

RENISSON NEPONUCENO DE ARAÚJO FILHO

**CARBON, MICROBIAL ACTIVITY AND NUTRIENTS IN SOIL IN A CAATINGA  
(PERNAMBUCO, BRAZIL) UNDER FOREST CHRONOSSEQUENCE  
MANAGEMENT**

RECIFE-PE

2016

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Thesis presented to Federal Rural University of Pernambuco, as part of the demanding of Graduate Program in Soil Science to obtain the Doctor Science title.

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UNIVERSIDADE FEDERAL RURAL DE PERNAMBUCO – UFRPE  
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS DO SOLO  
DEPARTAMENTO DE AGRONOMIA

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# CARBONO, ATIVIDADE MICROBIANA E NUTRIENTE EM SOLO EM UMA CAATINGA (PERNAMBUCO, BRASIL) SOB CRONOSEQUÊNCIA DE MANEJO FLORESTAL

## RESUMO

A alteração da estrutura da floresta de Caatinga por meio da talhadia simples modifica o fluxo de nutrientes e matéria orgânica do solo no ecossistema florestal. O trabalho foi desenvolvido em solos de Caatinga hiperxerófila, Floresta (PE), com o objetivo de avaliar os efeitos nos diferentes tempos de manejo florestal o carbono, atividade microbiana e nutrientes no solo ao longo de uma cronosequência de floresta de Caatinga na região semiárida do Nordeste do Brasil. As amostras de solo foram coletadas no mês de outubro de 2013 período seco, em trincheiras nas profundidades 0–5, 5–10 e 10–20 cm, com cinco repetições, nos diferentes tempos de manejo florestal: 0, 6, 9, 12, 25, 50 anos e Reserva (80 anos). Foram realizadas determinações de  $\text{Ca}^{+2}$ ,  $\text{Mg}^{+2}$ ,  $\text{K}^+$  e  $\text{Na}^+$ , carbono, frações húmicas e atividade microbiana. A análise estatística utilizada foi regressão e os coeficientes de correlação simples foram realizados para examinar as propriedades químicas e matéria orgânica do solo. Os cátions trocáveis  $\text{Ca}^{+2}$ ,  $\text{Mg}^{+2}$  e  $\text{K}^+$  aumentaram em função do tempo na cronosequência de floresta de Caatinga. O pH e o carbono influenciaram nas modificações dos cations trocáveis. Houve maior armazenamento de C no solo e nas frações húmicas nas áreas de maiores tempos após o corte no manejo florestal, havendo um aumento inicial rápido no armazenamento do carbono depois de 6 anos, alcançando um equilíbrio ao longo dos anos. O carbono microbiano e quociente microbiano foram alterados em função dos níveis de degradação. Conclui-se que seriam necessários longos períodos de tempo, para que sejam recuperadas 100% dos valores das propriedades químicas e carbono do solo. Para recuperação de pelo menos 50% é necessário pelo menos 33 anos, antes de um novo corte da Caatinga.

**Palavras-chave:** capacidade de troca de cátions, fertilidade, fracionamento, matéria orgânica, semiárido.



# **CARBON, MICROBIAL ACTIVITY AND NUTRIENTS IN SOIL IN A CAATINGA (PERNAMBUCO, BRAZIL) UNDER FOREST CHRONOSSEQUENCE MANAGEMENT**

## **ABSTRACT**

The amendment of the Caatinga forest structure through simple coppice modifies the flow of nutrients and soil organic matter on the forest ecosystem. The work was developed in hyperxerophilic Caatinga soils, Floresta (PE), with the objective of assess the effects of forest management in the carbon, microbial activity and nutrients in the soil along a chronosequence Caatinga forest in semiarid region of Northeastern Brazil. Soil samples were collected in October 2013 dry season in trenches in the depths of 0-5, 5-10 and 10-20 cm, with five repetitions at different times of forest management: 0, 6, 9, 12, 25, 50 and reserve (80 years). Determinations were performed  $\text{Ca}^{+2}$ ,  $\text{Mg}^{+2}$ ,  $\text{K}^{+}$  and  $\text{Na}^{+}$ , carbon, humic fractions and microbial activity. Statistical analysis used was regression and simple correlation coefficients were conducted to examine the chemical properties and soil organic matter. Exchangeable cations:  $\text{Ca}^{+2}$ ,  $\text{Mg}^{+2}$  and  $\text{K}^{+}$  increased in function of time in the chronosequence Caatinga forest. pH and carbon influenced in the changes of exchangeable cations. There was higher C storage in soil and humic fractions in the areas of longer times after cutting in forest management, with a rapid initial increase in carbon storage after 6 years, reaching a balance over the years. Microbial carbon and quotient microbial were changed in function on the levels of degradation. Microbial carbon and microbial quotient showed great sensitivity to increased levels of degradation. Concludes that it would require long periods of time, to be recovered 100% of the values of the chemical and soil carbon. For recovery of at least 50% is required at least 33 years before a new cut of the Caatinga.

**Keywords:** cation exchangeable capacity, fertility, fractionation, organic matter, semiarid region.

## 1. INTRODUCTION

The Caatinga forests are located in the semiarid of Brazil Northeast, occupying an area of around one million square kilometers, covered by deciduous vegetation. This biome has different physiognomies according of year period. In the rainy season, the landscape becomes green, while in the dry season most of the plants lose its leaves in response to water scarcity. From the original area, 40% is covered by native vegetation in different regeneration stages, after it had been cut for firewood production, the main purpose, or to open areas for planting in shifting cultivation system (Sampaio, 1995; Bezerra-Gusmão et al., 2011).

However, the need for development and accelerating urbanization, by increased pressure of the human population has led to removal of large area for cultivating natural forests, housing and wood production (Coelho et al., 2014). The main cause of Caatinga deforestation is the wood extraction, which is converted into firewood and charcoal, and used for plaster and ceramic poles in Northeastern Brazil (Travassos and Souza, 2014). Coal use in small and medium industries and in homes was also nominated (Bessa et al., 2005).

The forest management technique in Caatinga is the simple coppice type. This silviculture management technique is characterized, that after cutting of trees, the dormant buds or adventitious, stumps and/or roots that have remained in the woods, develop emitting sprouts that start a new forest cycle and is therefore applicable to those forest species that have the capacity to sprout after clearcutting (Hardesty et al., 1988).

Forest removal is the main disorder, because the intensive management for wood may affect nutrient distribution and fluxes in forest ecosystem (Likens and Bormann, 1995). This breakdown of forest structure for human activities, with forest vegetation removal, alters ecosystem processes, through nutrients and soil organic matter loss (Pritchett and Fisher, 1987). Besides, the interruption of plant nutrient uptake, and other processes such as evaporation, decomposition and transformation of elements in nutrient cycling processes are changed (Boring et al., 1981).

Although the SOM dynamics and quality have been widely studied in humid tropical soils in recent years, there are still few results generated in other

important biomes such as Caatinga. Specifically in this biome, which native forests are established in good natural fertility soils and strongly associated with climate. The balance between vegetation maintenance and soil biogeochemical processes, and soil C changes evaluation caused by human intervention in natural ecosystems, play important roles in environmental conservation monitoring (Tiessen et al., 2001).

Based on the scientific hypothesis that forest simple coppice modifies soil properties, the objective of this study was to evaluate effects of forest cuts in a chronosequence of hyperxerophilic Caatinga forest, on carbon, microbial activity and nutrients in soil at semiarid region of Pernambuco, Northeastern Brazil.

## **2. LITERATURE REVIEW**

### **2.1. Caatinga biome**

The semiarid Northeastern Brazil occupies an area of 1.037.517,80 km<sup>2</sup> distributed in 1133 municipalities, representing 70% of the Northeast Region and 13% of Brazilian territory (Alves-Junior et al., 2013). This region presents rich biodiversity, as well as being one of the most densely populated (Alves et al., 2008). The soils are relatively rich in nutrient, they show sometimes layer of pebbles and gravel on the surface. The maximum depth reached is between 40-60 cm above the rock, and the maintenance of fertility is through nutrient cycling (Sampaio, 1995; Lepsch, 2010).

The semiarid has as characteristic rain irregularity, with two seasons: wet winter (three to five months) and dry summer (seven to nine months). This rainfall irregularity promotes prolonged drought, with a negative hydric balance due to high evaporation (Correia et al., 2015). Caatinga is a xerophytic vegetation compound by tree, shrub and herbaceous plants, with wide variation in physiognomy and flora, and high species diversity (Trovão et al., 2007; Souto et al., 2009). It generally has deciduous behavior and thorns and small leaves presence, and succulent and herbaceous ephemeral plants, growing only during the short rainy season (Cardoso and Queiroz, 2007).

Caatinga term is a typical name from Brazilian Semiarid Northeastern Region and has indigenous origin (“caa” - woods; “tinga” - white, clear, open), meaning white forest (Nascimento et al., 2014). Dry forests correspond about nearly half of the tropical and subtropical existing forests, and Caatinga is considered one of the most exploited and degraded ecosystems in the world (Prado, 2003). Degradation process there is generally caused by deforestation and inappropriate use of natural resources. According to Drumond et al. (2000), 80% of Caatinga areas are successional and about 40% are kept in pioneering state of secondary succession, due to predatory and extractive use.

Deforestation in the Northeastern Brazil semiarid region, associated with long dry periods, promotes soil degradation with exposure to actions of high temperatures and winds, decreasing its productive potential, with irreversible damage to the environment (Trevisan et al., 2002; Souto et al., 2005; Menezes e Silva, 2008). Despite its great importance, Caatinga is the least studied and protected Brazilian floristic composition, although few studies have plant species of unquestionable importance in its formation (Trovão et al., 2004). Xerophytic character of this vegetation allows their survival in periods of prolonged drought, contributing to the ecosystem balance.

## **2.2. Main soils under Caatinga**

The main soils occupied by Caatinga in Pernambuco backwoods areas, in general, are shallow, not very evolved, have physical problems, and have basic reaction and high natural fertility.

Soils result from combined action of its formation factors, ie original material (Geology), climate, relief, organism's action and time. Pedogenetic horizons and/or layers which differ from each other and in relation to original material (rock and sediment) can be observed in vertical cuts of soils in landscapes, for example, in road banks. This differentiation occurs in function of the formation processes, ie, additions, losses, translocations and transformations of matter and energy in the soil profile (Buol et al., 1997; EMBRAPA, 2013). Soils are the main indicators of environmental variability and therefore are excellent stratifiers the natural environment, because they reflect formation factors and processes.

In Brazilian Northeast Region, soils found in Caatinga biome are Latossolos, Argissolos, Planossolos, Luvisolos and Neossolos. In low proportions have been the Nitossolos, Chernossolos, Cambissolos, Vertissolos, and Plintossolos (Araújo-Filho et al., 2000). The semiarid region exhibits a relatively large environmental variability, especially with respect to geological materials and relief, and also some important variations in relation to the weather. And this variability promotes significant differences in soil environments that integrate the area occupied by Caatinga biome. As moisture is getting scarce, especially when enters the semiarid environment, the climate will gradually lose importance (minor action of chemical weathering). And Geology (lithology) shall assume increasingly highlighted in the set of features and soil properties (Araújo-Filho et al., 2000).

Among the soil classes that predominate in Caatinga areas, the main are Neossolos. They are characterized by being pedogenetic undeveloped soils, with sequence of horizons type A-C or A-R, and presenting mineralogical characteristics relatively similar to original material (EMBRAPA, 2013).

Luvisolos are normally shallow soils, have high activity clay ( $CTC > 27 \text{ cmol}_c \text{ kg}^{-1} \text{ clay}$ ), high base saturation associated with high bases sum, and a pronounced change in clay content between the surface layer [(A) or (A+E) horizon], and underlying Bt horizon (textural B horizon). The most common colors are red or reddish-brown Bt horizon. They occur commonly associated with superficial stoniness (EMBRAPA, 2013). The most important agricultural limitations of these soils are because they have high susceptibility to erosion, little effective depth, surface stoniness and sometimes the bustling relief (Araújo-Filho et al., 2000).

Latossolos are soils with a high degree of weathering, usually deep, well drained and fairly uniform in the set of their morphological, physical, chemical and mineralogical characteristics in the diagnosis Bw horizon (B latosolic). They are medium to very clayey texture with small variations in clay content along soil profile and can present yellow, yellow red, red and even gray color (EMBRAPA, 2013). Its main agricultural restrictions generally are related to low nutrient availability for plants (Araújo-Filho et al., 2000).

Planossolos are imperfectly or poorly drained soils and characterized for presenting an abrupt transition between horizons, generally associated with an

abrupt textural change between the surface layer horizons [(A) or (A + E)] and underlying B planic horizon (Bt planic) practically waterproof. B planic horizon is a drainage impediment, has high bulk density, has slow or very slow permeability and, sometimes, is cemented (EMBRAPA, 2013). So it has gray color, commonly with the mottled presence. The main limitations of these agricultural soils are drainage deficiency, and restrictions related to effective depth, stoniness and sodicity (Araújo-Filho et al., 2000).

Caatinga forests management in Pernambuco is being developed in areas occupied by these soils classes. There is wide soil variability, as well as their potential use. In addition, it should be noted that adopted management in these areas, may have promoted significant changes in chemical and biological properties of these soils, influencing on its quality.

### **2.3. Caatinga forest management**

The main cause of Caatinga deforestation is the wood extraction of forest, which is converted into firewood and charcoal intended mainly for plaster poles and ceramic northeast (Travassos and Souza, 2014). Coal use in small and medium industries and in homes was also nominated (Bessa et al., 2005). Other factors reported were the areas created for biofuels and cattle ranching.

The biggest contributor to deforestation is the removal of natural forest plants, consisting of species locally in extinction as aroeira (*Schinus terebinthifolius*), baraúna (*Schinopsis brasiliensis*), imbuzeiro (*Spondia tuberosa*), quixabeira (*Bumelia sertorum*), imburana de cambão (*Bursera leptophloeos*) and cactaceae (Martins et al., 2004; Alves et al., 2008; Silva et al., 2014; Álvares-Carvalho et al., 2015; Oliveira et al., 2015). In order to mitigate this problem, there is a sustainable forest management plan in current Forest Code in Brazil, dating from 1965 through the number of Decree Law of 4771. This law was created as a way to regulate the exploitation of primary forests and other forms of vegetation in parts of the country, as its main objective the economic obtaining forest products (Garcia, 2012).

