectively, which shows a ~33% reduction in precipitation between years. The rainy period occurred between April and July in the two years of assessment, during which 71% (first year) and 56% (second year) of the total rainfall of the years was concentrated (Figure 2).

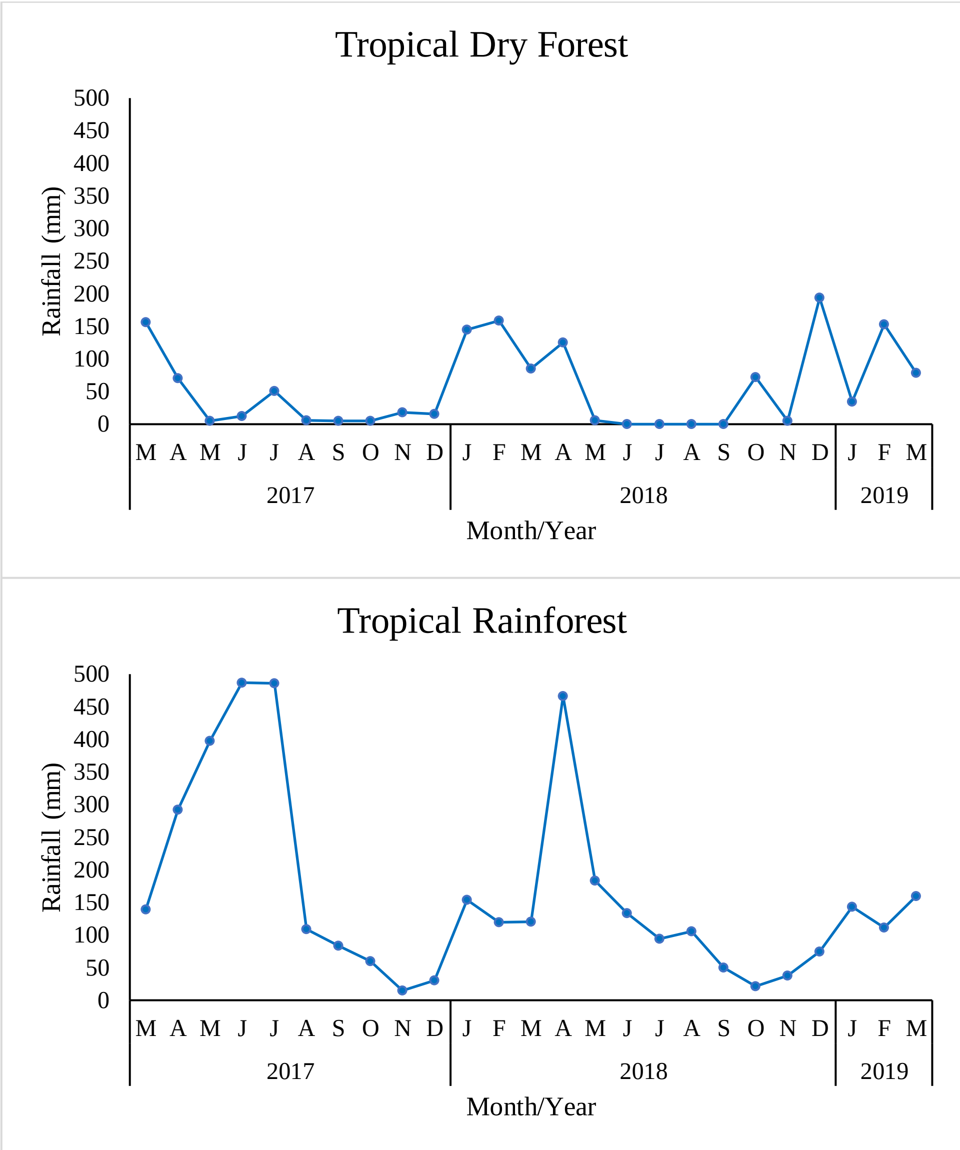

Figure 2 - Monthly rainfall in the Dry and Rainforest during the study period 2017 to 2019. Source: APAC data (2020).

2.2 Litterfall

In the forest fragments, 20 plots of 10 m x 25 m (250 m^2) were used, systematically distributed (Figure 3), where the collectors were installed for the litter deposition.

