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Soil Organic Carbon in the Brazilian Semi-arid Tropics

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ABSTRACT

The Brazilian semi-arid tropics occupies an area of 969,589 km^2 that represents 11% of the national territory and the Caatinga is its most representatives Biome with an area of 844.453 km². However, approximately 46% of this area is deforested. The conversion of Caatinga preserved vegetation in degraded areas has contributed to global climatic changes; therefore, a series of scientific research studies has as its objective to quantify the C reservoirs in different semi-arid regions of the world, as well as to identify the factors that control its dynamic. Recently, network research studies for measuring C stock and balance in natural vegetation and disturbed areas, firstly related to livestock and dry land farming that are dominant activities in the region, and secondly related to irrigated agricultural exploitation due to its high impact in the productive system, have been developed. The studies comprise C determination in soil, plant, micro-organism and atmosphere systems, involving C and energy balance and the effect of land use on C stock relations. C stocks in the Brazilian semi-arid tropics varies from 20 to 48.4 t ha^{-1} at 0-20 cm soil layer, while for the aerial part of natural vegetation the values vary from 1 to 80 mg ha^{-1}. It can be observed, for the same soil and vegetation type, that changes in land use decrease soil C stock and that plant cover management can behave as C source.

Keywords: Caatinga, land use, microorganism, soil

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INTRODUCTION

The Brazilian Northeast comprises an area of 1.56 million km^2, corresponding to 18.2% of the national territory, where there are 51.5 million inhabitants that represent 28% of the Brazilian population. The Tropical Semi-arid, which is located in this region, occupies an area of 982,563.3 km^2, being the most populated semi-arid region of the world with 22 million inhabitants. Caatinga is the most representative Biome of the Brazilian semi-arid (IBGE, 2007). According to the Brazilian Institute for Geography and Statistics (IBGE, 2007) its area corresponds, approximately, to 8444,453 km^2, being considered as a completely Brazilian Biome. The term "Caatinga" comes from the Brazilian native language which means "white forest", referring to the appearance of the vegetation in the dry season of the year, when most of tree leaves fall down and the tree trunks become whitish and bright, dominating all over the landscape (Prado 2003). The Caatinga comprises one of the most complex Brazilian vegetations, which main characteristics are arboreal or bushy forests, with trees and short bushes, some of them with thorns, microphylia, being xerophytes. There are also Cactaceae and Bromeliaceae species, while the lianas are scarcer (Araújo and Martins 1999). Some perenipholy species can be found and, according to Araújo *et al.* (2002), the total diversity of herbaceous species is significant and important due to its forage, medicinal and apiary values.

Studies have shown that Caatinga is the most resilient type of vegetation in Brazil. The areas where it occurs are under intense use since the primordial time of Brazilian colonization, in the sixteenth century; a great part of the area is disturbed (MMA 2010 – Action Plan for Prevention and Control of Caatinga Deforestation). The causes for this degradation process are associated to inadequate management for exploring its physic and biological resources, like extensive cattle raising associated to the vegetation overgrazing, predatory extractivism, replacing native vegetation by crops, by cleaning new area for planting using fire, and wood extraction, resulting in monocrop exploitation (spoiling cropping systems) in a rainfed condition agriculture, and also the irrigation cropping system that came up by deforesting native vegetation areas, besides an inadequate soil and water management. Man's actions have caused some changes in carbon (C) and nitrogen (N) cycles, two of the most important elements for maintaining the ecosystem dynamic, that are associated to climatic changes. Human interference on global C cycle has occurred since a hundred years ago. However, only in the last two years anthropic C flux has been similar to natural C cycle (IGBP 2003). Continuous soil use, by crop and cattle raising, and the withdrawal of the phytomass for energy generating, without adequate planning, are decreasing soil C supplies, as well as increasing CO_2 emission for the atmosphere in the Brazilian

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According to Pellegrini *et al*. (2007), evidence that global climatic changes will occur, due to an increase in the concentration of greenhouse gases, among them carbonic gas (CO_2), has been more consistent. These changes have directly affected Brazilian agriculture and forest areas. According to Nobre (2005) and Nobre *et al.* (2005), the behavior of Brazilian Biomes, at the use of Intergovernmental Panel On Climate Change-IPCC scenery for 2091-2100, in Potential Vegetation model of Centro de Previsão do Tempo e Estudos Climáticos/Intituto Nacional de Pesquisas Espaciais - CPTEC/INPE, shows a desertification of the Semi-arid, with a significant biodiversity lost due to the low adaptation capacity of the Caatinga Biome to climatic changes in a few decades.

Soil degradation is the most important factor for the desertification (Ribeiro *et al.* 2009). Soil susceptibility to erosion has a fundamental importance in the desertification and degradation processes of the Caatinga Biome. However, the degradation process can be restrained and reverted by using management systems that assure sustainability for the productive and extractivist processes in use. The proposed systems have to be flexible in terms of adaptability to the different semi-arid areas. They also have to increase the biological productivity to higher economic levels, besides being in a sustainable environmental balance. When establishing and operating those systems, various practices, methods and knowledge related to sustainable natural resource use, which make it possible to associate them with diversified systems for maximizing their economic and environmental efficiencies, have to be included, in spite of the products being explored.

However, some of these systems can be considered preliminary since they are still in a development stage, making it necessary to perform risk analysis and social, economic and environmental sustainability evaluation. It is necessary to evaluate and compare the mitigation and adaptation actions to be proposed for analyzing the systems in relation to the actual productive system sceneries.