Forest management is a collection of techniques used to carefully collect part of large trees, so that smaller ones are protected, to be harvested in the future. With the adoption of handled timber, production can be continued over

the years (Botelho, 1998). The main reasons to manage the forest are continuity of production, profitability, job security, rule of law, market opportunities, forest conservation and environmental services (Lamprecht, 1990).

There are several silvicultural systems that can be used according to different forest products. The adopted silvicultural system determines the distribution of tree ages, or the stand structure. According to Matthews (1994), silvicultural systems represent the driving process of forests, exploitation and regeneration, within which can establish different management regimes, according to each type of product to be obtained.

Among the main silvicultural systems, there is tall trees management. This management regime prioritizes wood in smaller diameters production and it is used to maximize production per area unit. Debranching is an operation that aims to obtain logs without knots presence, improving quality and increasing amount of wood. Thinning is a silvicultural activity that aims to remove some trees in order to favor remaining trees growth. This withdrawal is therefore intended to reduce the existing competition between plants, providing more resources, especially water and energy (Scolforo and Maestri, 1998).

In Caatinga, the adopted forest management technique is the simple coppice type. This sylviculture management technique has as characteristic that, after trees cutting, the dormant or adventitious buds, stumps and/or roots remained in the woods, develop and emit sprouts that start a new forest cycle. And it is applicable to those forest species that have the capacity to sprout after clearcutting (Hardesty et al., 1988).

This extraction is for wood production of small to medium in size, eliminates the seedling production, soil preparation and new planting. It is ease for planning short and medium timber production term, lower production costs per produced wood and shorter cycles in advance to financial returns (Lamprecht, 1990; Evans, 1992).

#### **2.4. Caatinga forest management effects on soil nutrients and pH**

Forest harvest can have an effect on nutrients in an ecosystem due to biomass removal, erosion and leaching promotion. Vegetation removal is the main disorder, because intensively managed forests for wood production may

affect distribution and nutrient fluxes in ecosystem (Likens and Bormann, 1995). This forest structure breakdown by human activities, with the removal of forest vegetation, alters ecosystem processes through soil nutrient and organic matter losses (Pritchett and Fisher, 1987). Besides, the interruption of plant elements uptake, and other processes as evaporation, substances decomposition and transformation, and nutrient cycling process are changed (Boring et al., 1981).

$\text{Ca}^{2+}$  (calcium),  $\text{K}^{+}$  (potassium) and  $\text{Mg}^{2+}$  (magnesium) are essential elements that play important roles in plant development (Vergutz et al., 2012). As well as interactions between N (nitrogen) and P (phosphorus) are potentially important for health and stability, since all these elements are macronutrients in terrestrial ecosystems (Lucas et al., 2011).

Other soil properties have also great importance on forest sustainability and may be changed by vegetation cuts. Some studies have shown that CEC increases with the addition of green manure, and this are promoting increasing in soil pH due free  $\text{H}^{+}$  and  $\text{Al}^{3+}$  complexation with anionic organic compounds from the residues, and increasing CEC soil saturation by  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^{+}$  added by plant residues, which would reduce the potential acidity (Franchini et al., 2001). In soil, CEC increases with clay fraction when compared with the sand fraction (Curtin and Smillie, 1976; Churchman and Burke, 1991). High CEC values in soils allow greater retention of cations, while low CEC soils are more likely to possess greater deficiency in magnesium and potassium (Carter et al., 1986).

Basically, forest removal with canopy openness through forest management changes the microclimate conditions and causes changes in soil physical (temperature, humidity, bulk density), chemical (C, N, P, and pH) and microbiological (alterations in metabolic activity) properties, dependent on these environmental factors (Ekschmitt et al, 2008; Karam et al, 2012).

## **2.5. Caatinga forest management effects on soil carbon and microbial activity**

Forests play an important role against climate change by their great potential to store more C than any other terrestrial ecosystem (Dixon et al. 1994). In the semiarid Northeastern Brazil, Caatinga forests are covering a wide



area characterized by deciduous vegetation which is overthrown often to production of firewood, and for planting in itinerant agriculture system (Sampaio, 1995; Bezerra-Gusmão et al., 2011). Forest management, with the harvest of biomass for forest products, can significantly affect C stock in soil (Nave et al., 2010).

The C stock is mainly distributed in the soil organic matter (SOM) that consists of plant tissues, animals and microbial biomass decomposed. These components of SOM are exchanged between biosphere and atmosphere, being able to affect atmospheric chemistry, energy balance, water and climate (Raich and Schlesinger, 1992; Conrad, 1996).

The knowledge of C stock potential helps us to understand how ecosystems would respond to natural and human disturbances, under different management strategies (He et al., 2008). Global climate change problematic can be mitigated with the evaluation of C sequestration potential in terrestrial ecosystems. This expectation is very important to get a wide database that retains information about intercurrent C stock under different plant species and different management strategies of this ecosystem to quantify changes in C stock (Wu et al., 2008).

Changes in macro and micro scale of soil environment also cause alterations in microbial growth, and result in different rates of SOM decomposition (Anderson and Domsch, 1989). From microbial biomass it is possible to detect changes in soil C, since it respond more quickly to changes caused by forest management (Jenkinson and Ladd, 1981; Powlson et al, 1987; Carter, 1992).

Another factor that allows determines changes in soil C is humic substances proportion. In addition to serving as a C reservoir, humic substances improve soil structure, increase productivity and quality of crops, protect phosphorus against adsorption on clay fraction, increase specific surface, CTC and buffer effect, and give greater stability to the soil. In this context, humic substances are important regulators of chemical and biological functions of soil, and represent therefore a strong factor for the sustainability of terrestrial ecosystems (Stevenson, 1994).

Although C levels in soils, humic substances and microbial biomass are widely studied in humid tropical soils, there are still few results generated in

other important biomes such as Caatinga. In this aspect, is very important to understand the capacity for native vegetation regeneration as C sink in the soil for the establishment of sustainable management in long term. Humic substances exert widely recognized influence on chemical, physical and biological soil properties. Humic substances contribute to C persistence in soil with its reactive and refractory chemical nature (Kiem and Kogel-Knabner, 2003; Rovira and Vallejo, 2007), as well as its important role in nutrient flows through ecological systems and C emissions to atmosphere (Lal, 2006).

Specifically in this biome, which native forests are established in good natural fertility soils and have their main characteristic associated with climate, maintenance balance between vegetation and soil biogeochemical processes is fundamental (Tiessen et al., 2001). Evaluation of changes in soil C, caused by human intervention in natural ecosystems, plays an important role in monitoring environmental conservation.

### **3. MATERIAL AND METHODS**

#### **3.1. Study area**

The study was conducted in a hyperxerophilic Caatinga area (8°30'S and 37°57'W) located in the municipality of Floresta, Pernambuco state, Brazil. The area is located in semiarid climate type Bsw'h, characterized as warm and dry (Köppen, 1948), with annual average temperature 28°C. The average annual precipitation is 500 mm, occurring between November and March, and the potential annual average evapotranspiration is 1.646 mm (EMBRAPA, 2007). The relief is flat to gently corrugated.

The choice of the experimental area was based in management plans on the existence of a well defined chronosequence in forest cut. Seven sites were selected: 50 and 25 years Itapemirim farm, owned by Excelsior Agrimex Agroindustrial S.A and another areas R, 12, 9, 6 e 0 years Fonseca farm owned particular, descriptions of each site are as follows:

The R (reserve) area has 80 ha extent, and in the last 80 years it had not been subjected to any kind of anthropogenic interference. It is located between coordinates 08°36,423' S and 37°59,290' W. The soil was classified as

Neossolo Litólico (EMBRAPA, 2013). The vegetation in this area was characterized by five species of highest importance value, totaling 2288 individuals. In percentage by species in the area are: 30,34% catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 26,51% jurema de embira (*Mimosa ophthalmocentra* Mart. ex Benth.); 7,05% quebra faca branca (*Croton rhamnifolius* Willd.); 6,27% maniçoba (*Manihot glaziovii* Müll. Arg.); 4,98% pinhão brabo (*Jatropha mollissima* (Pohl) Baill.) (CPRH, 2000; 2008).

The 50 years area has 60 ha. It is located between coordinates 08° 30,970' S and 37° 59,025' W. The history of this area is the removal of forest products only for domestic use. The soil class is Luvisolo Crômico (EMBRAPA, 2013). The vegetation in the area was characterized by the highest importance values five species, in total 1032 individuals. In percentage by species in the area are: 6,4% pereiro (*Aspidosperma pyrifolium* Mart.); 5,6% faveleira braba (*Cnidoscolus bahianus* (Ule) Pax & K. Hoffm.); 5,3% angico (*Anadenanthera colubrine* var. *cebil* (Griseb.) (Altschul); 11,9% jurema de embira (*Mimosa ophthalmo centra* Mart. ex Benth.); 34,3% catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz) (Alves Júnior et al., 2013).

The 25 years area has 60 ha. It is located between coordinates 08°30,970'S and 37°59,025'W. The history of this area was removal of all vegetation clearcutting and the area was abandoned during these years. The soil class is Latossolo Amarelo (EMBRAPA, 2013). The vegetation in the area was characterized by the highest importance values five species, in total 544 individuals. In percentage by species in the area are: 2,4% sipaúba (*Thiloa glaucocarpa* (Mart.) Eichler); 21,1% jurema de embira (*Mimosa ophtalmocentra* Mart. ex Benth); 5,3% quipembe (*Pityrocarpa moniliformis* (Benth.) Luckow & R. W. Jobson); 37,1% catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 8,9% pinhão brabo (*Jatropha molíssima* (Pohl) Baill.) (Ferraz et al., 2014).

The other areas were submitted to simple coppice forest management techniques and exploration performed manually by shallow cut in bevel form, at different time: 12, 9, 6 and 0 years ago (six months). The regenerative process was through the spontaneous germination, strains of budding, and sprouting roots. Rare trees have been preserved, protected by law, as: aroeira (*Myracrodruon urundeuva* Allemão), baraúna (*Schinopsis brasiliensis* Engl.), umbuzeiro (*Spondias tuberosa* Arruda), quixabeira-braba (*Erytroxylum* sp.),

imburana de cambão (*Commiphora leptophloeos* (Mart.) J. B. Gillett) and cactaceous. As well as creeks and streams borders. Furthermore, the species which do not have utility in charcoal production, and those with stem diameter less than 2 cm, had not been cut as well. All information of the areas was based on existing forest management plans (CPRH, 2000; 2008).

The 12 years area has 90 ha. It is located between coordinates 08°35,940'S and 37°59,409'W. The history of this area was shallow cut vegetation 12 years ago. The soil class was Planossolo Háplico (EMBRAPA, 2013). The vegetation in the area was characterized by the highest importance values five species, in total 261 individuals. In percentage by species in the area are: 7,41% aroeira (*Myracrodruon urundeuva* Allemão); 11,01% jurema de embira (*Mimosa ophthalmocentra* Mart. ex Benth.); 25,7% catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 8,08% quebra faca branca (*Croton rhamnifolius* Willd.); 9,29% maniçoba (*Manihot glaziovii* Müll. Arg.).

The 9 years area has 90 ha. It is located between coordinates 08°35,485'S and 37°59,351'W. The history of this area was shallow cut vegetation 9 years ago. The soil class was Planossolos Háplico (EMBRAPA, 2013). The vegetation in the area was characterized by the highest importance values five species, in total 196 individuals. In percentage by species in the area are: 6,02% aroeira (*Myracrodruon urundeuva* Allemão); 8,31% jurema de embira (*Mimosa ophthalmocentra* Mart. ex Benth.); 29,7% catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 8,1% quipembe (*Pityrocarpa moniliformis* (Benth.) Luckow & R. W. Jobson); 7,3% jurema de embira (*Mimosa ophthalmocentra* Mart. ex Benth.).

The 6 years area has 90 ha. It is located between coordinates 08°34,665'S and 38°00,910'W. The history of this area was shallow cut vegetation 6 years ago. The soil class was Latossolo Amarelo (EMBRAPA, 2013). The vegetation in the area was characterized by the highest importance values five species, in total 131 individuals. In percentage by species in the area are: 10,69% jurema de embira (*Mimosa ophthalmocentra* Mart. ex Benth.); 9,7% pinhão brabo (*Jatropha mollissima* (Pohl) Baill.); 36,31% catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 5,02% pereiro (*Aspidosperma pyriformis* Mart.); 5,08% aroeira (*Myracrodruon urundeuva* Allemão).

The 0 year area is 90 ha, where the vegetation was recently shallow cut, it has 0,5 year has. It is located between the coordinates 08°35,518´S and 37°59,741´W. The soil class was Planossolo Háplico (EMBRAPA, 2013). The vegetation found in the area before shallow cut with five species highest importance values were in the total 131 individuals. The percentages by species in the area are: 10,69% aroeira (*Myracrodruon urundeuva* Allemão); 8,31% pinhão brabo (*Jatropha mollissima* (Pohl) Baill.); 20,1% jurema de embira (*Mimosa ophtalmocentra* Mart. ex Benth.), 10,1% quipembe (*Pityrocarpa moniliformis* (Benth.) Luckow & R. W. Jobson); 29,7% catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz).

### **3.2. Soil sampling and physical and chemical analysis**

There were opened five trenches of 20 x 50 cm and 30 cm depth in each area along of the Caatinga forest chronosequence, defined equidistant from one to another by 50 m. Soil samples were collected in the dry period of October month 2013 at 0-5, 5-10 and 10-20 cm depth, with five trenches repetitions per area. The soil deformed samples were air dried in environment temperature and passed through a 2 mm sieve, to perform physical and chemical analyzes. Undisturbed samples, after toilet, were subjected to bulk density analysis.

#### **3.2.1. Chemical analysis**

The extraction of the soil solution was performed by preparation of the saturation paste and extraction vacuum system, whose procedures are described in USSL Staff (1954). The electrical conductivity was measured in the saturated paste extract (EC 25 ° C) (EMBRAPA, 2009).

The pH was measured in water in the ratio 1:2.5 with agitation for one minute and one hour of reaction time (EMBRAPA, 2009). Exchangeable cations Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup> and K<sup>+</sup> were extracted with ammonium acetate 1 mol L<sup>-1</sup> pH 7.0 (USSL Staff, 1954). The cations Ca<sup>2+</sup> and Mg<sup>2+</sup> were determined by atomic absorption spectrophotometry, and Na<sup>+</sup> and K<sup>+</sup> determined by flame-emission photometry (EMBRAPA, 2009).