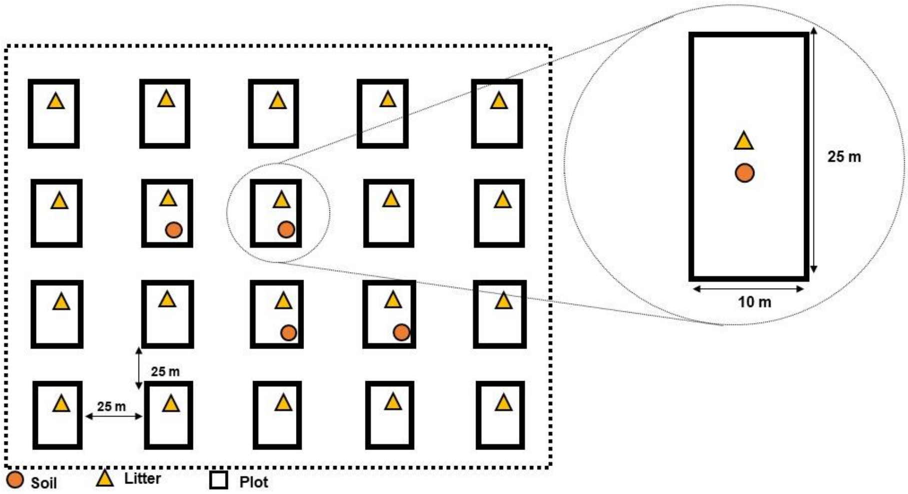

Figure 3 – Litter sampling design for carbon content determination in forest sites.

A total of 20 litter traps were installed in the center of each plot in each forest fragment. The collectors were made of PVC, with 1.0 m² of area and nylon mesh with 2.0 mm mesh, installed at approximately 1.0 m in height in relation to the soil surface.

The material deposited in the collectors was collected at 45; 90; 135; 180; 225; 270 and 315 days after its installation in April 2017 or April 2018, totaling 18 collections per area. In each collection, litter was taken from collectors and packed in identified plastic bags for further processing in the laboratory.

Litter samples were separated into fractions: leaves, branches+bark and miscellaneous. This last fraction included all particles of deposited material that did not fit into any other categories or that were not identified. After sorting, the material was packed in paper bags and dried in an oven at 60±5 °C until it reached constant weight. The dry mass of the material was obtained with a precision scale. Then, samples were ground in a Willey-type mill for further chemical analysis.

2.4 Carbon stock on litterfall

Samples were passed through a 60-mesh sieve and weighed in porcelain crucibles and then taken to the analysis of C levels by dry combustion in a LECO equipment (model C-144). The accumulated and produced litter C stock was calculated by multiplying the C content by the dry mass in kg ha^{-1}, extrapolated to hectare using the collector area.

2.5 Statistical analysis

A Shapiro-Wilk (SHAPIRO; WILK, 1965) and Levene (BROWN; FORSYTHE, 1974) tests (both at the 5% significance level) were used to test data's normality and homoscedasticity, respectively, as assumptions required for analysis of variance (ANOVA).

To the biomass of the leaf and the wood/manioc/stalk compartments and total biomass between land uses in the dry or humid environment, the data were submitted to two-way ANOVA with repeated measures over time for the effects of collection time, year of collection and its interaction in the biomass and carbon content of the total litter contributed and of each fraction.

3 RESULTS AND DISCUSSION

3.1 Tropical Dry Forest

The contribution of total litter and leaves showed the greatest temporal variations. Foliage biomass contributed most to the litter contributed, varying between 82.12 and 82.28% between years and exhibited the same time trend as the total litter (Figure 3), with higher production at 45 and 90 days, followed by decreased production up to 315 days in the two years of collection.

The fractions of leaves, branches+bark and total litter showed a seasonal pattern of unimodal input with peak production occurring in each month. The miscellaneous fraction showed an irregular pattern with several peaks of contribution (Figure 3).

Seasonal litter variations are common in all types of vegetation. Usually, the highest litter production rates are observed during the period of water limitation and warmer periods, and the lowest rates are expected during the wettest period (TAHMASBIAN *et al*., 2019).

In this study, the production peaks were observed for litter fractions at 45 days from the beginning of the assessments, corresponding to May 2018 and May 2017, which may be associated with the lower precipitations and consequent beginning of the water stress period in the region.

Lower production of leaf and total biomass observed after the 135 days of evaluation are associated with the deciduous vegetation. Under conditions of stress due to water deficit, Caatinga species use morphological and/or physiological adaptations that allows survival in dry conditions, such as senescence and deciduousness, thus depositing large amounts of deciduous leaves to reduce transpiration (DA SILVA *et al*., 2004).

The pattern of greater litter deposition right after the rainy season was also observed by Santana and Souto (2011) in a caatinga area in Seridó, in the state of Rio Grande do Norte. The authors related this pattern to the increase in water stress in the region.

The litter deposition peaks are influenced by species phenology, floristic composition, seasonal climatic conditions and leaf senescence (CUEVAS; LUGO, 1998; CAMPANELLA; BERTILLER, 2008; STAELENS *et al*., 2011; ZHANG *et al*., 2014).

The fraction branches+barks showed less variation in evaluated years (Figure 3). However, the highest productions were normally registered at 45 and 90 days, followed by a consistent contribution in the period between 135 and 270 days and an increase in contribution of this fraction with 315 days (Figure 3). The peak of the branches+bark fraction, as well as leaves, occurred during the dry period.