The adoption of systems that favor the sustainable use of the agro-ecosystem can improve significantly the soil's chemical, physical and biological properties. The evolution registration for these systems has been realized by defining soil quality parameters like properties and processes, and physical, chemical and biological characteristics that can be used for measuring soil changes (FAO 2003). Various indicators are related to many soil degradation types, as visual indicator, biological, physical and chemical indicators. The total organic carbon (TOC) and the soil organic matter (SOM) are considered as the main chemical indicators of soil quality (Larson and Pierce 1994; Nortcliff 2002). They have been used in evaluation studies, directly or indirectly, of chemical, biological and physical conditions of the soil system. The SOM sensitivity in relation to agricultural management practices and its effects on the soil emergent properties points out how important this soil attribute is, and grants it a great credibility in the evaluation of soil state under different soil management (Vezzani 2001).

Concerning the questions that comprise global climatic changes, a series of recent scientic research studies has been published, which objective it was to quantify the C reservoir, as well as to determine the factors that control its dynamic, in different semi-arid regions in the world (Sarah 2006; Bastida *et al.* 2007; Bhattacharyya *et al.* 2007; Perez *et al.* 2007; Vourlitis *et al.* 2007). In the Brazilian Semi-arid Tropics, studies related to C balance in disturbed and native vegetation areas are being carried out. Firstly, concerning cattle raising and dryland farming studies that constitute dominant activities in the region, and secondly, concerning irrigated agriculture studies due to its high impact on the productive system. Therefore, this manuscript aims at a systematized literature review with an emphasis on the actual knowledge of C in soil, plant, micro-organism and atmosphere systems. It will point out the relationship between the C balance and the energy balance, and the effect of land use in the C stock in Caatinga vegetation areas in the Brazilian Semi-arid Tropics.

CARBON IN SOIL SYSTEM

Soil functions in natural environments are characterized by its ability to: a) act as a support for plant growth, b) control and compartmentalize the water flux in the root zone, c) stock and promote the element breakdown in the biosphere, and d) act as an environmental stock solution (Karlen *et al.* 1997). The way the soil performs such functions characterizes its quality.

Doran and Parkin (1994) defined soil quality as its ability to function under limiting conditions in a natural or modified ecosystem to: a) sustain plant and animal productivities, b) maintain or increase water and air quality and c) promote plant, animal and man's health. Considering that soil ability to fulfill its function in natural environments is related to its chemical, physical and biological characteristics, Vezzani (2001) proposed an idea that a soil is qualified as a good one when its interaction with mineral, plant and micro-organism subsystems, is classified at a high level order. This organized system is obtained through the flux of organic compounds by growing crops that promote bigger and more complex structure formation at each planting cycle caused by mineral, micro-organism and plant interaction. The highest soil class level is mainly characterized by the high amount of micro-aggregates (diameter larger than 0.25 mm) and the high organic matter content. In this situation, chemical, physical and biological soil system attributes are in an excellent situation and emergent proprieties enable the soil to play its function in the natural environment. So, the soil system has higher: a) aggregate and structure stabilities, b) infiltration and holding capacity of water, c) resistance to erosion, d) biological activity, e) cation exchange capacity, f) nutrient availability to plants, and smaller: a) nutrient seepage losses, b) emission of CO_2 and other gases to the atmosphere (Stevenson 1994). Based on this theory, the soil with these attributes offers the necessary conditions for plants to show their productive potential. So, crop productivity, from a soil science view, is a reflex of soil quality (Vezzani 2001). In this context, the soils under agricultural exploitation, as well as in native vegetation situations, behave as open systems, exchanging energy and material with the environment, reaching a stable stage when addition and decomposition are equivalent (Addiscott 1995). The addition of C to soil system occurs through organic compound synthesis in the photosynthesis process. The added C amount in certain edapho-climatic conditions depends on the species and cropping system used. On the other hand, the losses occur by breath CO_2 release, microbial residue and soil organic matter decompositions, and nutrient losses by seepage and erosion of organic C. The magnitude of those processes, in some edapho-climatic conditions, depends, directly or indirectly, on agro-ecosystems, soil management (Mielniczuk 2008), ecosystems and extractivism.

It is important to know the soil of the Brazilian semi-arid tropics to find out its capacity to store C and to understand the C dynamic in the ecosystem. Therefore, it is necessary to determine the formation factors of the regional soils. The geology for the Brazilian semi-arid tropics is modeled according to two types of structure. The first constitutes crystalline base formation that occurs in 70% of the semi-arid region; the second is formed by the sedimentary basins. Many rocks, which originated between the Tertiary and Quaternary periods of the Cenozoic era, characterize the Semi-arid geomorphology. According to Ab'saber (1996), the rock formations are distributed throughout the landscape as the inter-plateau lowlands that are the most typical characteristic of the Northeastern Semi-arid, being intermingled by ancient hills and sporadic plateau. These sceneries constitute most of the Semi-arid region, where some sandy soil formations with high iron oxide concentrations can be observed, which bring out acid and poor soils.

Considering the above point of view, Jacomine (1996) divided the region in three areas according to original material type: a) crystalline area, b) crystalline area covered by materials more or less sandy, and c) sedimentary area. On the crystalline basin, the soils are generally shallow (about 0.6 m), with low infiltration capacity, high soil surface runoff and low natural drainage. In sedimentary basins, the soils are generally deep (higher than 2 m, being possible to go over 6 m) with high water infiltration capacity, low water surface runoff and good natural drainage.

The Brazilian semi-arid tropics shows four predominant soil classes, out of fifteen classes, which represent 68% of the area (Jacomine *et al.* 1977; Cunha *et al.* 2008; Salcedo and Sampaio 2008) although they are spatially fractioned as a mosaic.