Potential acidity (H + Al) was extracted with buffered solution of calcium acetate  $0.5 \text{ mol L}^{-1}$  (pH 7.0) and determined by titration with NaOH  $0.025 \text{ mol L}^{-1}$ . Base sum (BS) was calculated with the sum of exchangeable cations; cation exchange capacity (CEC) was calculated by base sum (BS) and (H + Al); and base saturation (V) was calculated as the ratio between SB and CEC, multiplied by 100 (EMBRAPA, 2009).

The samples were macerated in porcelain mortar with pistil, until a fine powder was obtained. After passed the fine powder by sieve with mesh size of  $150 \mu\text{m}$  for determination N by the dry combustion method (CHNS/O) in an elemental analyzer (Model PE-2400 Series II Perkin Elmer).

### **3.2.2. Physical analysis**

The physical analysis to determine particle size distribution was performed in deformed samples by pipette method, modified by Ruiz (2005).

Soil bulk density was performed by volumetric ring method, where rings were taken from undisturbed soil samples, collected through stainless steel rings with 5 cm diameter and 10 cm length. It was not possible to insert the rings in soil at 50 years area soil. So, clod samples were collected and applied the paraffin clod method (EMBRAPA, 1997).

### **3.2.3. Carbon and organic matter soil analysis**

The samples were macerated in porcelain mortar with pistil until a fine powder had been formed. The C determination was made in this fine powder after it had been passed in a mesh size sieve of  $150 \mu\text{m}$ , by dry combustion method (CHNS/O) in an elemental analyzer (Model PE-2400 Series II Perkin Elmer).

Humic substances chemical fractionation was performed according to method suggested by International Humic Substances Society (SWIFT, 1996). There were obtained fulvic acids (FA), humic acids (HA) and humin (Hum), based on the solubility in acid and alkali. The extraction process was started with a mixture of 200 g of soil with HCl  $0.1 \text{ mol L}^{-1}$  solution in a proportion of 1 g of

soil:10 mL of solution, and stirred manually for 1 hour. After this time, the extracts stood for 4 hours.

Later, supernatant extract was siphoned and reserved (I extract FA). So, NaOH 0.1 mol L<sup>-1</sup> solution was added to precipitated in the same proportion cited earlier (1:10) and also performed manual agitation. After this period the solution was allowed to stand for 16 hours. Siphoning was performed again, and precipitate was separated (HU plus mineral fraction). The supernatant, referring to FA and HA fractions were centrifuged for 10 minutes at 10000 rpm.

Then, the supernatant was acidified, adding 50 mL of HCl 6 mol L<sup>-1</sup> until reaching pH value between 1 and 2 and stirred manually for two minutes. After this procedure, the solution is allowed to stand for 12 hours. Then separated by siphoning the supernatant (II extract FA), the precipitate is related to HA.

After the fractioning, the samples were frozen and lyophilized for determination of C in the humic fraction by dry combustion method (CHNS/O) in an elemental analyzer (Model PE-2400 Series II Perkin Elmer).

The light organic matter (LOM), organic material fraction with density <1 kg dm<sup>-3</sup> was determined by flotation in water, adjusted by Fraga (2002). Soil samples (50 g) were passed through sieve 0.5 mm mesh. Then this material was placed on sieve 0.053 mm mesh and washed in flowing water until the solution came out limpid. It indicates that silt and clay fractions had been removed of the sample. The material retained on the sieve was transferred to 500 mL Becker to be filled with distilled water.

Using a glass rod, the sample was stirred for the LOM stay suspended in the water. The sample was left to stand for a 24 hours period until the suspension stayed limpid. After rest period, material filtering in flotation was proceeded in a 0.053 mm mesh sieve. The collected material was washed with distilled water and dried in air forced circulation stove at 60 °C until constant weight, so it was weighed on analytical balance accuracy. The LOM samples were macerated in porcelain mortar with pistil until form fine powder. After, fine powder was passed by 150 µm mesh sieve for C determination. The C determination of light fraction (LF-C) was also performed by dry combustion method (CHNS/O) in an elemental analyzer (Model PE-2400 Series II Perkin Elmer).

Labile carbon (C-labile) was determined by oxidation with potassium permanganate solution ( $\text{KMnO}_4$ )  $0.033 \text{ mol L}^{-1}$  (Blair et al., 1995). Soil sample was passed in a 0.5 mm mesh sieve, and 25 mg of this sample was put in a centrifuge tube (30 mL), after added 25 mL of  $\text{KMnO}_4$  solution  $333 \text{ mmol L}^{-1}$ . The tubes were covered and shaken for one hour in a vertical shaker at 12 rpm; then they were centrifuged at 2.000 rpm for five minutes, and 1.0 mL of the supernatant was transferred to a 250 mL volumetric balloon, completing the volume with distilled water. Aliquots of 1.0 mL of  $\text{KMnO}_4$  six standard solutions with concentrations varying 280-333  $\text{mmol L}^{-1}$  had the same dilution. The samples were determined by the absorbance of the diluted solutions in a spectrophotometer set to wavelength 565 nm. The  $\text{KMnO}_4$  concentration change was estimated from a standard curve, used to determine C oxidized amount (labile C), assuming that 1.0 mol of  $\text{MnO}_4$  is consumed in the oxidation of 0.75 mol (9 grams) of carbon.

C concentrations were converted to soil stock in  $\text{Mg ha}^{-1}$  for each sampled depth as follows (Veldkamp, 1994):

$$\text{C Stock (Mg ha}^{-1}\text{)} = [\text{C (kg Mg}^{-1}\text{)} \times \text{BD (Mg m}^{-3}\text{)} \times \text{SVD (m}^3\text{)}] \times 1000$$

C stock – C stock at soil layer; C – C concentration in soil sample; BD – Soil bulk density in the layer; SVD – Sampled volume depth.

After C stock calculated for each layer, the correction of soil C stock was made, taking into account differences in soil mass (Sisti et al., 2004). Total C stock at 0-20 cm depth was calculated by adding up the values obtained in each sampled layer, except for MBC sum that was performed in 0-10 cm depth.

#### **3.2.4. Microbiological analysis**

Deformed soil samples were collected at 0-5 and 5-10 cm depths, and kept refrigerated until determinations. There were performed: basal respiration (BR) (Isermeyer, 1952); microbial biomass carbon (MBC) by irradiation extracting method using power microwave oven (900 W and 2450 MHz frequency), according to method described by Islam and Weil (1998), and the extracts C were determined from irradiated and non-irradiated samples using colorimetric method (Bartlett and Ross, 1988); metabolic quotient ( $q\text{CO}_2$ ),



obtained by dividing the basal respiration per unit of MBC (Anderson and Domsch, 1985); and microbial quotient ( $qMIC$ ), obtained dividing MBC by soil C.

In C-BMS determination it was used the method of extracting irradiation, which analyzes the extractable microbial biomass in  $K_2SO_4$   $0.5 \text{ mol L}^{-1}$  aqueous solution. Irradiation of 20 g of soil was done using a domestic microwave oven. Irradiation, beyond of kill, breaks microbial cells releasing the cytoplasm, allowing determination of C present in the sample.

The same amount of soil was not submitted to irradiation, making the direct extraction with  $K_2SO_4$   $0.5 \text{ mol L}^{-1}$ . And C was determined in extracts of irradiated and non-irradiated samples utilizing the colorimetric method, which uses potassium permanganate in acid medium as the oxidizing agent. It was determined from a C standard curve, and subsequent extracts reading of irradiated and non-irradiated samples to C determination by spectrophotometer.

T basal soil respiration determination, soil samples were taken in triplicate (25 g), moistened until they reached corresponding volume to 80% soil moisture holding capacity. The wetted samples were stored in sealed glass jars with 25 mL of  $NaOH$   $0.1 \text{ mol L}^{-1}$  solution.  $CO_2$  released by respiration was measured, by reaction with  $NaOH$   $0.1 \text{ mol L}^{-1}$  and it was titrated with  $HCl$   $1 \text{ mol L}^{-1}$ , with phenolphthalein as indicator, after 3 days (72 hours) incubation at 25-28 °C. Control (white) bottles were kept, containing the reactants and no soil sample. The calculation was made based on difference between  $HCl$  amount consumed by the soil samples extracts and the "white".  $CO_2$  content was expressed in  $mg \text{ kg}^{-1} \text{ s h}^{-1}$ .

### **3.3. Statistical analysis**

Evaluated parameters (chemical properties, C concentrations, C stocks in soil humic fractions, LOM and labile-C fraction of the soil) were submitted to variance analysis, and there were adjusted regressions between them and time after clearcutting, along Caatinga forest chronosequence, at 0-5, 5-10 and 10-20 cm soil depths. To microbiological activity and C stocks in microbial biomass, soil layers were 0-5 and 5-10 cm, following the same chronosequence.

There were also tested correlations between soil properties related to soil quality following Caatinga forest chronosequence at soil evaluated layers.

## 4. RESULTS AND DISCUSSION

### 4.1. Soil physical characteristics

In general, the particle size composition of soils had the predominance of sand fraction in the areas at soil evaluated depths (Table 1). The most common texture at 0-5 and 5-10 cm depths was sandy loam, but at 10-20 cm depth it was sandy clay loam. This has been found in semiarid soils, under lower weathering degree, ie the sand dominance and high silt content favor high silt/clay ratio (Jacomine, 1996). It is different in more weathered soils, where clay dominates and sand is only highlighted when this fraction is composed primarily of quartz, for their high resistance to weathering (Araujo et al., 2014).

In studies by Oliveira and Nascimento (2006), evaluating manganese and iron forms in Pernambuco reference soils, were verified values near in Haplargid soil class (59% sand, 17.2% silt and 23.9% clay), Haplustalf soil class (74.8% sand, 15.7% silt and 9.5% clay) and Haplustox soil class (78.2% sand, 6.3% silt and 15.6% clay). Melo et al. (2008), in study on soil physical properties under Caatinga vegetation, found in Ustorthent soil class 68% sand, 18% silt and 13% clay.

Bulk density is another important soil variable, a physical attribute dependent on particle size composition and organic matter content of the soil, but can be influenced by management adopted in field (Ballabio et al., 2016). The soil bulk density varied between plots at each depth studied, at 0-5 cm (1.18 to 1.69 g cm<sup>-3</sup>), 5-10 cm (1.30 to 1.74 g cm<sup>-3</sup>) and 10-20 cm (1.39 to 1.75 g cm<sup>-3</sup>).

Vegetation removal in recently clearcutting areas, leaving uncovered soil, contributes for compaction through the rain drops, and it can alter soil bulk density, structure, pore size distribution, air and water infiltrability, water retention, and hydraulic conductivity (Allman et al., 2015). In areas with fine textured soils, the impacts of compaction can be more pronounced (Paul Dinsmore et al., 2013).

In studies by Liu et al. (2013), evaluating semiarid sandy grasslands in northern China, were verified similar values to bulk density 1.61 g cm<sup>-3</sup>. Xu et al. (2014), working with vegetation response and soil carbon and nitrogen storage

in Semiarid Grasslands in the Agro-Pastoral Zone of Northern China, also were found similar values of 1.05 to 1.47 g cm<sup>-3</sup> at 0-20 cm depth.

Table 1. Soil characteristics in Caatinga forest chronosequence areas at three layers<sup>1</sup>

| Plot     | Sand           | Silt  | Clay  | Bulk density       | Texture         |
|----------|----------------|-------|-------|--------------------|-----------------|
|          | -----%-----    |       |       | g cm <sup>-3</sup> |                 |
|          | Depth 0-5 cm   |       |       |                    |                 |
| Reserve  | 43.89          | 32.72 | 23.39 | 1.18               | Loam            |
| 50 years | 58.59          | 15.90 | 25.50 | 1.20               | Sandy clay loam |
| 25 years | 77.83          | 7.39  | 14.76 | 1.44               | Sandy loam      |
| 12 years | 66.32          | 18.38 | 15.29 | 1.69               | Sandy loam      |
| 9 years  | 65.78          | 17.62 | 16.58 | 1.68               | Sandy loam      |
| 6 years  | 78.37          | 6.98  | 14.64 | 1.42               | Sandy loam      |
| 0 year   | 63.18          | 19.13 | 17.67 | 1.67               | Sandy loam      |
|          | Depth 5-10 cm  |       |       |                    |                 |
| Reserve  | 43.66          | 33.48 | 22.85 | 1.36               | Loam            |
| 50 years | 58.58          | 15.81 | 25.60 | 1.30               | Sandy clay loam |
| 25 years | 79.32          | 6.33  | 14.33 | 1.53               | Sandy loam      |
| 12 years | 62.40          | 19.89 | 17.69 | 1.74               | Sandy loam      |
| 9 years  | 68.06          | 18.88 | 16.05 | 1.70               | Sandy loam      |
| 6 years  | 78.34          | 6.73  | 14.92 | 1.50               | Sandy loam      |
| 0 year   | 66.22          | 17.54 | 16.23 | 1.69               | Sandy loam      |
|          | Depth 10-20 cm |       |       |                    |                 |
| Reserve  | 48.90          | 26.51 | 24.57 | 1.41               | Sandy clay loam |
| 50 years | 60.72          | 14.57 | 24.69 | 1.39               | Sandy clay loam |
| 25 years | 79.98          | 6.39  | 13.61 | 1.57               | Sandy loam      |
| 12 years | 55.88          | 14.58 | 29.53 | 1.75               | Sandy clay loam |
| 9 years  | 54.93          | 15.30 | 29.75 | 1.74               | Sandy clay loam |
| 6 years  | 79.04          | 6.50  | 14.45 | 1.52               | Sandy loam      |
| 0 year   | 54.90          | 16.21 | 28.87 | 1.72               | Sandy clay loam |

<sup>(1)</sup> Medium values caatinga forest areas.

#### 4.2. Changes in soil pH, C, N, C:N and EC

The pH has increased linearly along the chronosequence of Caatinga forest among the evaluated depths (Figure 1). In all areas soil pH values ranged

from 5.57 to 6.65 at 0-5 cm, from 5.46 to 6.69 at 5-10 cm, and from 5.59 to 6.75 at 10-20 cm depth.