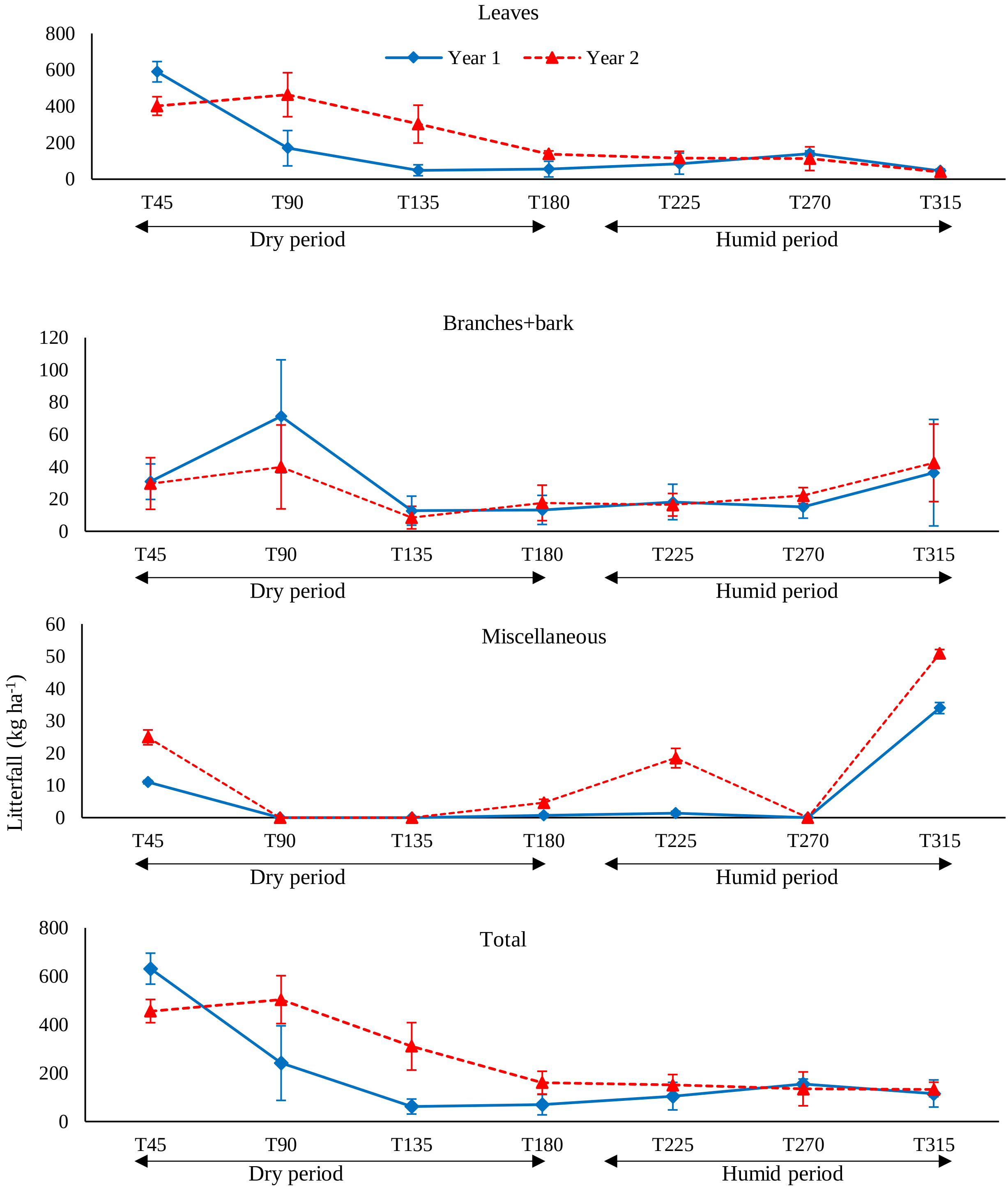

Figure 3 - Total litter, leaves and branches litterfall deposition every 45 days during the two years in the Tropical Dry Forest.

The contribution of the miscellaneous fraction during the two years of evaluation was not continuous (Figure 3). At 90, 135 and 270 days, production of this fraction was not recorded in both years of evaluation (Figure 3).

Comparing the two years of evaluation, it appears that deposition of the leaf, miscellaneous and total litter fractions were greater in the second year, which was the driest year. The branch+bark fraction did not vary between years. According to Macinnis-Ng and Schwendenmann (2015), the dry period is an important driver for litter deposition, reducing leaf area which decrease their water loss through transpiration, consequently protecting trees from water stress (CHAVES *et al*., 2003).

The leaf biomass was the one that most contributed to total carbon of the litter between the observed years (~84.15%). Carbon of the leaf fraction showed the same trend of temporal variation as in total litter (Figure 4), with higher productions at 45 and 90 days and decreased carbon return until 315 days of the two years of study.