Vertisol and Inceptisol soil types present the highest levels of TOC (12.3 and 12.2 g kg^{-1}), but, considering both areas, they represent 5% of the total area of the Semi-arid only. The Ultisol and Psamment soil types present 11.5 and 10.4 g kg^{-1} of total organic carbon, respectively, covering an area of 32%. According to the relative importance, in relation to carbon content, Oxisol and Vertisol soil types occupy 36% of the region and show 9.7 and 8.9 g kg^{-1}, respectively. With an area of 8%, Albic sub-order and Orthent soil types show the lowest levels of TOC, 7.4 and 4.9 g kg^{-1}, respectively.

Research studies to find out soil C stock are incipient in the Brazilian Semi-arid Tropics yet. Tiessen *et al.* (1998) estimated a C stock of 20 t ha^{-1}, at 0-20 cm depth, for the Brazilian semi-arid tropics soils. However, in Chromic Ultisol soil type, Maia *et al.* (2007) in a hyperxerophyla Caatinga vegetation in the semi-arid of Ceará State and Kauffman *et al.* (1993) in a Caatinga vegetation condition of Pernambuco State Semi-arid determined C stock of 48.4 and 26.2 Mg ha^{-1}, respectively, at the same soil depth (0 – 20 cm). Amorim (2009) evaluated the seasonal variation of average C stock in an Acrisol soil type under Caatinga vegetation in the municipality of Petrolina – Pernambuco State. Obtained values were 16.5, 11.8 and 9.89 Mg ha^{-1} in the dry season and 14.2, 10.0 and 8.99 t ha^{-1} after the rainy season at 0-20, 10-20 and 20-30 soil depths, respectively. Average C stocks at 0-20 cm soil depth were superior to the values obtained by Tiessen *et al.* (1998), being 28.3 and 24.2 t ha^{-1} for the dry season and after the rain season, respectively. Fraga and Salcedo (2004) in Hiperxerophyla Caatinga vegetation C contents of 17.9 and 28.6 t ha^{-1} for 0-7.5 and 0-15 soil depths, respectively. Based on these results, a great variation in soil C content can be observed in the region.

In a general way, Lithic Psamment soil type shows the highest C stock (27.4 t ha^{-1}), followed by Ultisol, Vertisol, Inceptisol and Oxisol soil types, while Orthent shows the lowest C stock (12.1 t ha^{-1}) (Salcedo and Sampaio 2008).

A great proportion of semi-arid soils, about 82% of the area, present low productivity potential, due to nutrient content, soil profile depth, deficient drainage, high exchangeable N concentration, or low OM content (Silva 2000; CNRBC 2004). Inadequate practices of crop and animal production, associated to limiting soil use characteristic or low productive potential, have contributed to degradation process of many vulnerable areas for many years, being unpractical soil reclamation (Silva 2000).

The indiscriminate natural resource use, by vegetation suppression in great areas for cropping and animal raising exploitation, vegetation burning practice, unplanned firewood cutting, mining exploitation and overgrazing of Caatinga vegetation have had a negative effect on the stability and regenerative capacity of soils and natural vegetation, inhibiting the natural recovery and rendering soil permeability. According to the semi-aridity characteristic, the supporting capacity of the Brazilian semi-arid tropics is smaller than in humid tropics or temperate climate zones of the world.

CARBON IN PLANT SYSTEM

To define the contribution of plant system to C balance for an ecosystem or agro-ecosystem it is necessary to know its details. Dominant agro-ecosystems in the Semi-arid comprise monocrop planting system, with low crop variability, and direct or indirect estimations are easily done. However, estimating the Caatinga native vegetation contribution remains a challenge. It is observed, however, that due to the great territorial extension and the different places where it can be found, Caatinga vegetation comprises a huge variability of evidenced phyto-geographic squares, mainly by physiognomic differences, density, species component and phenological aspects (Andrade-Lima 1981; Rodal *et al.* 1992; Sampaio *et al.* 1998; MMA 2010). The lack of information on Caatinga vegetation is evident when data related to phyto-sociological structure, plant population dynamic, ecological succession process and local eco-system natural recovery are needed, for example (Araújo Filho and Carvalho 1997). It can be affirmed that Biome Caatinga is compounded by different "caatingas" characterized by arboreal-bushy formation, which are classified as different typologies; some of them are still unknown from an ecological point of view. Aiming at adapting the Brazilian vegetation classification to a universal system, the Caatinga vegetation was classified in the nineties as steppic savanna, and divided into four types:

1. Forest state – it is compounded by species which height varies from 5.0 to 7.0 m, more or less dense, with thick trunks, ramified brunches and thorn and/or aculeus. The plants are deciduous in the unfavorable period and dominant genera are: *Cavanillesia*, *Chorisia*, *Acacia*, *Mimosa* and others of the *Leguminosae* family;
2. Arboreal state – it shows the same floristic characteristics of Forest state Caatinga. It differs only in individual height (shorter) and plant spacing, with a larger open area among individuals. Predominant species and genera are *Spondias tuberosa*, *Commiphora leptophloeos*, *Cnidoscolus phyllacanthus*, *Aspidosperma pyrifolium* and *Mimosa*;
3. Plain state – its main characteristic is the pseudo-orientation of rickety and woody plants on a dense cover of woody gramineous of hemicriptophytes and carnefythes, consisting mainly of *Mimosa acustipula*, *Auxema oncolalyx*, *Combretum leprosum* and *Aspidosperma pyrifolium*. This vegetation covers small plain lands that are flooded in the rainy season due to bad drainage of predominant soils;
4. Woody-gramineous state – it is also known as thorn plain characterized by a large gramineous cover intermingled by short, woody and thorny plants and individuals of *Jatropha* generus – *Euphorbiaceae* family. The plains are entirely covered by grass (*Aristida* sp.) with a pale color in the dry season turning into greenish colors in the rainy season.