Changes in pH may be a result of organic material adding through the forest, and depend on basic cations concentrations, organic anions, N in the materials and soil pH initial level (Xu et al., 2006). Soil pH elevation may occur by exchange or complexation of  $H^+$  and  $Al^{+3}$  for  $Ca^{2+}$ ,  $Mg^{2+}$ ,  $K^+$  and some organic compounds in the soil (Amaral et al., 2004). During anions and organic acids decarboxylation in SOM mineralization, the redox reactions promote protons consumption, also contributing to changes in pH (Mokolobate and Haynes, 2003).

In a study of Zhang et al. (2013) with exchangeable cations along a chronosequence in China semiarid, there were higher values from 6.5 to 7.5 at 0-30 cm depth. Cao et al. (2008), studying chemical and microbiological properties along a chronosequence in Northeastern China, also verified higher pH values from 7.06 to 7.73, at 0-20 cm depth.

Nunes et al. (2009) studied four Caatinga areas under different management conditions in Ceará state (Brazil) at 0-10 cm depth, and observed similar values in preserved Caatinga (6.4), deforested Caatinga (6.6), and deforested burned Caatinga (6.6).

However some nutrients may be unavailable in this pH values interval, interfering on common harvesting plants development, Caatinga species can grow in these conditions. They should have special mechanisms to help them in this concern.

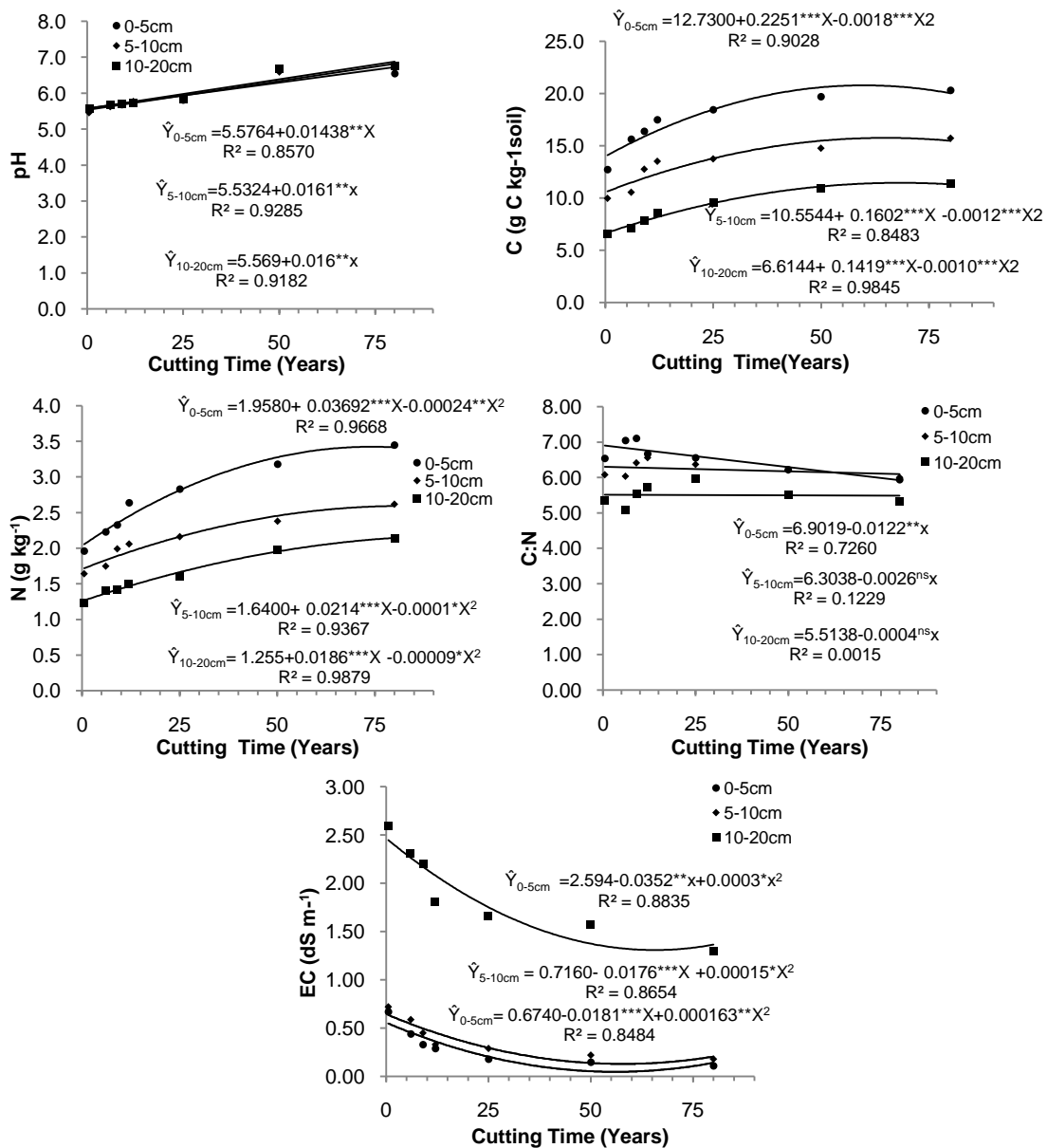


Figure 1. Adjusted regressions on soil pH, C, N, C:N and EC at 0-5, 5-10 and 10-20 cm depths, in function of clearcutting time in a Caatinga forest chronosequence at Northeastern Brazil. Significant at \* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$  and ns= not significant.

The variables C and N increased quadratically with the Caatinga cutting time, following substantially the same tendency to equilibrium along time, but with noticeable differences among the three depths evaluated (Figure 1). The spatial distribution of nutrients in arid and semiarid climate is associated with vegetation (Austin et al., 2004; Schade and Hobbie, 2005).

Kirmse et al. (1987); Hu et al. (2009); and Fu et al. (2010) report the importance of biomass permanence along time, allowing organic matter

accumulation, which in turn is associated with C and N concentrations, consequently, soil fertility.

According Sampaio et al. (1995), the soils of semiarid region of Northeastern Brazil are generally limited as N availability. But it is possible that the predominant tree species in Caatinga are able to use this element naturally because the symbioses with micro-organisms, as a survival strategy.

In these Caatinga areas, C and N contents decreased along depth (Figure 1). It was expected because C and N are released from organic compounds decomposition especially on soil surface. According Schumacher et al. (2004), forest ecosystems accumulate part of atmospheric carbon in their tissues, returning to the soil through litter fall with its subsequent decomposition, releasing nutrients. The largest amount of C is found on the surface due to the fact that the surface of the soil is the area where organic materials deposition occurs more intensively (Neves et al., 2004).

Soil C concentration ranged at 0-5 cm from 12.73 to 20.32 g kg<sup>-1</sup>, at 5-10 cm from 9.97 to 15.72 g kg<sup>-1</sup> and at 10-20 cm depth from 6.60 to 11.39 g kg<sup>-1</sup>. Certainly the larger C primary production rates have increased in consequence the litter inputs on the soil surface (Lloyd, 1999). Martins et al. (2010), in studies of chemical and microbiological attributes in an area in desertification process in semiarid of Pernambuco-Brazil, showed similar C values in different environments: preserved (13.77 g kg<sup>-1</sup>), moderate (10.92 g kg<sup>-1</sup>) and degraded (5.81 g kg<sup>-1</sup>). Fraga and Salcedo (2004), in a study on organic nutrient decline in semiarid region, observed C value in forest undisturbed of 17.8 g kg<sup>-1</sup>, and degraded 8.9 g kg<sup>-1</sup>.

The N concentration ranged at 0-5 cm (1.96 to 3.45 g kg<sup>-1</sup>), 5-10 cm (1.64 to 2.62 g kg<sup>-1</sup>) and 10-20 cm depth (1.23 to 2.14 g kg<sup>-1</sup>) (Figure 1). The N reduction with degradation may be related to interactions of plant N absorption, N transformation and soil environmental conditions in terms of different times of vegetation communities (Delaune et al., 2005; Hefting et al., 2005). Barros et al. (2015), in their studies with C and N stocks in soil under different management systems in semiarid of Paraíba-Brazil, found lower N values in native Caatinga (1.1 g kg<sup>-1</sup>) and sparse vegetation (0.8 g kg<sup>-1</sup>). Sacramento et al. (2013), working with C and N stocks in semiarid Brazilian soil, found N value in natural Caatinga of 1.1 g kg<sup>-1</sup>, lower than that found in this work. These differences may be

associated with the soil and dominant species compound the vegetation, some of them can have association with bacteria allowing access more N naturally in soil environment.

Another important factor is C:N ratio, which indicates the speed at which organic matter decomposition occurs in the soil, so the extent that C:N ratio decreases, faster is material decomposition (Silgram and Shepherd, 1999).

C:N ratio values are low in these soils, with little variation at 0-5 (5.89 to 7.03), 5-10 (6.00 to 6.56) and 10-20 cm depths (5.10 to 5.97) along the Caatinga forest chronosequence. When it rains, all organic matter is decomposed in a short time, and this possibly occurs due to high N contents in plant tissues.

Su and Ha (2003), in studies of soil properties and plant species in a sequence of years in Horqin Sandy Land, Northern China, presented data similar to this work, ranging from 3.8 to 7.2, and after 21 years the C:N ratio was stabilized. Singh et al. (2001), working with restoration of soil in the Nepal Himalaya forest, found that increased C:N ratios at the plantation age was due to litter accumulation and shrub establishment, which had become almost constant after 21 years, indicating C and N stabilizing.

In this study, C:N ratio in function of cutting time was significant only for the first layer (0-5 cm). To the others layers, C:N ration was not influenced by time, although there were increments in N content with time in the other layers. The N increments were balanced by C contents, increasing on time too (Figure 1).

With respect to EC (Figure 1), the values ranged at 0-5 (0.67 to 0.11  $\text{dS m}^{-1}$ ), 5-10 (0.72 to 0.18  $\text{dS m}^{-1}$ ) and 10-20 cm depths (2.59 to 1.30  $\text{dS m}^{-1}$ ). A trend of higher EC values at a depth of 10-20 cm could be related to higher  $\text{Na}^+$  ions concentrations observed. However, despite the variability in terms of EC, most areas of soil possessed values less than 4  $\text{dS m}^{-1}$ , being below the classifying limit for saline soils (USSL Staff, 1954). The study of Zhang et al. (2013) with exchangeable cations along a chronosequence in China semiarid showed values from 1.8 to 4.0  $\text{dS cm}^{-1}$  at 0-30 cm depth.

Another important factor observed was that, instead the other variables, soil EC values decreased quadratically along the Caatinga forest chronosequence (Figure 1). In soil protected by vegetation, where evaporation is

less intense, salts had been less accumulated on the surface (Santos et al., 2013).

#### **4.3. Basic exchangeable cations along the Caatinga forest chronosequence**

Exchangeable soil  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^{+}$ , essential elements to plants, and CEC, had their concentration increased quadratically along the Caatinga forest chronosequence (Figure 2). In respect to soil depths, only the  $\text{Mg}^{2+}$  had higher contents at 10-20 cm. To  $\text{Ca}^{2+}$  and  $\text{K}^{+}$ , the concentration was higher at surface layer, following the same observed to C and N (Figure 1).

Although sandy soils are normally infertile, Caatinga soils have exchangeable cations in high concentration, enough to plant development, in contrast with the majority of Brazilian soils (Sampaio et al., 2005). Under semiarid climate and small precipitation rates, these soils have low weathering, and this became possible basic cations retention, causing differences to Oxisols and Ultisols from humid regions of Brazil, generally acid and less fertile soils (Santos et al., 2012).



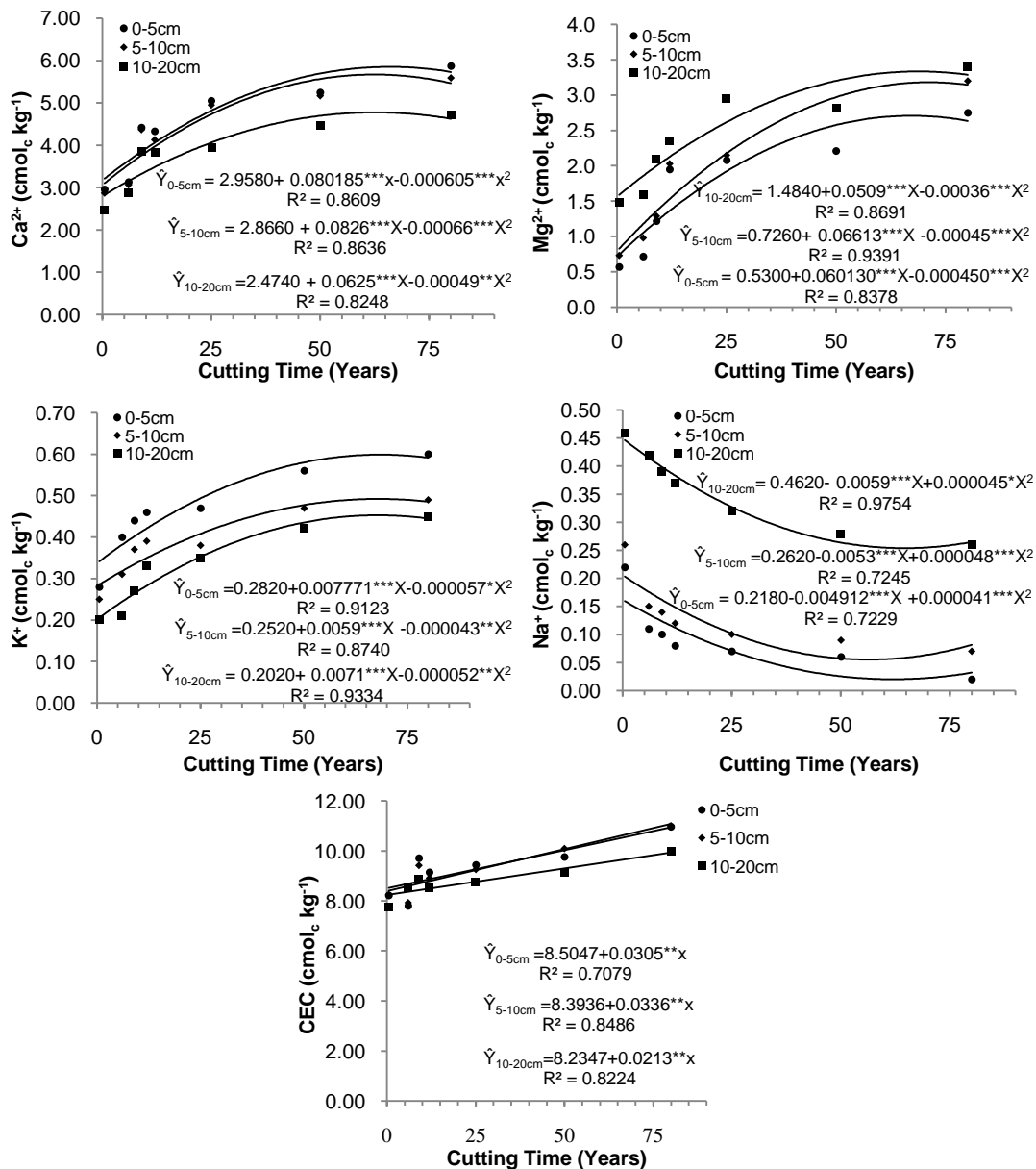


Figure 2. Adjusted regressions on soil exchangeable cations (Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup>, Na<sup>+</sup>), and CEC at 0-5, 5-10 and 10-20 cm depths, in function of clearcutting time in a Caatinga forest chronosequence. Significant at \*P <0.05, \*\*P <0.01, \*\*\*P <0.001 and ns= not significant.