Carbon of the branches+bark fraction showed less variation during the years (Figure 4). However, the highest productions were registered with 45 and 90 days with a general tendency to decreased contribution and lesser variation between 135 and 270 days, and an increase in carbon contribution with 315 days (Figure 4).

The highest C contributions of the miscellaneous fraction during the two years of evaluation were recorded at 45 and 315 days (Figure 4), not varying between years.

Contributions of C by leaves, branches+bark and total litter fractions were higher during the beginning of the dry period, related to greater deposition of the biomass from these fractions in this period due to strategies from the Caatinga plants to decrease water loss. The smallest contributions were observed during the humid period, suggesting that adequate soil moisture conditions, less transpiration and lower temperatures favored the maintenance of plant tissues.

Overall, the second collection year showed higher biomass and carbon content in leaf, miscellaneous and total annual litter fractions brought to the soil in the dry forest (Figure 4).

Considering total litter, the driest year (second year) represented an increase of 34% in litter deposited and of 33% of total C contributed via litter. These results demonstrate that decrease in water availability increases carbon deposits in the soil, which has implications for carbon stocks in biomass and litter deposits and for carbon sequestration in the face of predicted climate changes.

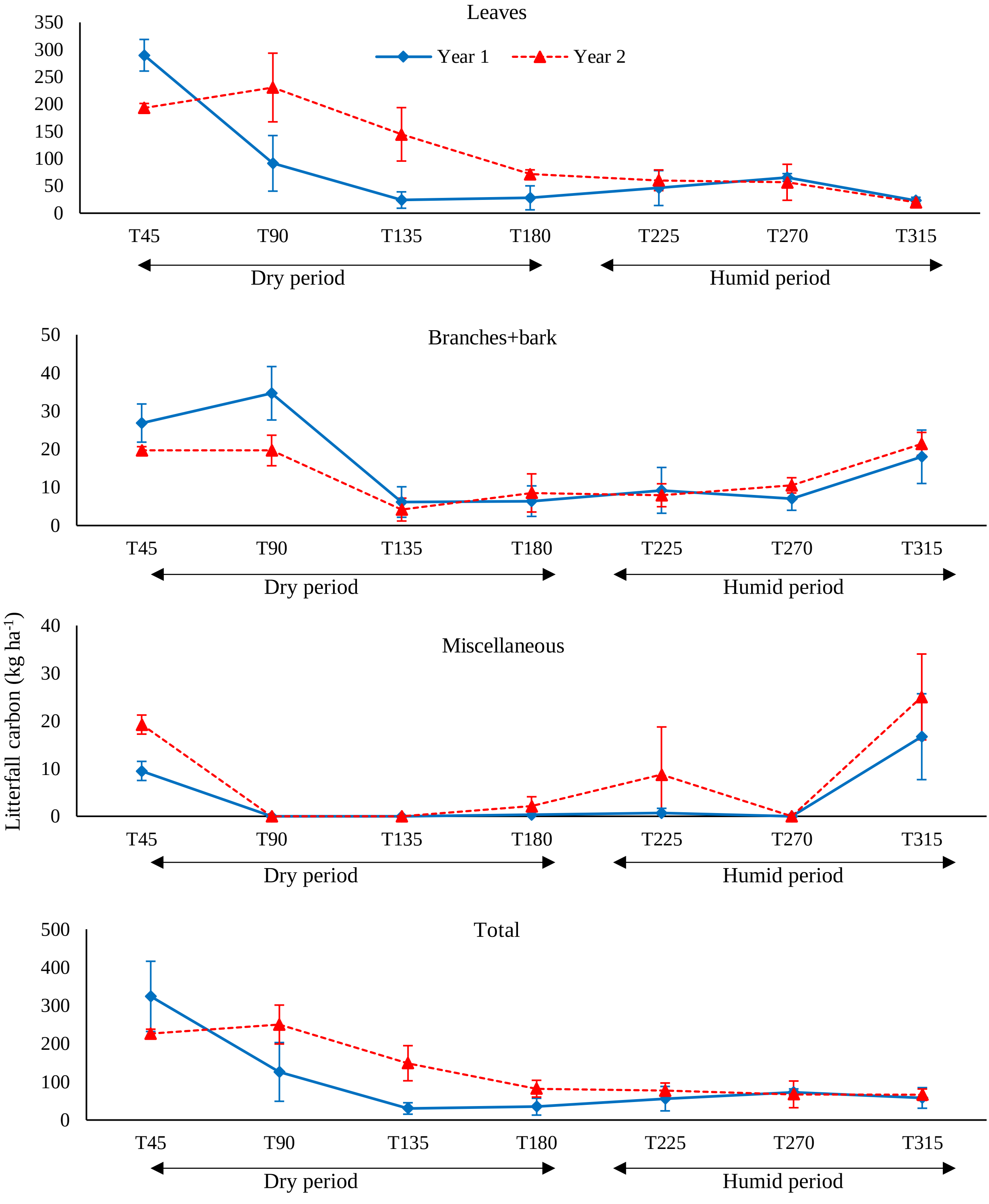

Figure 4 - Carbon return via total litter, leaves and branches litterfall every 45 days during the two years in the Tropical Dry Forest.