Caatinga vegetation is spread over 17 great landscape units, being subdivided into 105 geo-environmental units (Rodal and Sampaio 2002), from a total of 172 units of the Brazilian Northeast (Silva *et al.* 1993). Caatinga vegetation was recognized as one of the 37 natural regions of the planet earth. According to Giulietti *et al.* (2002), about 1,500 species were registered in the region up to now, and the most numerous families in the area are *Leguminosae* (18.4%), *Convolvulaceae* (6.82%), *Euphorbiaceae* (4.83%), Malpighiaceae (4.7%), and *Poaceae* (4.37%). The presence of endemic species indicates that the natural environment has a great biodiversity, where the flora is represented by about 20 genera and more than 300 species; the *Leguminosae*, with 80 species, surpasses all the other families (Giulietti *et al.* 2002). Plant capacity to absorb and store C became a mitigating strategy for the changing climatic effects. Therefore, the quantification of C stock in eco-system biomasses is very important to characterize the Biome status for developing sustainable strategies.

According to Sampaio and Freitas (2008), there are five principal reasons for an interest in biomass stock and production in the natural vegetation of the Brazilian Semi-arid

Tropics, such as: firewood production, natural pasture use and recovery of degraded or discontinued agricultural areas to be used in the C market. Therefore, it is observed that natural vegetation is the best indicator of the production system capacity, but there are few scientific research studies on aerial plant parts of Caatinga vegetation.

The biomass must be determined and estimated in a credible way to have consistency in the quantification of fixed C in the forest eco-systems (Sanquetta and Balbinot 2004) and agro-eco-systems. Knowing the right C levels in a biome is one of the key-points for elaborating environmental projects related to C sequestration (Vieira *et al.* 2009). Generally, a fixed value is adopted, which is equivalent to 50% of phytomass (IPCC 2003) that can induce estimating errors.

The C percentage for Cerrado vegetation and Caatinga vegetation species were determined by Vieira *et al.* (2009) in different plant compartments: leaves, brunches, roots, barks and trunks. Average levels for Cerrado species were: 43.24% for leaves, 42.06 for brunches, 40.09 for roots, 40.60% for barks and 41.01 for trunks. For Caatinga vegetation species, percentage results were: 47.39% for leaves, 44.68% for brunches, 44.38% for roots, 44.60% for barks and 43.75% for trunks. In the studied species, statistical analyses showed differences for C levels between the two biomasses studied; values were always higher for Caatinga vegetation species. Leaves were the compartments that showed higher C level for both Cerrado and Caatinga Biomass. Therefore, it can be concluded that C levels are always lower than the suggested ones by IPCC (2003), which would result in an overestimation for the stocked phytomass amount.

Although direct determination of C levels is important, it is difficult to estimate total average biomass output for the Caatinga vegetation due to the high spatial and seasonal variability in this region associated to rainfall regime and soil type. Kauffman *et al.* (1993), doing direct measurement of the total upper part phytomass in a Caatinga vegetation area of Pernambuco State determined a quantity of 75 t ha^{-1}. However, there are sparse and low vegetation areas and dense and high vegetation areas with estimated variation between 2 and 156 t ha^{-1} (Salcedo and Sampaio 2008). The total biomass production for stubble, measured in Caatinga vegetation preserved area, can vary from 6.5 to 20.1 t ha^{-1} (Martins *et al.* 2008; Amorim 2009).

Estimation for annual phytomass production for Caatinga vegetation varies from 1.0 to 7.0 t ha^{-1} $year^{-1}$ and its biomass accumulation capacity can be figured out as the number of years needed to replace the stock. The required time for renewing firewood vegetation that allows a sustainable exploitation varies from 10 to 15 years (PNUD/FAO/IBAMA 1992). The time needed for vegetation recovery in the soil resting process, in itinerant agriculture exploitation, by nutrient accumulation in plant biomass and in the soil, enough for starting again the cycle, has been estimated for the same year range. The climate and soil variability, as well as degradation intensity during conventional agricultural cycles, make general averages less valid in relation to the high diversity situations.

Another way to estimate arboreal and bushy vegetation productivity is measuring the amount of fallen leaves and debris. The leaf biomass, which corresponds to 5-10% of total Biomass area, is renewed each year and constitutes a great part of the foliage (60-80%) (Salcedo and Sampaio 2008). Arboreal Caatinga vegetation can produce from 2.0 to 5.3 t ha^{-1} $year^{-1}$ of leaves (Dantas 2003). Considering that aerial phytomass contains 40% of C, it can be estimated that Arboreal Caatinga vegetation produces from 1.16 to 2.12 t ha^{-1} $year^{-1}$ of C as fallen leaves only.

There is little information in the literature about biomass production and stock of plant aerial part and root system in Caatinga Biome (Sampaio and Freitas 2008). Information related to root systems are limited to three research papers, two of them are restricted to thin roots in the soil surface layer. Salcedo *et al.* (1999) quantification of root stock up to 5 mm in thickness at 30 cm soil depth varied from 3 to 8 t ha^{-1}, while Tiessen *et al.* (1992) obtained a 12 t ha^{-1} stock for all roots at 1 m soil depth. Medeiros (1999) estimated the production of thin roots up to 2.0 mm in thickness by difference on soil C stock throughout the year and obtained a value corresponding to 2.4 t ha^{-1} $year^{-1}$.

Production variability of aerial and root phytomass occurs because there is a great variety in landscape and environment in the semi-arid. The region relief is very variable; this characteristic contributes to the high landscape unit numbers. Average altitude varies from 400 to 500 m, but it can reach up to 1,000 m. About 37% of the area present slopes which declivity varies from 4 to 12%, being higher than 12% in 20% of the region, causing a striking erosion process in the disturbed areas (Silva 2000).