Exchangeable Ca<sup>2+</sup> in soil ranged at 0-5 (2.96 to 5.87 cmol<sub>c</sub> kg<sup>-1</sup>), 5-10 (2.87 to 5.59 cmol<sub>c</sub> kg<sup>-1</sup>) and 10-20 cm depths (2.47 to 4.71 cmol<sub>c</sub> kg<sup>-1</sup>), along Caatinga forest chronosequence (Figure 2). In drylands, the soils generally have large amounts of exchangeable Ca<sup>2+</sup>, occupying a high percentage in the soil sorption complex (Troeh and Thompson, 1993).

It occurs, probably, by  $\text{Ca}^{2+}$  predominance in the rocks, as well as the low weathering degree of soil. According Sumner (1995), various soils that occur in semiarid climates have appreciable amounts of weathered minerals (feldspars, hornblendes, plagioclase, calcite and gypsum), which can maintain high activities of calcium, magnesium and sodium ions when they are solubilized.

The  $\text{Ca}^{2+}$  is absorbed by plants and stored in the cell wall, being an important structural element in plant constitution. It facilitates, for example, trees development, and has an important function for timber production (Hirschi, 2004). Along decomposition of middle lamella tissues of plant cell wall,  $\text{Ca}^{2+}$  can be accumulated in the soil surface by litter (Jobbàgy and Jackson, 2001; White and Broadley, 2003; Schumacher et al., 2004).

The resulting organic compounds from litter decomposition, through their functional groups, have close affinity to exchangeable  $\text{Ca}^{2+}$ , in relation to other cations in the soil. Therefore, retained  $\text{Ca}^{2+}$  by functional groups has been increased in soils after a residence vegetation time, since other cationic components can be easily lost through leaching (Russel, 1973; Rengasamy et al., 1986; Caravaca et al., 2004).

Martins et al. (2010), in study on chemical attributes in a desertification process area in Pernambuco semiarid, showed  $\text{Ca}^{2+}$  concentrations higher than this research in different environments: preserved ( $11.21 \text{ cmol}_c \text{ kg}^{-1}$ ), moderate ( $11.28 \text{ cmol}_c \text{ kg}^{-1}$ ) and degraded ( $11.17 \text{ cmol}_c \text{ kg}^{-1}$ ). However, the soils had more clay, which has higher cations exchange capacity.

In a study of Zhang et al. (2013), with exchangeable cations along a China semiarid chronosequence,  $\text{Ca}^{2+}$  values varied from 12 to 19  $\text{mmol}_c \text{ kg}^{-1}$ , at 0-30 cm depth. Travassos et al. (2011) observed results ranging between 4.75 and 5.40  $\text{cmol}_c \text{ kg}^{-1}$  in a preserved Caatinga area, and from 3.50 to 3.85  $\text{cmol}_c \text{ kg}^{-1}$  in soil in a degraded area, under desertification process in Paraíba, Brazil.

For all time periods and depths, it was observed that the  $\text{Ca}^{2+}$  content was always higher than those of  $\text{Mg}^{2+}$  and  $\text{K}^+$ . The exchangeable  $\text{Mg}^{2+}$  in soil ranged at 0-5 ( $0.57$  to  $2.75 \text{ cmol}_c \text{ kg}^{-1}$ ), 5-10 ( $0.73$  to  $3.20 \text{ cmol}_c \text{ kg}^{-1}$ ) and 10-20 cm depths ( $1.48$  to  $3.40 \text{ cmol}_c \text{ kg}^{-1}$ ).

In Azevedo et al. (2013), a study on different soils in a Caatinga area, were presented similar  $Mg^{2+}$  values ranging from 2.05 to 2.00  $cmol_c kg^{-1}$  at 0-30 cm depth. Travassos et al. (2011) presented similar results of  $Mg^{2+}$  in a Caatinga preserved area from 0.35 to 2.25  $cmol_c kg^{-1}$ , and degraded area from 1.15 to 5.20  $cmol_c kg^{-1}$  in a soil under desertification process in Paraíba, Brazil.

Comparing to  $Ca^{2+}$  and  $Mg^{2+}$ , exchangeable  $K^+$  in soil was less available (Figure 2), however it was not lower as expected, ranging at 0-5 (0.28 to 0.60  $cmol_c kg^{-1}$ ), 5-10 (0.25 to 0.49  $cmol_c kg^{-1}$ ) and 10-20 cm (0.20 to 0.45  $cmol_c kg^{-1}$ ). This may be due to decomposition and accumulation of vegetation residue effect on soil surface, provided by litter parts (Bose et al., 2011). The  $K^+$  contributes in various biochemical activities, but it is a non-structural element in plants, being easily leached from dead soil matter (Hawkesford et al., 2012). When there is  $K^+$  adsorption by negative charges of soil surface particles, the leaching loss is hampered, and this ion is maintained in soil. This is an important process in soil fertility, as it provides a source of the nutrient for plant roots (Forth, 1990).

Evaluating potassium forms in soils of Paraíba, Brazil, Medeiros et al. (2014) found similar  $K^+$  concentrations, ranging from 0.18 to 0.64  $cmol_c kg^{-1}$ . According to the authors, the least developed soils formed under semiarid climate are the ones that presented the largest exchangeable and non-exchangeable  $K^+$  reserves. Maia et al. (2006), in different agro-forestry and conventional treatments at semiarid native areas in Ceará-Brazil, observed  $K^+$  values close to this research, at 0-6 (0.60  $cmol_c kg^{-1}$ ), 6-12 (0.53  $cmol_c kg^{-1}$ ) and 12-20 cm depths (0.49  $cmol_c kg^{-1}$ ).

Increasing contents of  $Ca^{2+}$ ,  $Mg^{2+}$  and  $K^+$  along the time in this Caatinga chronosequence is an indication that the soil fertility has been improved, since they are macronutrients for plant development (Epstein and Bloom, 2006).

Although it has not been considered an essential element for plants,  $Na^+$  is another important ion present at exchangeable soil phase. It may promotes a negative influence on soil colloidal particles aggregation process, as well as in plant nutrition, inducing imbalance between the nutrients or causing toxic effects in plants (Freire and Freire, 2007). In these Caatinga areas, exchangeable  $Na^+$  decreased quadratically, at 0-5 (0.22 to 0.02  $cmol_c kg^{-1}$ ), 5-10 (0.26 to 0.07

cmol<sub>c</sub> kg<sup>-1</sup>) and 10-20 cm depths (0.46 to 0.26 cmol<sub>c</sub> kg<sup>-1</sup>), along the chronosequence (Figure 2).

Naturally, Na<sup>+</sup> ions are less adsorbed than the other basic cations on soil colloid surfaces, being intensively leached from soils. However, in semiarid regions it has been accumulated, especially in deeper layers (Freire et al., 2003). It is due to its small valence and high ionic hydrated radius, as it is located at the end of adsorption selectivity on lyotropic series. This is also a favorable factor for its replacement, and in equal concentration conditions, Na<sup>+</sup> is the last of common cations to be adsorbed on electrical loads of soil colloids (Holanda et al., 1998).

The excess of Na<sup>+</sup> adsorbed increases the diffuse double layer thickness on surface of colloids, minimizing the attraction forces between them, favoring the dispersion of soil particles, causing thus physical-hydric problems (Freire and Freire, 2007). In plants, Na<sup>+</sup> predominance may promote a nutritional imbalance by competing with other cations as Ca<sup>2+</sup>, Mg<sup>2+</sup> and K<sup>+</sup>, or even to provoke toxic effects (Epstein and Bloom, 2006).

The results of Martins et al. (2010) for Na<sup>+</sup> concentrations in soils at Pernambuco semiarid, Brazil, were similar to these in different environments: preserved (0.09 cmol<sub>c</sub> kg<sup>-1</sup>), moderate (0.11 cmol<sub>c</sub> kg<sup>-1</sup>) and degraded (0.32 cmol<sub>c</sub> kg<sup>-1</sup>). On the other hand, in native areas in semiarid region of Ceará, Brazil, Maia et al. (2006) observed values at 0-6 (0.17 cmol<sub>c</sub> kg<sup>-1</sup>), 6-12 (0.18 cmol<sub>c</sub> kg<sup>-1</sup>) and 12-20 cm depths (0.22 cmol<sub>c</sub> kg<sup>-1</sup>). It may be attributed to differences between mineral and rocks forming the soils in each area, some of them are richer in Na<sup>+</sup> contents than others.

Cation exchangeable capacity (CEC), other soil property studied in this research, increased linearly along Caatinga forest chronosequence, ranging at 0-5 (8.23 to 10.97 cmol<sub>c</sub> kg<sup>-1</sup>), 5-10 (8.25 to 11.01 cmol<sub>c</sub> kg<sup>-1</sup>) and 10-20 cm depths (7.75 to 9.98 cmol<sub>c</sub> kg<sup>-1</sup>). Despite the soils are predominantly sandy, CEC has considerable value, probably because clay type and organic matter influence. Both organic matter and clay can provide higher CEC and result in exchangeable basic cations accumulation (Havlin et al., 2004).

Lira et al. (2012), working with effects of farming systems and Caatinga management in Apodi soils, Rio Grande do Norte (Brazil), verified CEC values in native forest (7.50 cmol<sub>c</sub> kg<sup>-1</sup>), seven years managed caatinga (7.23 cmol<sub>c</sub> kg<sup>-1</sup>),

five years managed Caatinga ( $6.94 \text{ cmol}_c \text{ kg}^{-1}$ ) and crop area ( $6.80 \text{ cmol}_c \text{ kg}^{-1}$ ). In a study of Zhang et al. (2013), with CEC along the China semiarid chronosequence, there were observed lower values of 1.40 to  $2.50 \text{ mmol}_c \text{ kg}^{-1}$  at 0-30 cm depth.

In cations proportions evaluating, exchangeables  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$  and  $\text{Na}^+$  chalked up 31.87-53.46, 6.93-34.07, 2.47-5.74, and 0.18-5.94%, respectively, along Caatinga forest chronosequence (Table 2). In general,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^+$  saturations increased in the Caatinga forest chronosequence, while saturation of  $\text{Na}^+$  decreased along time (Table 1). Sodium ions are less firmly held to the soil particles than  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ , so  $\text{Na}^+$  is more readily leached from the soil than other cations (Marschner and Rengel, 2007), but in unprotected soils (recent cutting), the  $\text{Na}^+$  saturation is higher than in soils under vegetation for a long time.

Table 2. Relative cations saturations in soils under Caatinga forest chronosequence at different depths, Northeastern Brazil

| Time    | Soil depth | Ca <sup>2+</sup> saturation | Mg <sup>2+</sup> saturation | K <sup>+</sup> saturation | Na <sup>+</sup> saturation |
|---------|------------|-----------------------------|-----------------------------|---------------------------|----------------------------|
| Years   | cm         | %                           |                             |                           |                            |
| 0       | 0-5        | 35.97                       | 6.93                        | 3.40                      | 2.67                       |
|         | 5-10       | 34.79                       | 8.85                        | 3.03                      | 3.15                       |
|         | 10-20      | 31.87                       | 19.10                       | 2.58                      | 5.94                       |
| 6       | 0-5        | 40.08                       | 9.22                        | 5.12                      | 1.41                       |
|         | 5-10       | 38.71                       | 12.36                       | 3.91                      | 1.89                       |
|         | 10-20      | 33.73                       | 18.68                       | 2.47                      | 4.94                       |
| 9       | 0-5        | 45.47                       | 12.55                       | 4.53                      | 1.03                       |
|         | 5-10       | 46.39                       | 13.69                       | 3.93                      | 1.49                       |
|         | 10-20      | 43.63                       | 23.56                       | 3.04                      | 4.40                       |
| 12      | 0-5        | 47.32                       | 21.31                       | 5.03                      | 0.87                       |
|         | 5-10       | 46.30                       | 22.76                       | 4.37                      | 1.35                       |
|         | 10-20      | 44.90                       | 27.55                       | 3.87                      | 4.34                       |
| 25      | 0-5        | 53.44                       | 22.01                       | 4.97                      | 0.74                       |
|         | 5-10       | 53.46                       | 23.22                       | 4.10                      | 1.08                       |
|         | 10-20      | 45.14                       | 33.71                       | 4.00                      | 3.66                       |
| 50      | 0-5        | 53.79                       | 22.64                       | 5.74                      | 0.61                       |
|         | 5-10       | 51.19                       | 27.92                       | 4.65                      | 0.89                       |
|         | 10-20      | 48.91                       | 30.85                       | 4.60                      | 3.06                       |
| Reserve | 0-5        | 53.51                       | 25.07                       | 5.47                      | 0.18                       |
|         | 5-10       | 50.77                       | 29.06                       | 4.45                      | 0.64                       |
|         | 10-20      | 47.19                       | 34.07                       | 4.51                      | 2.61                       |

Medium values

Despite Na<sup>+</sup> saturation is not high enough to cause problems to soils and plants, it is becoming similar to K<sup>+</sup> saturation at recently deforested area (0 year), and it may promote a competition between these cations, making difficult K<sup>+</sup> absorption by plants. Mean while, with time after clearcutting, the nutrient cations are in higher proportions and Na<sup>+</sup> is lower. So, the forest vegetation is protecting soil against evaporations, and even against sodification, indicating a better soil condition after long time without forest cut.