The leaf fraction contributed with the highest proportion of biomass (~82.28 - 85.12%) and carbon (~82.66 - 85.27%) of the total litter brought to the soil in the two years (Table 3). As seen in other studies, annual variations in nutrient content returned to the soil through total litter are strongly associated with the amounts of nutrients stored in the leaves, since it is the fraction with the highest proportion in litter (DE HOLANDA *et al*., 2017; MUQADDAS; LEWIS, 2020).

Table 3 - Annual contribution of leaves, branches and barks, miscellaneous and total litter and carbon return via litterfall in the Tropical Dry Forest

		Year I	Year II	Average
		-------------------kg $ha^{-1}year^{-1}$-------------------		
Leaves	Biomass	1298.87 ± 329.51 b	1800.08 ± 116.94 a	1549.48 ± 427.78
	%	82.28	85.12	83.91
	C	664.97 ± 179.78 b	895.65 ± 65.69 a	780.31 ± 234.17
Branches+bark	Biomass	225.95 ± 122.91	201.82 ± 59.95	213.89 ± 167.31
	%	14.31	9.54	11.58
	C	110.29 ± 58.95	98.83 ± 30.64	104.56 ± 81.29
Miscellaneous	Biomass	53.79 ± 24.91 b	112.85 ± 29.88 a	83.32 ± 47.59
	%	3,41	5.34	4.51
	C	25.94 ± 11.90 b	54.56 ± 13.72 a	40.25 ± 22.21
Total	Biomass	1578.61 ± 152.31 b	2114.75 ± 81.45 a	1846.68 ± 262.28
	C	785.56 ± 37.16 b	1041.23 ± 46.40 a	913.40 ± 65.66

C: carbon. Means followed by the same letter on the line do not differ by the F test at 5% significance.

According to Martínez-Yrízar (1995) in dry tropical forests the leaf litter is the one that most contributes to the total litter content, representing about 70% of the total biomass in these environments. For this reason, the leaf fraction is also the one that most influences nutrients cycling, in addition to be the one with the most stored nutrients. Thus, it is responsible for the rapid return of nutrients to the soil, related to the greater specific surface of the leaves in relation to other fractions of litter (GODINHO *et al*., 2013).

The biomass and carbon in the branches+bark fraction did not vary between years (Table 3), representing an average of 11.58 and 11.45% of the total, respectively.

The total amount of litter observed for the studied dry forest is lower than averages found in most studies on several physiognomies and rainfall conditions of dry forests in Brazil (Table 4).

In general, it appears that regions with higher average rainfall contribute with more plant litter when compared to areas with water restriction (Table 4). These results corroborate with Zhang *et al*. (2014), who states that precipitation and radiation are the limiting factors for litter supply in tropical forests.

Table 4 - Average annual contribution of total litter found in studies in the Brazilian Tropical Dry Forest

Location	Vegetation type	Average annual rainfall	Litterfall (kg $ha^{-1}year^{-1}$)	Author (Year)
Araripina, Pernambuco	Steppe savannah - Carrasco	<700 mm	1846.68	This study
Iguatu, Ceará	Steppe savannah in regeneration	867.10 mm	4227.20	Brasil *et al*. (2017)
Pombal, Paraíba	Steppe forested savanna	963.07 mm	3785.67	De Holanda *et al*. (2017)
Várzea, Paraíba	Steppe shrub-tree savanna	700 mm	2370.00	Da Silva *et al.* (2019)
Iguatu, Ceará	Steppe shrub-tree savanna	1026.40 mm	4038.79	Moura *et al*. (2016)
Manga, Minas Gerais	Steppe savanna	871 mm	4000.00	Souza *et al*. (2019)
Floresta, Pernambuco	Steppe shrub-tree savanna	489 mm	637.00	De Queiroz *et al.* (2019)

3.2 Tropical Rainforest

The leaf supply showed the same time trend as the total litter (Figure 5), with higher production at 180 and 225 days, followed by a decrease in production up to 315 days in both years and lower yields in the first 135 days of evaluation. (Figure 5).

These results corroborate with Zhang *et al.* (2014) who states that in tropical forests, peaks of litter production occur during the driest period, usually during spring and winter. During the dry period, leaf abscission occurs due to water stress, and plants are adapted to these conditions (NDAKARA, 2011; MACINNIS-NG; SCHWENDENMANN, 2015).