The establishment of commercial cropping systems in the Brazilian semi-arid tropics is an alternative to supply the region's demand for forest products and decrease cutting of native species. So, introducing high biomass production species that are adapted to the semi-arid edapho-climatic condition seems to be an alternative income for the farmers, benefiting from the Biome preservation and making it possible to stock C in aerial and root phytomass. Based on this, Drumond *et al.* (2008) evaluated the production and distribution of biomass for some arboreal introduced species, for multi-use in the semi-arid region, in low fertility soils, comparing them to local native species with high biomass production potential. Among the studied species, *Mimosa tenuiflora* showed the lowest dry biomass production in aerial and root parts, respectively, 21.6 and 6.60 t ha^{-1}, while for *Caesalpinia velutina* aerial and root a production were 51.6 and 12.0 t ha^{-1}. The importance of generating more information on C stock in aerial and root system phytomass of Caatinga vegetation and in established agro-ecosystems in the Brazilian semi-arid tropics is evident. It is also necessary to develop network research studies to characterize the great variability of the Brazilian semi-arid tropics. Therefore, it is important that all the available research results are gathered to guide the punctual initiatives and plan future research strategies.

MICROBIAN ACTIVITY AND C MICROBIAN STOCK IN THE BRAZILIAN SEMI-ARID TROPICS

The strong climatic seasonality existing in the Brazilian semi-arid tropics significantly affects soil biological processes in the Caatinga vegetation. Average rainfall varies from 400 to 800 mm per/a $year^{-1}$, with very irregular spatial distribution that occurs from 7 to 9 months without significant rainfall precipitation. C additions to soil are limited to a short period in these conditions. When the rainy season starts, recovery of natural vegetation growth is very quick and C addition to the soil is resumed as photosynthesis activity and root metabolite exudation restart. Along this period, C addition will mainly happen by insect actions, promoting addition of leaves and new branches debris to the soil. The soil micro-biota activity resumes from populations that were limited to soil micro-niches that could maintain them in the dry season or from resistant structure (spores) existing in the soil. At the end of the rainy season, as tree leaves and small branches fall and thin roots die, there is the peak of soil biological activity that soon returns to previous conditions. The soil humidity level drops quickly and vegetation Biomass starts to accumulate in the soil, undergoing a quick dehydration process, remaining intact until the next rainfall period. Nevertheless, the wind or the water soil surface runoff will probably remove a significant amount of this organic matter to lower parts of the relief.

Along the dry season of the year, the soil can undergo humidity levels near to zero and very high temperatures. Results obtained by Correia *et al.* (2009) show that the soil surface temperature can vary along the day between 22 and 52ºC in the hottest period of the year (October and November studied condition), whatever soil vegetation cover. The authors point out that soil humidity remained around 1%

along a six month measurement period. Similar results were obtained by Gorlach-Lira and Coutinho (2007) in soil surface temperature remained around 30ºC at winter end and around 58ºC at dry season, and between 30 and 48ºC at 10 cm soil depth at the same periods. In this case, soil humidity levels varied between 1 and 3% during the dry season. In both studies the microbial activity was significantly affected (Gorlach-Lira and Coutinho 2007; Correia *et al.* 2009). Thus, it can be concluded that, under Semi-arid conditions, the high temperatures, low and irregular rainfall, low C input and low soil organic matter levels, microbial populations are seasonally stimulated and selected (Schimmel 1995; Grisi 1997).

The microbial biomass is the most dynamic component of soil organic matter (OM), undergoing quick changes in function of abiotic stress, in the same way that it significantly interferes in the other C stock components. From available data for some Brazilian Semi-arid Tropics areas, a strong influence of edapho-climatic and different local Caatinga vegetation on the C biomass content is observed. Studies of Luna *et al.* (2008) show that the SMB was decreased by almost 50% in the dry season in most of the studied edapho-climatic conditions.

In general, deforesting the Caatinga vegetation for conventional agricultural exploitation, as subsistence agriculture and pasture, decreases C stock content in SMB. As it can be observed, Caatinga vegetation used for silvipastoril or agrosilvipastoril exploitation results in a lower reduction in C stock of the microbial Biomass; similar results were obtained by Maia *et al.* (2006).

The traditional soil cropping in the Brazilian semi-arid tropics is done by removing Caatinga vegetation at different successive stages by firing, cropping the soil. The rate of CO_2 emission in traditionally cultivated areas and the estimated specific respiratory activity significantly increase, showing equilibrium between C addition and consumption in natural areas, being altered by agricultural operations (Maia *et al.* 2006; Nunes *et al.* 2009).

In the irrigated pole of the São Francisco River Valley, Petrolina-PE, there was a significant decrease in SMB-C in annual crop cultivated areas with cropping rotation of onions, melon, pumpkin and beans in the last seven years. However, the estimated specific biological activity is very high, evidencing the disequilibrium between C addition and emission rates. The continuous soil revolving, high temperature, continuous water and mineral nutrient availability and addition of C as plant tissue with low lignifications may explain this behavior. Nevertheless, the continuous incorporation of pruning debris and animal manure to mango and grape cropping systems resulted in SBM-C content inferior to natural vegetation; however, the estimated specific biological activity was superior to Caatinga vegetation and inferior to annual cropping. The results, in this condition, express the lack of soil revolving and the constant addition of organic matter. As a result, cropping perennial crops causes less impact on soil organic Carbon (SOC) that is still less than for Caatinga vegetation situation despite the annual organic matter input in adopted cropping systems (Bernard *et al.* 2006).