#### 4.4. Relations between basic exchangeable cations and other chemical properties

Evaluating chemical properties together, there were observed interactions between exchangeable cations and N in soil with pH, C and EC, and

they were positively correlated with pH and C and negatively correlated with EC (Figure 3).

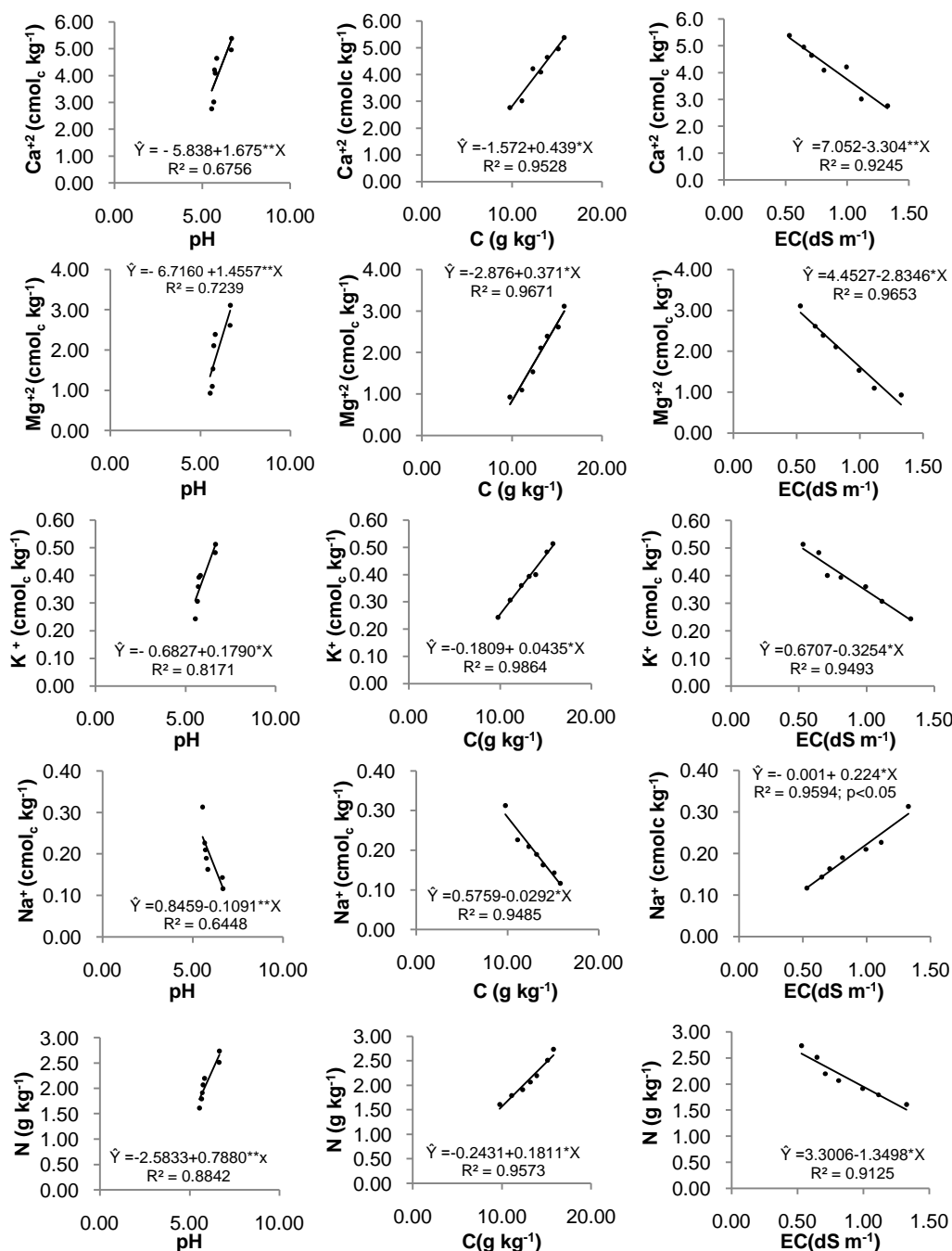


Figure 3. Correlations between exchangeable cations and N in soil with pH, C, and EC, along Caatinga forest chronosequence. Significant at \*P < 0.05, \*\*P < 0.01, \*\*\*P < 0.001 and ns= not significant.

Positive relation between basic cations and pH were observed to Ca<sup>2+</sup>, Mg<sup>2+</sup> and K<sup>+</sup>, however, there was a negative relation between Na<sup>+</sup> and pH (Figure 3). It may have happened because Ca<sup>2+</sup> is in high concentrations in

these soils, followed by  $Mg^{2+}$ , whereas  $Na^+$  is in low concentrations to compete with these others for electric charges of colloidal particles.

According Quaggio (2000), it has been expected by cations retention standard, because  $Ca^{2+}$  is more strongly retained on the colloidal matrix soil than  $Mg^{2+}$  and  $K^+$ . The more hydrated cations are large, and tend to have difficult to occupy space on soil CEC, becoming less concentrated than other cations that are more strongly held. This availability is influenced by hydrated cation diameter and electric charges, ie bivalent and smaller diameters cations, as  $Ca^{2+}$  are more strongly adsorbed at clay surface (Marschner and Rengel, 2007).

In respect to N, its positive relation to pH may be attributed to pH increment may promotes more biologic activity in soils, and N is an element closely associated with biologic activity, having its concentration raised in higher biologic activity environments. The high correlation between pH and N, is explained by the high solubility of inorganic nitrogen salts in the entire pH range, where the mineralization of N is greater between pH 6.0 and 8.0 (Brady and Weil, 2007).

Exchangeable cations are also dependent on organic matter content and soil texture, ie the colloidal particles (mineral and organic) exert influence on surface charges of soil. These electric charges can adsorb and maintain exchangeable cations in soils (Hepper et al, 2006; Gogo and Pearce, 2009). So, the results support that SOM is one of the dominant actors influencing CEC in soils.

Cation  $Na^+$  was the only one in negative correlation with soil pH and C, and positive with EC (Figure 3). As the salts are being accumulated in soils, the EC is growing in the same way of  $Na^+$  cation, and these two variables are used to classified salt affected soils. The soils in this area are not classified as saline or sodic soils yet, but the salinity and the sodicity are being increased in function of soil exposition to sun and wind, under high evapotranspiration. So if the vegetation could not return to protect the soils, they may become degraded by salt accumulation.

In the same way related before, as C has been increased in these soils, essential elements  $Ca^{2+}$ ,  $Mg^{2+}$ ,  $K^+$ , and N, have also been raised in natural conditions, while  $Na^{2+}$  is lower, following a way for better soil quality.



According to Figure 3, we can deduce that the pH and C were determining factors in the basic cations and N changes along the chronosequence of Caatinga forest. In Caatinga ecosystem maintenance and forest preservation allowed himself higher stock of basic cations and N. In time was observed that the cations and CEC were controlled by forest and soil interaction. The interaction of chemical and biological properties is what controls and provides nutrients to the terrestrial ecosystem (Zhang et al., 2013).

#### **4.5. Exchangeable cations variation along Caatinga forest chronosequence**

Exchangeable cations  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ , and CEC were positively correlated with time after clearcutting along Caatinga forest chronosequence (Table 3), indicating cations accumulation in more preserved conditions. This positive correlation is due to the organic matter accumulation in soils (Figure 1), promoting greater retention of these cations by functional groups of organic matter.

The increase of soil exchangeable cations  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$  and CEC is directly linked to organic matter levels, and it can contribute to cation leaching minimizing in soil profile (Barros et al., 2010). According Jiang et al. (2007) and Cao et al. (2008), this environment with higher maintenance of Caatinga vegetation creates a favorable conditions for microorganisms population and promotes nutrients release through plant residues decomposition and water availability for plant growth.

In this study it was possible verify how the soil is changed after Caatinga forest has been cut, this is promoting loss of nutrients ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^+$ ) and CEC, while  $\text{Na}^+$  is being accumulated, and it has harmful effects to plants and soils. So it is necessary have enough time to environment recovery before a new cut.

Table 3. Correlations between base cations and woody plant along the chronosequence of Caatinga forest, Northeastern, Brazil.

| Variables <sup>1</sup>        | Correlation coefficient ( $R^2$ ) | Significance ( $p$ ) |
|-------------------------------|-----------------------------------|----------------------|
| Exchangeable Ca <sup>2+</sup> | 0.769                             | <0.05                |
| Exchangeable Mg <sup>2+</sup> | 0.877                             | <0.05                |
| Exchangeable K <sup>+</sup>   | 0.432                             | ns*                  |
| Exchangeable Na <sup>+</sup>  | -0.815                            | <0.05                |
| CEC                           | 0.777                             | <0.05                |

<sup>1</sup>number observations (n) =105, \*ns= not significant

#### 4.6. C concentrations in soil and humic fractions

The average C values varied due to time after management in this Caatinga forest chronosequence (Figure 4). Carbon concentrations in soil and in humic fractions (fulvic acid, humic acid and humin) increased quadratic at all depths along the Caatinga forest chronosequence. The C values in the soil were influenced by changes caused in forestry times, varying at 0-5 cm (12.73 to 20.32 g kg<sup>-1</sup>), 5-10 cm (9.97 to 15.72g kg<sup>-1</sup>) and 10-20 cm depths (6.60 to 11.39 g kg<sup>-1</sup>) (Figure 4).

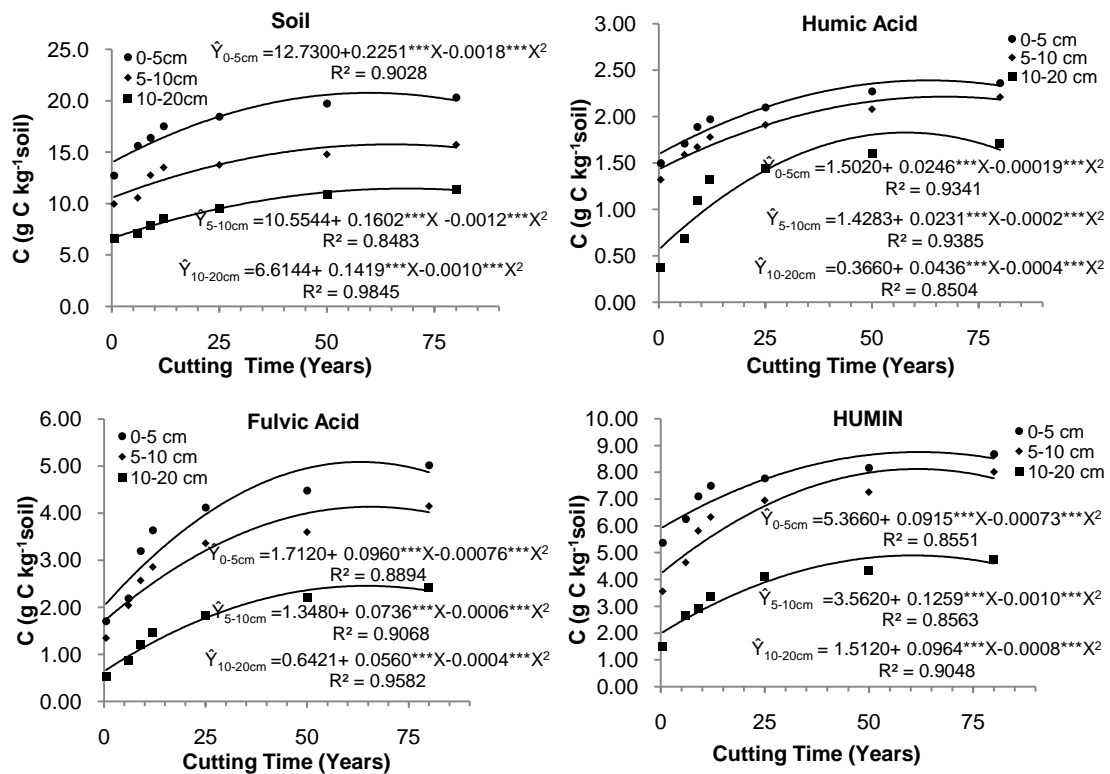


Figure 4. Carbon concentration in whole soil and soil humic fractions at 0-5, 5-10 and 10-20 cm depth along Caatinga forest chronosequence. Significant at \*P <0.05, \*\*P <0.01, \*\*\*P <0.001 and ns= not significant.

The highest C concentrations at first layer soil and humic fractions can be due to death of fine roots, mainly herbaceous that does not support water deficit, which is a seasonal behavior in Caatinga areas. According to Salcedo and Sampaio (2008), the highest C concentrations and stocks in soil are due to deposition of litter and death of fine roots, which are the main inputs of C in the soil. Due this incorporation of plant biomass, Caatinga in absence of soil disturbance for a long time, combined with efficient biomass decomposition in the soil, provided major contributions of C compounds, possibly favoring the higher C stocks in most of humic fractions.

These increases throughout the soil of these elements are probably supported by higher input and lower output of C, may be due to biochemical recalcitrance of vegetation compartments or lack of water or nutrients important to decompose the inputs of additional materials.

The C increase C in the soil along the forestry times is associated with the production of plant biomass and decomposition rate, which in turn is

connected to the climatic patterns in the studied region. In soils of tropical climates, differently from soils under temperate conditions, organic matter is decomposed quickly and has not been accumulated in soil in considerable amount (Qiu et al., 2015).

According to Giongo et al. (2011), this decomposition occurs through of favorable climatic conditions and soil microbial activity. Caatinga environment behavior is influenced by climatic conditions of the region, defined seasonality, with rainfall ranging around four months, high temperatures, collaborating with lower moisture conditions in the soil (Sampaio, 1995). These high temperatures and sun rays on soil surface in areas recently cut, with little or sparse vegetation can accelerate C oxidation in the soil, changing stock balance.