The branches+bark fraction showed the greatest temporal variations (Figure 5). However, in general, the highest production were recorded at 45 days and the lowest at 270 days for branches and barks (Figure 5). These results may be related to the close relation of the branch fraction to biotic and abiotic events prior to its contribution to the soil, which characterizes its high variability in temporal production (PINTO *et al*., 2008). The contribution of the miscellaneous fraction during both years was continuous (Figure 5). At 45 days, the highest production of this fraction was observed in both years (Figure 5).

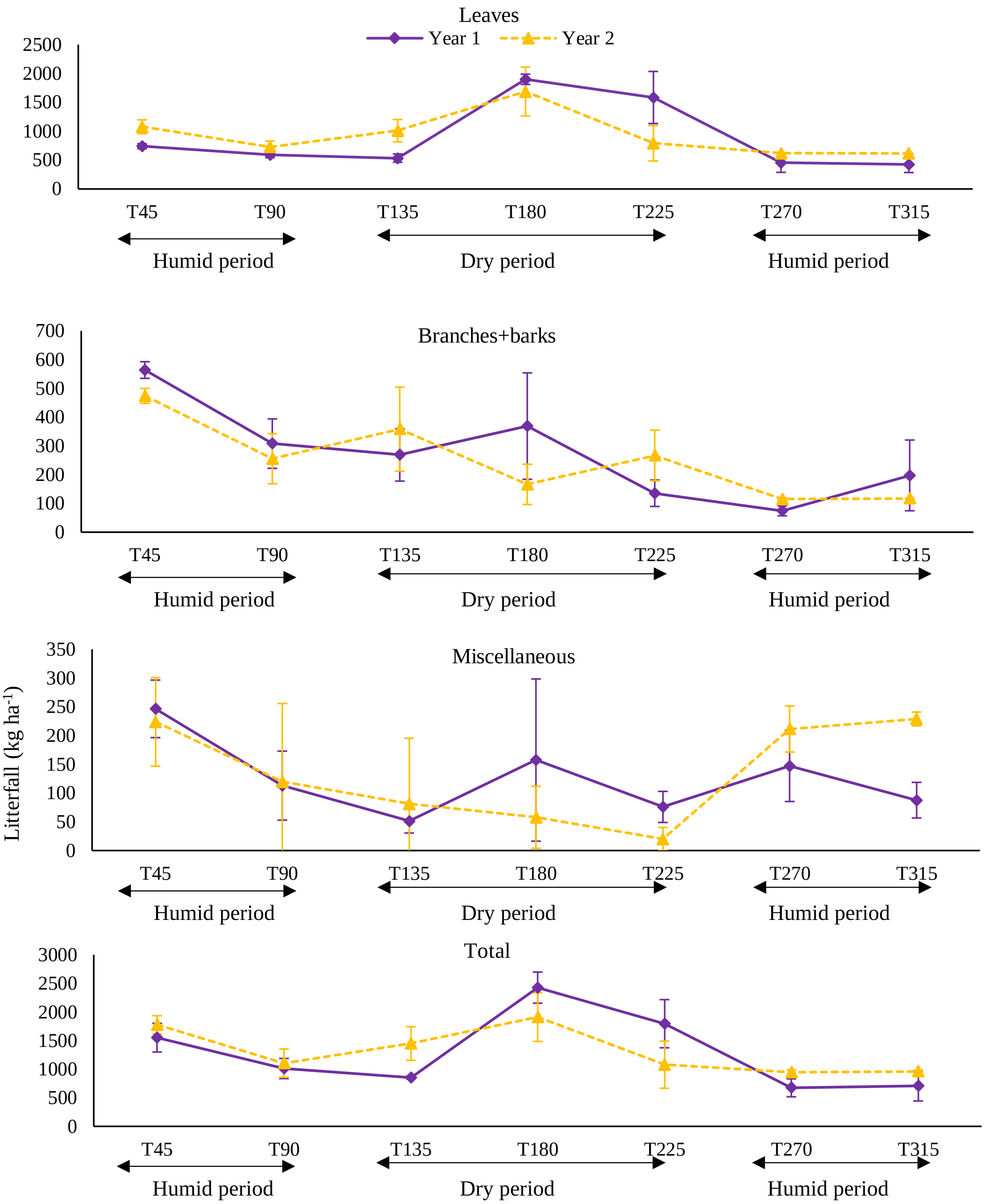

Figure 5 – Total litter, leaves and branches litterfall deposition every 45 days during the two years in the Tropical Rainforest.

Leaf biomass had the main contribution to total carbon in litter between years in the humid environment (~70%). Carbon in the leaf fraction showed the same temporal trend as C in total litter (Figure 6), with higher production at 180 and 225 days and a decrease in carbon return up to 315 days and up to 135 days in the first and second years of study, respectively.