RELATION BETWEEN CARBON BALANCE AND ENERGY BALANCE

The stable equilibrium (steady-state) of C reservoir in the soil is the balance between addition (from plant debris and organic fertilizers) and losses (by decomposition and mineralization of organic matter, resulting in liberation of CO_2 to the atmosphere, and by erosion). SOM is a dynamic component and many models have been used to describe its transformation through time. It is known that, depending on the system used and management adopted, the soil can act as source or drain of atmospheric CO_2 (Parton 1987), affecting directly the greenhouse effect. From an agricultural point of view, the soil becomes a CO_2 source for the atmosphere when C losses by oxidation are higher than the additions. Management systems that use soil plough before cropping are the cause of those losses (Bruce *et al.* 1999; Perez *et al.* 2007); on the other hand, at high biomass production and debris addition conditions, they act as C source for the soil (Campos *et al.* 1999).

Classical definitions for agricultural sustainability consider, in general, environmental, economic and social aspects, emphasizing the maintenance of environmental resources, the economic viability and the social correctness. Addiscott (1995), in his paper "Entropy and sustainability" proposes a thermodynamic view for sustainability that considers the environmental factor only, but it is extremely useful to analyze areas under degradation process. Thermodynamic work is realized when energy in heat form is transferred from a high temperature source to a low temperature drain. So, continuous dynamic work requires isothermal reservoirs effectively infinite to high and low temperatures that are furnished to biosphere by the sun and space, respectively. During this work the energy flows from the sun to space and entropy is produced, but the work in the processes at the earth's surface can lead to considerable increases in the order and decrease the entropy at a local scale. Besides the processes that allow organizing, there also are disorganizing processes at local scale. Photosynthesis is an organizing process that allows the formation of complex substances with high molecular weight from simple molecules as CO_2, H_2O, Ca and P. Respiration, SOM oxidation and decomposition of soil aggregates are disorganizing processes. Both processes (organizing and disorganizing) have a straight relation with C and energy balances. Agricultural sustainability depends on an equilibrium maintenance between order and disorder, which are processes that decrease or increase the entropy.

It is necessary to refine energetic analysis methods to allow a better use of natural resources and the evaluation of the environmental impacts on intensive processes in energy. The solution is based on the fact that living organisms (Schneider and Key 1995) and the soil are not closed systems, being open processes that do not obey to Thermodynamic Law established for closed systems.

All elements that are in the physic and biological structure of the Caatinga Biome, in both preserved and disturbed systems, integrate a combination of environmental variables that characterize it at present. From this point of view, the interactions in the mineral system, plant and microorganisms, managed by man through agricultural systems or impacts that bring out changes in the C and energy balance, cause different effects on soil-plant-atmosphere fluxes. Each component, in relation to its interaction with the C, N and solar radiation cycles, promotes conditions for absorption and transmission of energy and matter, which are able to maintain their own factors that act on the C and energy balance of preserved and disturbed Caatinga vegetation.

In Brazil, many researches has been done to show the changes in the energy balance in the anthropization process of the Biomes. By simulating substitution of forest by pasture, Nobre *et al.* (2002) found evidence that for the energy balance, the solar radiation absorbed at soil surface is lower in pasture areas (180 W m^{-2}) than in forest areas (204 W m^{-2}) due to albedo variations that increase from 12.5% in forest areas to 21.6% in pasture areas, evidencing that the type of soil cover is a determinant factor in the energy balance. In this context, the conversion effect of preserved Caatinga vegetation into agricultural areas (disturbed) can implicate an alteration in the energy equilibrium, meaning a strong environmental impact, since the solar rays would be absorbed in a higher amount due to changes in local albedo, causing variation in energy balance and in C stocks in both soil and phytomass. It is necessary to determine available energy flux (Rn – G) and albedo in referential areas of the Brazilian semi-arid tropics. This may make it possible to: a) determine the solar radiation balance components, b) obtain the heat flux at soil surface, c) measure the temperature and humidity of the air and soil, d) determine the reflective power (albedo), and e) do a systemic analysis, using thermodynamic concepts for open systems, for existing relations among man, plant, mineral, micro-organisms and atmosphere in C balance of reference areas of the Brazilian semi-arid tropics. Therefore, subsidies to discuss adaptable and mitigating providences for the different canaries proposed by IPCC and to develop sustainable production systems will be available.

In this way, it is necessary to carry out studies on C and energy exchange processes in the biosphere system of the Caatinga Biome, taking into account different anthropizing types, for understanding the land use changes at radiation, heat and C magnitude fluxes.

Nevertheless, studies on C, water and energy cycles in preserved Caatinga vegetation and on different disturbed systems in the Brazilian semi-arid tropics are scarce and that information is necessary for understanding soil-vegetation-atmosphere interactions, as well as the consequences of possible changes presented by that Biome, such as soil use changes, climatic variation and increase in CO_2 content in the atmosphere. Those changes can affect the structure and operation of agricultural systems and extractivism in exploited areas, having detrimental consequences on local and regional climatic processes. So, the conversion effect of preserved Caatinga vegetation into degradated areas can cause a change in the energy equilibrium, meaning a strong environmental impact that causes modification in the local albedo, exposing soil surface to straight solar radiation. This can cause variation in the energy balance and increase thermal amplitude, resulting in an adverse environment for regenerating some species.

Solar radiation is an important factor to measure the energy balance. It can directly affect air and soil heating processes and evaporation and photosynthesis. The wind can cause mechanic turbulence that makes heat and CO_2 exchanges easier. In this way, the scientific research of microclimatic changes at a vegetation canopy implies studying the energy balance components in the limiting surface layer and the consequent interactive processes, where wind and solar radiation are essential (Ribeiro *et al.* 2008), causing changes in C balance.