Fraga and Salcedo (2004), in work on the decline of organic nutrient in semiarid region, found C concentration in undisturbed Caatinga forest around  $17.8 \text{ g kg}^{-1}$ , and  $8.9 \text{ g kg}^{-1}$  in degraded area. Yu and Jia (2014), studying changes in soil organic carbon and nitrogen capacities of *Salix cheilophila* Schneid. along a revegetation chronosequence in semiarid degraded sandy land in Gonghe Basin, Tibetan Plateau- China, presented lower values between the times 0 and 21 years, ranging at 0-10 cm depth ( $1.8$  to  $14.2 \text{ g kg}^{-1}$ ), and similar values at 10-20 cm depth ( $4.5$  to  $10.0 \text{ g kg}^{-1}$ ).

Following the same tendency found to soil C, the C in humic fractions presented higher values for this variable at upper soil layer (Figure 4). The C distribution in humic fractions ranged from  $0.52$  to  $5.02 \text{ g kg}^{-1}$  to FA-C, from  $0.37$  to  $2.36 \text{ g kg}^{-1}$  to HA-C, and from  $1.51$  to  $8.68 \text{ g kg}^{-1}$  to HUM-C (Figure 4).

Humic fraction had the highest C content among the remaining fractions (Figure 4). Study in soil under tropical climate showed similar results as the higher C content in humic fraction (Aranda and Comino, 2014). This fraction has more recalcitrant and stable organic matter, and occurs an association of the C compounds with soil mineral matrix, existing difficulties in C changes with management practices (Stevenson, 1994). This fraction has been considered the most important fraction in terms of C sequestration. Another fact is that the strong humic stabilization with soil mineral matrix difficult microbial activity acting on C decomposition process (Moraes et al., 2011).

The C content in fulvic acid fraction was higher than in humic acid fraction (Figure 4). This can be partly explained by the polyphenol theory

(Stevenson, 1994). According to the theory, the formation of fulvic acid occurs prior to that of humic acid. According to Guggenberger and Zech (1994), humic substances in forest soils showed high levels of fulvic acids compared with humic acids.

This fulvic acid fraction has simple structure of low molecular weight, and it is soluble in water under all pH conditions. It is the first form among humic substances and then is altered to form humic acid (Dou et al., 2003). According Orlov (1998) and Canellas et al. (2007), the larger proportion of fulvic acids means that the soil has good quality humus or an effective biological activity. Humic acids, in turn, have more complex compounds arranged in supramolecular structures, including low molecular weight hydrophobic and amphiphilic compounds, resulting from the deterioration and decomposition of dead biological material (Sutton and Sposito, 2005). Abakumov et al. (2013) observed FA-C and HA-C increase in restoration time of vegetation.

Cheng and An (2015), in studies about C concentrations in semiarid succession vegetation on the Loess Plateau of China with the increase of restoration time, verified FA-C values at from 0.5 to 2.9 g kg<sup>-1</sup>, HA-C from 0.7 to 1.9 g kg<sup>-1</sup>, and HUM-C from 1.5 to 4.3 g kg<sup>-1</sup> at 0-20 cm depth in soil.

In our study, the C contents in FA and HUMIN fractions have represented an important contribution to C storage in the soil, when it was assessed the impact of vegetation cut succession on soil quality.

#### **4.7. C stocks in soil and humic fractions**

The C concentrations in soil and humic fractions in g kg<sup>-1</sup> were converted in C Mg ha<sup>-1</sup> stocks, using the bulk density. In these Caatinga woodland subjected to different times after clearcutting, there were significant quadratic increase in C stock in soil and humic fractions along Caatinga forest chronosequence (Figure 5).

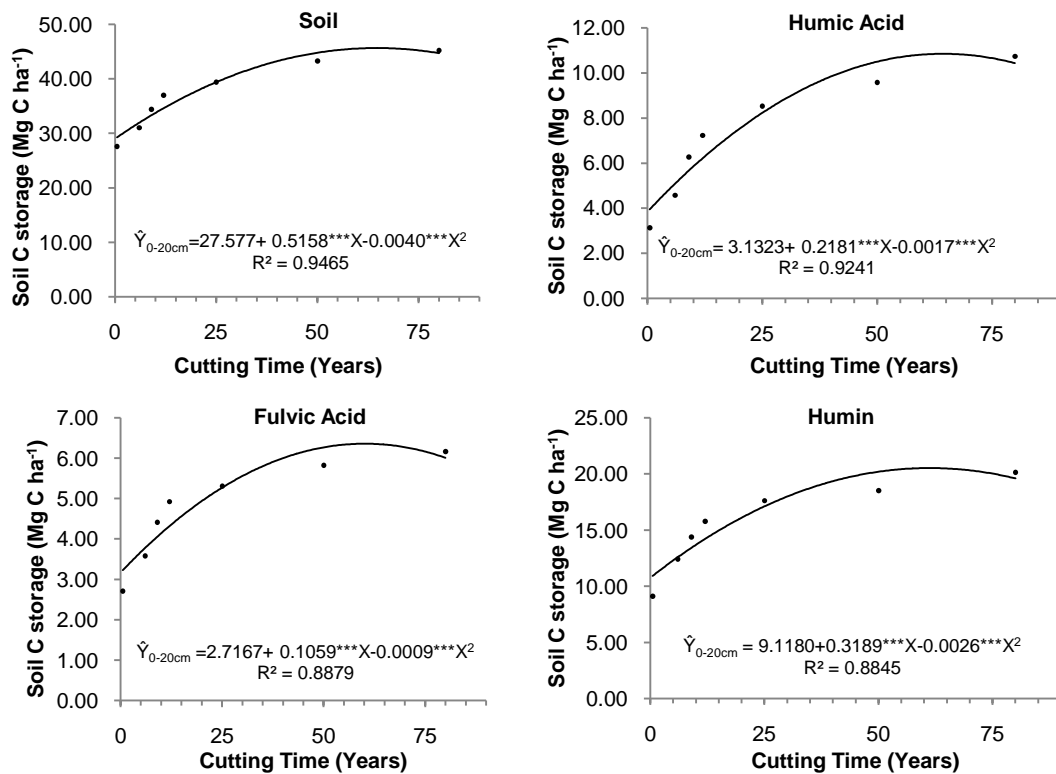


Figure 5. Carbon stocks in whole soil and soil humic fractions at 0-20 cm depth along Caatinga forest chronosequence. Significant at \*P <0.05, \*\*P <0.01, \*\*\*P <0.001 and ns= not significant.

The C stock average rates varied markedly among the woodland managed in function of time after clearcutting. The C storage in soil at 0-20 cm layer increased from 27.57 at recently cut area to 45.21 Mg C ha<sup>-1</sup> at Reserve area, the most preserved vegetation (Figure 5).

According to Baker et al. (2007), in forest soil with minimal disturbance by human practices, litter tends to accumulate and helps soil carbon increase. Caatinga plant residues entries by surface layer and their gradual decomposition guarantee constant incorporation of organic matter in soil (Fracetto et al., 2012).

Most of the soil C stock appears be associated with humin fraction of humic substances (Figure 5). This possibly occurs because these compounds concentrations, soil density influence, and clay content in forest soils, demonstrating the potential of these soils in C stocking. As this humic fraction is the most recalcitrant in soils, when it dominates is easier to maintain more C in soils. This is an important aim in present days because the environmental focus of society looking for a better humanity survives in future. Nowadays, it is very

important to contribute to improve C sequestration, especially in susceptible degradation areas, as Caatinga biome studied in this research.

Carbon storage values found in primary forest soil in Bukit Timah Nature Reserve, Singapore, were similar to this study at a depth of 0-20 cm (34.4 Mg C ha<sup>-1</sup>) (Ngo et al., 2013). Tiessen et al. (1998) estimated the C stock in 20 Mg C ha<sup>-1</sup> at 0-20 cm depth in tropical soils from Brazilian semiarid region. In Fraga and Salcedo (2004), studying hyperxerophilic Caatinga, C soil content were 17.9 and 28.6 Mg C ha<sup>-1</sup> at 0-7.5 and 0-15 cm depths, respectively.

#### 4.8. Labile-C concentrations in soil

Labile-C concentrations, in parallel with soil C, had significant increase at all depths along of the Caatinga forest chronosequence. The upper layer (0-5 cm) recorded the highest levels, and subsequent layers had decreased the concentrations of this element (Figure 6). This can be mainly attributed to high inputs of plant litter and presence of fine roots in the surface soil layers (Sierra et al., 2013).

According Blair et al. (1995), it is expected a decrease in the labile C in soils of recent areas management. Considering the vertical profile, Wang et al. (2010), studying spatial variability of soil organic carbon and its stock in the hilly area of the Loess Plateau, China, found that labile-C concentration decreased with soil depth increase in all land use.

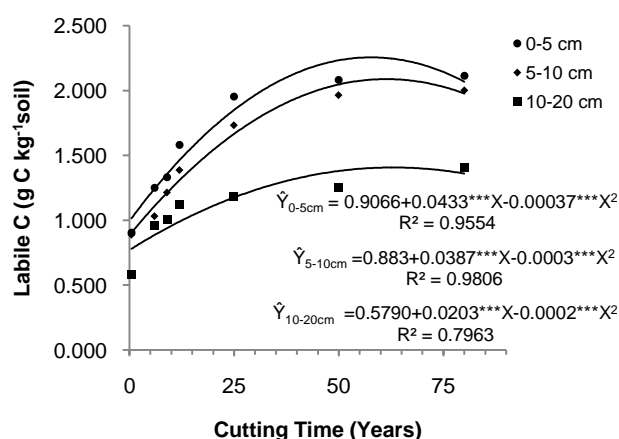


Figure 6. Labile-C concentration at 0-5, 5-10 and 10-20 cm depth along Caatinga forest chronosequence. Significant at \*P < 0.05, \*\*P < 0.01, \*\*\*P < 0.001 and ns= not significant.

Labile-C contents distribution varied in function of clearcutting time in this Caatinga forest, following soil C changes (Figure 2). Estimating the labile-C proportion in relation to soil C, we found the labile-C percentages at 0-5 cm (7.1 to 11.2%), 5-10 cm (8.9 to 14.5%) and 10-20 cm depth (8.7 to 14.9%), of the oxidized C by potassium permanganate.

Labile fraction modifications led to the possible hypothesis that, for these soils, the oxidative power of the potassium permanganate solution favored the complete oxidation of the C fractions less resistant, or that these soils presented a significant proportion of C more resistant to decomposition (Tiessen et al., 1994). Oxidation of C releases soil mineral nutrients and thus influences nutrient cycling for improving soil quality (Mosquera et al., 2012), being important to improve the vegetation growth in short rainy periods.

Similar proportions between C oxidized and total carbon in soil have been found by many researchers, with results between 14 and 25% in Ustalfs from Australia semiarid region (Lefroy et al., 1993); 17-27% in three Australian soil classes (Blair et al., 1995); 50% in Ustox in semiarid region of Pernambuco-Brazil (Shang and Tiessen, 1997).

#### **4.9. C stocks in Labile and MBC fractions**

There was a significant relationship between C stock in Labile fraction and time after clearcutting at soil studied layer (Figure 7). According to Blair (2000), maintenance of soil C stocks, especially labile fraction, is essential to improve soil quality and sustainability of these production systems.



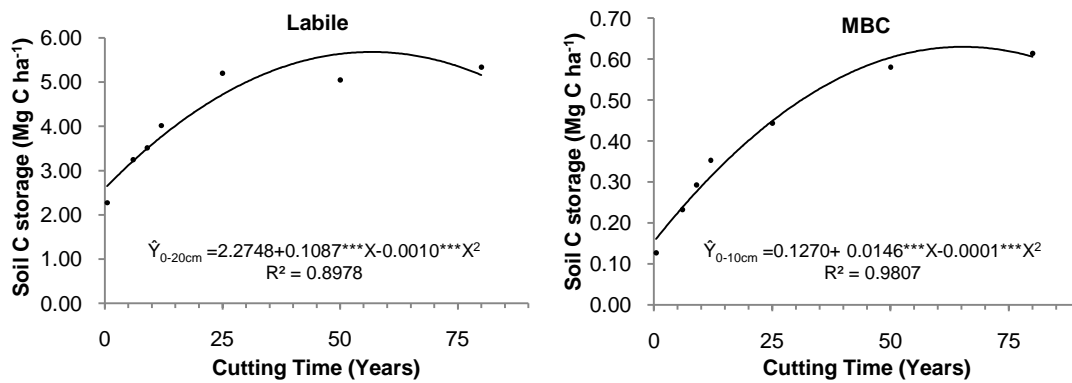


Figure 7. Carbon stocks in labile and MBC fractions along Caatinga forest chronosequence. Significant at \*P <0.05, \*\*P <0.01, \*\*\*P <0.001 and ns= not significant.

However, MBC is also very important to environmental quality, because it is a microbiological activity indicator in soils, and in low microbiological activities in soils, organic residues decomposition will be reduced. Residue inputs in areas cut at longer times may have contributed to larger C stocks in MBC (Figure 7). This increase was promoted by soluble compounds release during usable organic residue decomposition as energy source by microorganisms (Kuzyakov and Domanski, 2000). Mendham et al. (2002) reported that the MBC increased at crop residues presence on surface of Eucalyptus cultivated soils in first and fifth years after its establishment, in southwest Australia.

Caatinga vegetation maintenance for long time periods has conducted to better soil conditions in biological activity aspect too, as established by these data. In short periods, there were no conditions to recover soil capacity to take and stock C in all these forms. There is a requirement to rise the time between successive cuts in Caatinga forest environments, allowing the soil quality recovery.

#### 4.10. C in light organic matter

A directly proportional relationship between total soil C with C in free light fraction in soil is expected, since the light fraction is an intermediary fraction among the accumulated residues organic matter by plants, and SOM humified.

Depending on the managements times, the C contents resulted in a different behavior in free light fraction in soil ranging at 0-5 cm (0.351 to 0.594 g kg<sup>-1</sup>), 5-10 cm (0.318 to 0.562 g kg<sup>-1</sup>) and 10-20 cm depths (0.239 to 0.472 g kg<sup>-1</sup>) (Figure 8).

In preserved vegetation conditions, most of this fraction is located within the aggregates, which are protected of losses by erosion and mineralization (Oades, 1989; Cambardela and Elliot, 1994). After removal of vegetation for some purpose, the light fraction is lost faster than the most protected fraction (Dalal and Mayer, 1986; Magid and Kjaergaard, 2001). It was confirmed in this Caatinga area, where the organic matter light fraction has increased with time after clearcutting, and it was the lowest at recently cut area.