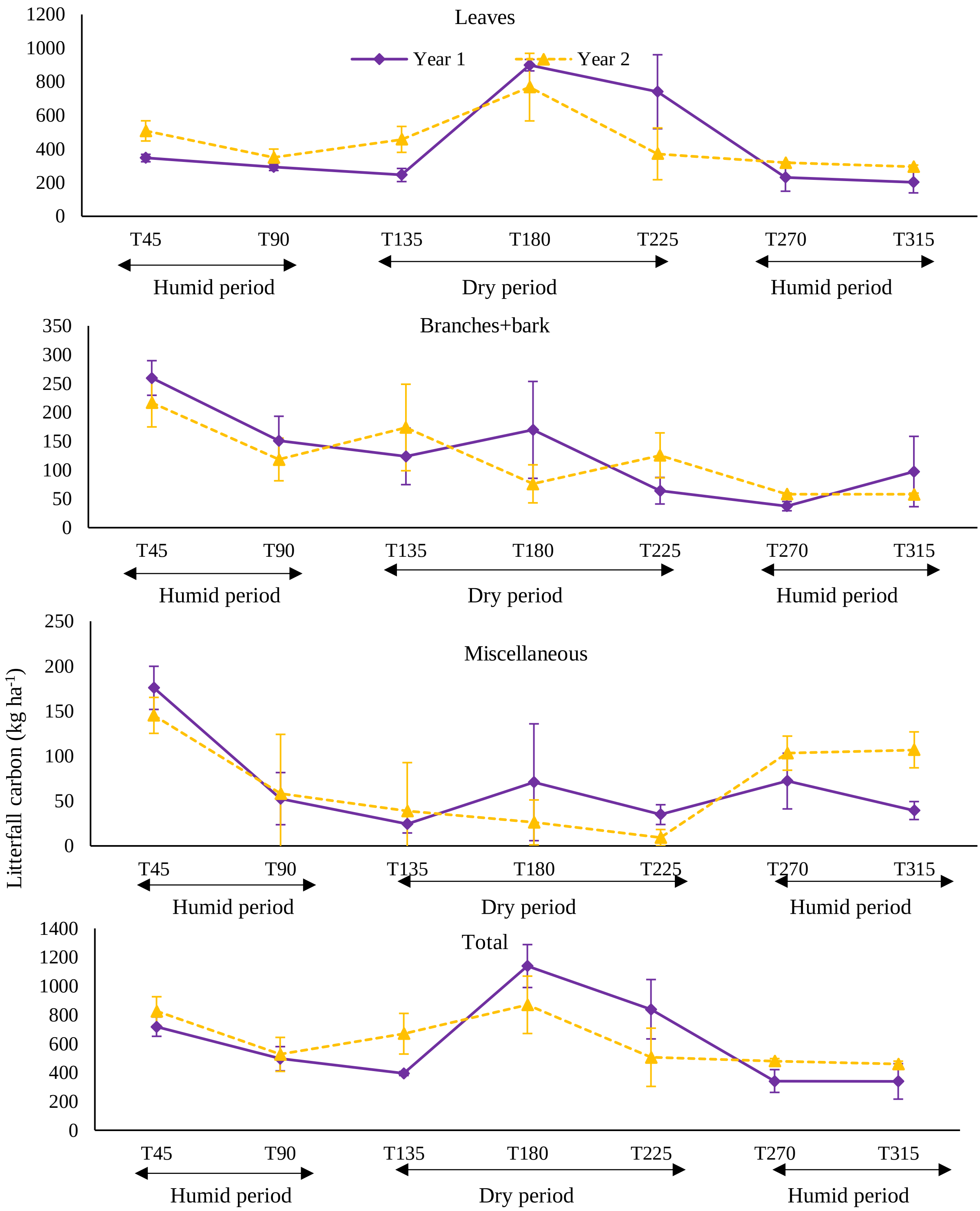

Figure 6 – Carbon return via total litter, leaves and branches litterfall every 45 days during the two years in the Tropical Rainforest.

Carbon in the branches+bark fraction showed different behavior between the two years of collection after the 135 days of evaluation (Figure 6). However, the highest production was registered at 45 days with a general tendency to decrease in contribution at 225 days (Figure 6).

The highest C contributions of the miscellaneous fraction during the two years were recorded at 45 days (Figure 6). There was no significant difference between years in biomass and carbon content in the fractions of leaves, branches+bark, miscellaneous and total annual litter landed in the rainforest (Table 6).