Oliveira Filho *et al.* (2006) evaluated the seasonal variation of CO_2 flux, water steam and energy in natural Caatinga vegetation. The evaporation rate was very low in the dry season as well as in the rainy season due to the low water availability, with values close to zero at the end of the dry season. During the dry season, about 60% of available energy was used to heat the air and the evapo-transpiration rate corresponded to 10% of available energy, on average. The rates were 46 and 17%, respectively, for the rainy season. Referring to the CO_2 flux, the ecosystem acts in the CO_2 vanishing at the beginning of the dry season, when the soil is still humid from the previous rainy season; this also happens in the rainy season. At the end of the dry season, the system acts as a CO_2 source because the photosynthesis rate is nil due to leaf pores shutting up and leaves falling down.

From the studies on balance and energy done in the Caatinga Biome, in preserved areas and disturbed systems, which have been carried out in reference areas and in long term experiments, it will be possible to amplify the scientific and technological bases to continue the studies involving others areas, making it possible to estimate the impact on the Biome Caatinga and its anthropization in the global heating.

It will also be possible, from the studies which have been carried out by Brazilian research groups, to develop soil and crop management systems that benefit the accumulation of C in the soil-plant systems, causing a positive matter and energy balance, decreasing the greenhouse effect gases emission and/or increasing C sequester in the Brazilian Semi-arid Tropics.

In agricultural systems, in and out fluxes are not stable. A specific superior order level will only be achieved when the magnitude of the fluxes is positive, furnishing high amounts of energy for maintaining a specific order level and an energy to improve to a superior order level, assuring sustainability and quality to the system.

EFFECT OF LAND USE ON THE ORGANIC CARBON BALANCE

In 1984, the Caatinga Biome cover was estimated to be about 68% of its remaining vegetation, 32% being disturbed areas, which are areas occupied by agricultural exploitation or altered by man's action (CNRBC 2004). Later on, in 1990, the data was updated by the Northeastern Development Agency (SUDENE) and the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA). These institutions detected an expressive reduction in the remaining vegetation cover. According to that update, the total area of the Caatinga vegetation changed from 68 to 47%. In the same period of time, disturbed areas increased from 32 to 53% of the Biome's total surface.

In 2004, mapping of Caatinga Biomes was resumed through the Maintenance and Sustainable Use of Brazilian Biological Diversity Project. The obtained results showed a remaining vegetation area superior to 43% of the Caatinga's total Biome area. Based on this survey, the remaining Caatinga vegetation was estimated to be 363,115 km^{-2}.

To develop the survey for the Caatinga Biome in 2008, 163 digital images were obtained. One hundred eleven scenes came from orbital sensors CBERS2B and 52 came from TM Landsat 5. Starting from delimitation/quantification of disturbed areas, maps were drawn, statistical analysis was done to establish, identify and spatially visualize the suppression distribution of the Caatinga Biome vegetation in the Brazilian states, municipalities and hydrographic basins. The area of Caatinga vegetation, with scale and minimum detecting area accuracies, was 55.67% in 2002; in 2008, a decrease to 53.62% was observed. All this statistical information was based on the total area of the Caatinga Biome and calculated by the software ArcGIS (MMA 2010). The remaining vegetation in 2008 was higher than in 2004; this happened due to the use of a more accurate methodology but not due to actions that promote vegetation recovery in altered areas.

Deforesting processes due to agricultural subsistence exploitation spreads through the Caatinga Biome due to annual cleaning of new cropping areas. This phenomenon occurs because subsistence agriculture, plant cropping under rainfall only, comprises the intensive use of the same production area for 3 to 4 continuous years, remaining useless for 7 to 8 years, following a soil resting cycle or vegetation recovering for a new wood cutting, burning, pasture or cropping. However, different from other country Biomes, agricultural production in those areas of subsistence agriculture does not create new deforestation areas in the Caatinga Biome (MMA 2010).

Commercial agriculture exploitation, which uses irrigation and external inputs and which is based on large-scale production, aiming at export markets, became very profitable for the region in the last 30 years. Irrigated cropping systems are relevant since new job opportunities have been offered, being a main income for people of some production poles of The Brazilian Semi-arid Tropics. Some of the main explored crops are mango, grapes, passionflower, melon, papaya, banana, Antilles berry and cashew, among others (CNRBC 2004).

Commercial cropping systems as soybean ad castor bean are part of a growing regional economy. Castor bean is part of the Brazilian bio-fuel production and the Brazilian Semi-arid Tropics is responsible for 50% of national production. Increasing new areas for cropping these crops have impacted the Caatinga Biome deforestation process.

The agricultural production, especially in irrigated areas, can affect the fragmentation, removing and conversion processes of natural area uses in the Brazilian Semi-arid Tropics, while subsistence agriculture occupies small areas and does not cause new area cleaning for cropping or new frontier danger. However, the existing demand for firewood and

Table 1 Soil organic matter (SOM) content in different land use systems and soil depths in a YELLOW ULTISOL – Euthrofic latosolic, medium clay texture, located at Embrapa Semi-arid Experimental Station, Petrolina-PE.

Soil depth	Preserved Caatinga area	Altered Caatinga area	Buffel grass area	Mango system area
	TOC stock			
cm	---------------------------- Mg ha^{-1} ----------------------------			
0.0 – 2.5	4.54 a	2.20 bc	2.29 b	1.43 c
2.5 – 5.0	2.53 a	1.71 bc	1.87 b	1.22 c
5.0 – 7.5	1.99 a	1.61 ab	1.36 bc	1.01 c
7.5 – 10.0	1.71 a	1.51 a	1.31 a	0.85 b
10.0 – 15.0	2.48 a	2.82 a	2.26 a	1.33 b
15.0 – 20.0	2.23 a	2.41 a	1.82 a	1.08 b
0 – 20.0	15.48	12.26	9.60	6.92

*Means followed by different letters in a row differ significantly by Tukey's test ($P \leq 0.05$).

charcoal amplifies (accento) the deforested areas because family income of small farmers is improved by selling Caatinga vegetation wood. The portion of natural vegetation used as firewood and charcoal corresponds to more than 30% of energetic matrix (Campello 2008). Thus, the use of woody vegetation for producing firewood and charcoal, together with use conversion aiming at cropping and cattle-raising, are pointed out as the greatest threat to natural area fragmentation.