Table 6 – Annual contribution of leaves, branches and barks, miscellaneous and total litter and carbon return via litterfall in the Tropical Rainforest

		Year I	Year II	Average
		-------------------kg $ha^{-1}year^{-1}$	-------------------	
Leaves	Biomass	7116.10 ± 728.55	7465.53 ± 397.28	7290.82 ± 1015.26
	%	69.02	70.79	69.92
	C	3380.47 ± 345.03	3505.69 ± 180.72	3443.08 ± 476.53
Branches+bark	Biomass	2189.50 ± 314.64	2002.93 ± 221.12	2096.22 ± 470.50
	%	21.24	18.99	20.10
	C	1031.85 ± 160.68	944.41 ± 106.16	988.13 ± 235.62
Miscellaneous	Biomass	1004.09 ± 365.18	1077.06 ± 328.64	1040.58 ± 601.07
	%	9.77	10.22	9.98
	C	464.88 ± 169.30	507.50 ± 149.90	486.19 ± 276.66
Total	Biomass	10309.69 ± 1200.95	10545.52 ± 682.45	10427.61 ±1689.97
	C	4877.20 ± 606.93	4957.60 ± 324.16	4917.40 ± 841.83

These results suggest that a 30% decrease in total precipitation between years did not change the seasonal pattern of litter deposition and the amount of litter deposited in the rainforest.

The leaf fraction contributed with the largest biomass and C (~ 70%) of the total litter brought to the soil in the two years of collection (Table 6), which demonstrates the importance of this fraction for the cycling of nutrients in this ecosystem.

The second largest contribution was from the branches + barks fraction, representing ~20% of litter total biomass of carbon returned to the soil. The miscellaneous fraction showed the lowest contributions of biomass and C to total litter brought to the soil in the two years of evaluation, with an average of 9.98 and 9.89%, respectively.

Most studies in humid forest, especially the Atlantic Forest, found that leaves predominate in deposited litter (ESPIG *et al*., 2009; MENEZES *et al*., 2010; BIANCHIN *et al*., 2016). This higher proportion is related to the fact that leaves are the physiologically active organs through photosynthesis, fixing and transferring of carbon and nutrients to forest soils, helping to mainten fertility in these ecosystems.

The annual total carbon contribution to the soil through litter fractions was proportional to the amounts of litter biomass. The supply of carbon and other nutrients through litter is variable, especially in tropical forests, and depends on the functional characteristics of elements in the plants metabolism such as edaphoclimatic conditions, nutritional status, phrenology, conservation degree and successional stage of the forest, and the presence or absence of nutrient retention mechanisms (VITOUSEK; SANFORD, 1986).

The average contribution of total litter during both years of evaluation was 10.43 Mg ha^{-1} $year^{-1}$. According to Golley *et al*., (1978), the litter supply in tropical forests in the world varies between 4 and 25 Mg ha^{-1} $year^{-1}$.

The result of total litter brought to the soil was slightly higher than that found by Espig *et al*. (2009) in a study developed in the same area 15 years ago (Table 7), indicating little variability in litter production in this forest that may be related to the advanced degree of conservation and successional stage of the forest.

Table 7 – Average annual contribution of total litter found in studies in the Brazilian Tropical Rainforest

Location	Vegetation type	Average annual rainfall	Litterfall (kg $ha^{-1}year^{-1}$)	Author (Year)
Recife, Pernambuco	Lowland Dense Ombrophilous Forest	1500 mm	10427.61	This study
Antonina, Paraná	Dense Submontane Rainforest	2000 – 3000 mm	8090.50	Bianchin *et al*. (2016)
Recife, Pernambuco	Lowland Dense Ombrophilous Forest	1500 mm	10070.00	Espig *et al.* (2009)
Linhares, Espírito Santo	Seasonal Semideciduous Forest	1159 mm	12100.00	Menezes *et al*. (2020)
Sirinhaém, Pernambuco	Lowland Dense Ombrophilous Forest	1860 mm	8261.15	Lima *et al*. (2019)
Além Paraíba, Minas Gerais	Seasonally Semi-deciduous Forest	1390 mm	7790.00	Machado *et al*. (2018)
Pinheiral, Rio de Janeiro	Semideciduous Submontane Seasonal Forest	1300 mm	10980.00	Mendonça *et al*. (2019)

In general, litter production in humid forests is variable and does not show a positive association with average rainfall (Table 7), since litter supply in environments with higher average rainfall was lower than that of forests located in environments with lower rainfall averages. However, it is noteworthy that the floristic composition, forest type, density, successional stage and degree of anthropic pressure can alter the litter production.

4 CONCLUSIONS

Leaf biomass contributed most to the litter provided in the dry and humid forests.

The largest contributions of C through litter occurred during the period of water limitation and is related to leaf senescence of Caatinga species.

In the dry forest, the lower annual water availability increases carbon deposits to the soil, which has implications for carbon release to the atmosphere.

Most of the carbon supplied to the soil comes from the leaf fraction in dry and humid forests.

The peaks of C input through litter in the humid forest occur during winter and spring, the driest period.

The 30% reduction in total rainfall over the years did not change the pattern and seasonal amount of litter and carbon deposition in the rainforest.

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