Changes due to antropizing processes of the Caatinga Biome modify soil and vegetation C stocks. This effect can be evidenced in the study, developed in 2009, to evaluate the TCO stock in preserved Caatinga vegetation, altered Caatinga vegetation, Buffel grass (*Cenchurs ciliairis* L.) pasture and irrigated mango cropping in a Yellow Ultisol (**Table 1**). Soil C stock in preserved Caatinga is significantly superior to all the other land use systems at a 10 cm soil depth. The studied, preserved Caatinga has a 400 ha area, approximately. The land belonged to small farmers that used adjacent areas for subsistence agriculture by cropping maize and beans, as well as for goat, sheep and bovine raising in Caatinga natural vegetation. In 1974, the area was alienated, remaining fenced without any anthropic intervention in its natural ecosystem. The altered Caatinga area has 76 ha and was deforested in 1983. Deforesting was done by firing and ploughing. After cleaning, the area was cropped with species of *Prosopis juliflora*. The cropped area was plough and hoe cleaned until 1989. After that period of time, the area was abandoned and, actually, there are few mesquite trees and little bushy vegetation. The Buffel grass area has 30 ha and was established in 1977 after cleaning the Caatinga natural vegetation. Mineral fertilizers were never applied to the area, being preserved by annual ploughing. The irrigated mango area, which was cleaned in 1998 and cropped with annual crops from 1999 to 2004, has 1 ha and was established in 2004.

Preserved Caatinga, altered Caatinga and Buffel grass areas did not significantly differ at 10 to 20 cm depth, but all these systems have a soil TOC stock higher than in irrigated mango systems (**Table 1**). It is valid to point out that changes in land use of the Caatinga Biome significantly altered soil C stock. Mango cropping significantly decreased TOC at all soil depths. High temperatures and insolation intensities, which are climatic characteristics of Semi-arid regions, associated to high water availability in the irrigated mango system, increase the entropy system, benefiting the minimum energy state and maximum disorder, resulting in a C stock reduction.

It will be possible to increase the scientific and technological bases to develop agro-ecosystems that accumulate C, decreasing greenhouse effect gas emissions and/or increasing its sequestration, through research studies on C stock and dynamic of the Caatinga Biome in preserved areas and disturbed systems.

FINAL REMARKS

Caatinga is the most representative Biome of the Brazilian Semi-arid Tropics, besides being considered as a completely Brazilian Biome with one of the most complex vegetation types, which main characteristics are arboreal or bushy forests, comprising low trees and bushes, many of them with thorns and microphylia, with xerophytic characteristics. There are also Cactaceae and Bromeliaceae species, lianas and herbaceous plants that are important due to their forage, medicinal and apiary values, constituting Brazil's most resilient type of vegetation. However, a great part of this vegetation was taken out to be used as a source of energy or the area was cleaned for extensive livestock raising, dry land farming and irrigated agriculture exploitation. Actually only 53.6% of the Caatinga Biome is maintained as natural vegetation.

The Caatinga Biome is compounded by arboreal-bushy vegetations that are classified in many typologies, distributed in 17 great landscape units that are subdivided in 105 geo-environmental units. In this diversity, data on production and stock of Biomass of aerial plant part and root system are scarce, evidencing the need for (further) research studies.

Natural content of TOC in soils of the Brazilian semi-arid tropics are normally low, varying according to its taxonomic classification. Among the existing different soil classes, Vertisols and Inceptisols show the highest TOC contents, 12.3 and 12.2 g.kg^{-1}, respectively, but they only represent 5% of total Brazilian Semi-arid Tropics area. The most representative soil classes, but with lower COT contents, are Ultisols and Lithic Psamments (between 11.5 and 10.4 g kg^{-1}) and Oxisols and Ultisols (between 9.7 and 8.9), comprising 68% of the total area. Albic sub-order and Orthents show the lowest COT contents, 7.4 and 4.9 g kg^{-1} respectively, comprising only 8% of the total area.

The existing strong seasonality in the Brazilian Semi-arid Tropics significantly affects the biological process of Caatinga soil. The microbiologic component can help to understand the C dynamic flux in this environment. In Brazilian Semi-arid conditions, it's possible to observe, in a general way, that the use of Caatinga area in silvopasture agroforestry and cleaning the natural vegetation for conventional agriculture exploitation, like subsistence agriculture and livestock pasture, reduce the soil microbial Biomass. Microbial studies associated to energy balance demonstrate that the ecosystem acts as a CO_2 consumer in the beginning of dry season when the soil is still humid from the previous rainfall season, as well as in the rainy season. At the end of the dry season, the system acts as a CO_2 source because the photosynthesis rate is nil due to leaf pores closing up and leaves fallen down.

Ongoing research studies show that changes due to antropizing processes in the Caatinga Biome decreased soil and vegetation C stocks. In the soil, TOC was higher in Caatinga preserved than in Caatinga altered, *Cenchrus ciliares* L. pasture and irrigated mango tree. Management practices, for both irrigated agriculture and dry land farming, as a mitigating alternative to climatic changes that increase C stock stored in the soil system has been studied. It will be possible to amplify scientific and technological bases to develop agro-ecosystems that accumulate C, decreasing greenhouse effect gas emissions and/or increasing its sequester, by studying C stock and dynamic flux in the Caatinga Biome in preserved and disturbed areas.

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