Christensen (1992) states that the accumulation of light fraction of organic matter is influenced by management, vegetation type and other factors, which alter the balance between production and decomposition of organic matter. According to Janzen et al. (1992), under relatively arid conditions, the LOM tends to decompose at slower rates and accumulate to high levels.

This behavior is associated mainly to the reduction of microbial activity, which was also observed in this study, ie, the area with the highest LOM concentration coincided with the low microbial activity. Cookson et al. (2008) found changes induced by management, and they were observed in soil pH, LOM, dissolved organic matter and microbial biomass, indicating the important role such as regulators of C cycling rates. This shows the importance of such fraction for degraded areas regeneration.

Fraga and Salcedo (2004), in work on decline of organic nutrient in semiarid northeastern Brazil, showed higher values of light fraction at 0-7.5 cm (0.583 g kg<sup>-1</sup>), 7.5-15 cm depths (0.471 g kg<sup>-1</sup>) in undisturbed forest and 0-7.5 cm (0.479 g kg<sup>-1</sup>), and 7.5-15 cm (0.371 g kg<sup>-1</sup>) in degraded areas. Medeiros (1999), working with light fraction in Caatinga area in semiarid Pernambuco-Brazil found similar value of 0.431 g kg<sup>-1</sup>.

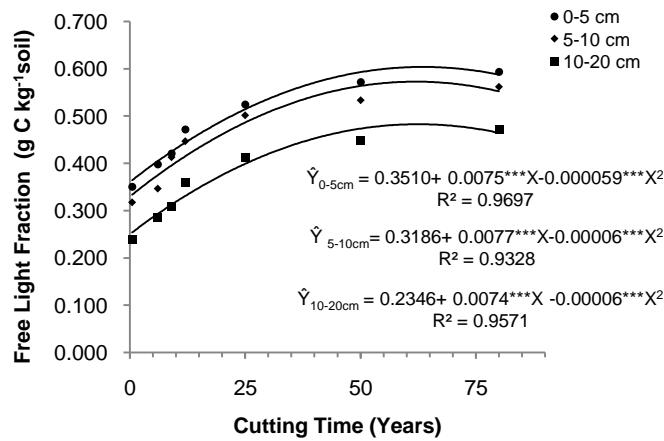


Figure 8. C concentration in light fraction in soil at 0–5, 5-10 and 10-20 cm along Caatinga forest chronosequence. Significant at \*P <0.05, \*\*P <0.01, \*\*\*P <0.001 and ns= not significant.

#### 4.11. Microbiological activity

As microbiological activity indicators evaluated in Caatinga forest chronosequence, MBC, BR, *q*MIC increased quadratically with time after clearcutting, with great increments, and possible equilibrium after long time (Figure 9). Plant residues incorporation over time promotes increase in microbial biomass, through improvement chemical and physical soil conditions (Pimentel et al., 2011). This has occurred in the upper layers, which had higher biological activities. According Pacchioni et al. (2014), soil characteristics affect microbial diversity through humidity, temperature, structure, and nutrients availability for microbial development.

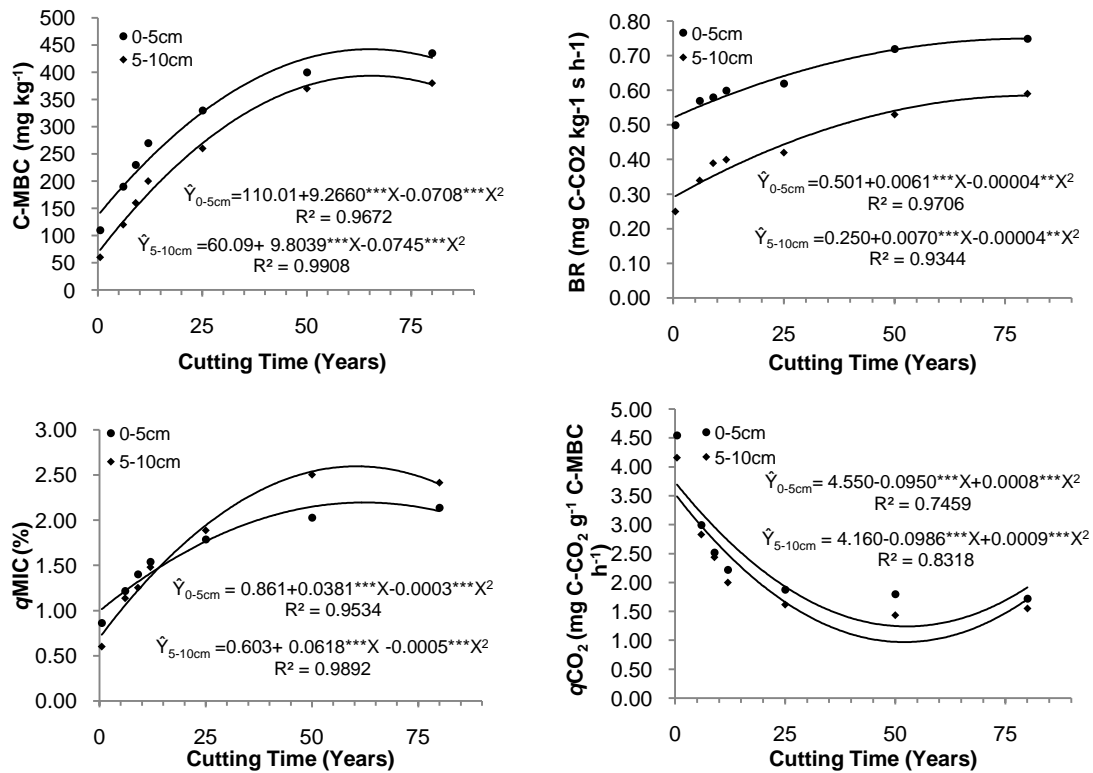


Figure 9. Microbial biomass C (MBC), basal respiration (BR), microbial quotient (qMIC) and metabolic quotient (qCO<sub>2</sub>) at 0–5 and 5–10 cm depths along Caatinga forest chronosequence. Significant at \*P < 0.05, \*\*P < 0.01, \*\*\*P < 0.001 and ns= not significant.

MBC concentrations ranged at 0-5 (110.01 to 435.10 mg kg<sup>-1</sup>) and 5-10 cm depths (60.09 to 380.02 mg kg<sup>-1</sup>) (Figure 9). Once the growth of microorganisms is limited by organic substrates availability, there was a significant reduction in MBC concentrations with degradation. The results demonstrate the sensitivity of the MBC to identify changes in soil at different times after forest clearcutting. Reductions in MBC levels are more pronounced with organic matter reductions through vegetation cover removal (Balota et al., 2003), as happened in this research.

Kaschuk et al. (2010), in studies with soil microbial biomass during three decades in Brazilian ecosystems, verified values ranging from 72 to 385 mg C kg<sup>-1</sup> in Caatinga forest soils. Wick et al. (2000), evaluating quality changes following natural vegetation conversion into silvo-pastoral systems in semiarid NE Brazil, presented lower values ranging from 167 to 29 mg C kg<sup>-1</sup>.

Activity and MBC reducing due to loss of vegetation cover was also observed by Bastida et al. (2006), in studies of soil microbial activity in degraded areas in semiarid regions of Spain. Garcia et al. (2002) observed that the decline in vegetation cover affected the chemical and microbiological parameters, evidencing reduction MBC, BR and  $q\text{CO}_2$  values.

BR had the same MBC behavior, ranging at 0-5 (0.50 to 0.75 mg C- $\text{CO}_2$   $\text{kg}^{-1}$   $\text{s h}^{-1}$ ) and 5-10 cm depths (0.25 to 0.59 mg C- $\text{CO}_2$   $\text{kg}^{-1}$   $\text{s h}^{-1}$ ) (Figure 9). The higher respiration rate can be a desirable feature in most preserved areas that have a high biological diversity, promoting a higher organic residues decomposition rate, and releasing available nutrients for plants growth.

Therefore, microbial activity in soils can be attributed to organic residues inputs in soil, beyond soil chemical and physical properties. In addition, the most preserved areas have appropriate amount of humidity in soil, important for microbial development (Balogh et al., 2011).

Martins et al. (2010), working with chemical and microbial attributes in a land desertification process area in semiarid Pernambuco-Brazil, showed higher values in different environments: preserved (3.2 mg C- $\text{CO}_2$   $\text{kg}^{-1}$   $\text{s h}^{-1}$ ), moderate (1.98 mg C- $\text{CO}_2$   $\text{kg}^{-1}$   $\text{s h}^{-1}$ ) and degraded (2.12 mg C- $\text{CO}_2$   $\text{kg}^{-1}$   $\text{s h}^{-1}$ ).

Even though this study has been made in the same state, there is a great soil variability in Pernambuco state, and soil type is an important factor on biological activity, mainly in respect to granulometric composition on water availability and nutrients retention.

On the other hand, Garcia et al. (2002), in their studies about plant cover effect on chemical and microbiological parameters under Mediterranean climate, presented soil basal respiration in closer values, ranging between 1.26 mg C- $\text{CO}_2$   $\text{kg}^{-1}$   $\text{s h}^{-1}$  in soil under greater vegetation cover and 0.54 mg C- $\text{CO}_2$   $\text{kg}^{-1}$   $\text{s h}^{-1}$  in soil under lower vegetation cover. So this parameter is a particular property of each soil and it reflects the status of biological activity in special conditions. It can be used as a soil quality attribute.

The highest  $q\text{MIC}$  values were observed 5-10 cm depth in most areas (Figure 9), which suggests a poor ability to humification, and that the mineralization processes are predominating in this layer, because the addition of organic matter to the soil generally makes this ratio increase (Powlson et al., 1987). With the addition of good quality organic matter or the end of a stressful

situation, there is an increase in microbial biomass, resulting in a high microbial quotient (Wardle and Ghani, 1995).

The contribution of MBC to soil carbon was remarkable at two evaluated depths, it represented around 1% on soil C average (Figure 9). Jenkinson and Ladd (1981) report that, under normal conditions, the MBC represents 1-4% of the COT; generally  $qMIC$  values of less than 1% may be attributed to some limiting factor on microbial biomass activity. This wide range of ratio values may be due to differences in chemical, physical and biological soil properties, vegetation and land use (Anderson and Domsch, 1989).

The  $qCO_2$  values had been decreased along the studied Caatinga forest chronosequence (Figure 9). However, the interpretation of these biological activity results should be made with criterion, because low breathing values do not always indicate undesirable conditions (Parkin et al., 1996). Agreeing with Jakelaitis et al. (2008), the lower average  $qCO_2$  soil values indicated environments with lesser disturbance degree or microbial communities under favorable conditions. This demonstrates that microbial biomass becomes effective from the moment that less carbon is lost as  $CO_2$  form by respiration, allowing thus higher carbon incorporation into microbial tissues (Fialho et al., 2006).

Forest management in Caatinga areas highlights greater care on the exploration. The impacts caused promote the loss of nutrients, carbon and microbial activity. This may be higher if they are removed from areas forest products in shorter time than evaluated in this study. Larger cutting times Caatinga forest become possible, contributing to improved chemical characteristics, preserving the biological activity and reducing nutrient losses in forest soils. The cutting time used in forest management plans in Brazil is not suitable for the Caatinga biome, requiring more time for recovery of forest soils.

Faced with long periods for recovery of the Caatinga forest soils in semiarid of Pernambuco were performed derived from quadratic equations obtained in this work finding the maximum increment and calculate by the time the maximum value for each variable in the study. As a suggestion has been possible to obtain increment values 50 to 100% and translated in time for soil recovery (Table 4). That would be a possible alternative for us to achieve sustainable management for the Caatinga forest soils.

Table 4. Recovery times of soil variables in relation to the maximum increments.

| Variables        | Depths<br>(cm) | Recovery Time (Years) |       |       |       |       |        |
|------------------|----------------|-----------------------|-------|-------|-------|-------|--------|
|                  |                | 50%                   | 60%   | 70%   | 80%   | 90%   | 100%   |
| C soil           | 0-5            | 31.27                 | 37.52 | 43.77 | 50.02 | 56.28 | 62.53  |
| C soil           | 5-10           | 33.38                 | 40.05 | 46.73 | 53.40 | 60.08 | 66.75  |
| C soil           | 10-20          | 35.48                 | 42.57 | 49.67 | 56.76 | 63.86 | 70.95  |
| N soil           | 0-5            | 38.46                 | 46.15 | 53.84 | 61.54 | 69.23 | 76.92  |
| N soil           | 5-10           | 53.50                 | 64.20 | 74.90 | 85.60 | 96.30 | 107.00 |
| N soil           | 10-20          | 51.50                 | 61.80 | 72.10 | 82.40 | 92.70 | 103.00 |
| EC               | 0-5            | 27.76                 | 33.31 | 38.86 | 44.42 | 49.97 | 55.52  |
| EC               | 5-10           | 29.33                 | 35.20 | 41.06 | 46.93 | 52.79 | 58.66  |
| EC               | 10-20          | 29.25                 | 35.10 | 40.95 | 46.80 | 52.65 | 58.50  |
| Ca <sup>2+</sup> | 0-5            | 33.13                 | 39.76 | 46.38 | 53.01 | 59.63 | 66.26  |
| Ca <sup>2+</sup> | 5-10           | 31.29                 | 37.54 | 43.80 | 50.06 | 56.31 | 62.57  |
| Ca <sup>2+</sup> | 10-20          | 31.89                 | 38.26 | 44.64 | 51.02 | 57.39 | 63.77  |
| Mg <sup>2+</sup> | 0-5            | 33.41                 | 40.09 | 46.77 | 53.45 | 60.13 | 66.81  |
| Mg <sup>2+</sup> | 5-10           | 36.74                 | 44.08 | 51.43 | 58.78 | 66.12 | 73.47  |
| Mg <sup>2+</sup> | 10-20          | 35.35                 | 42.41 | 49.48 | 56.55 | 63.62 | 70.69  |
| K <sup>+</sup>   | 0-5            | 34.08                 | 40.90 | 47.71 | 54.53 | 61.34 | 68.16  |
| K <sup>+</sup>   | 5-10           | 34.30                 | 41.16 | 48.02 | 54.88 | 61.74 | 68.60  |
| K <sup>+</sup>   | 10-20          | 23.05                 | 27.66 | 32.27 | 36.88 | 41.49 | 46.10  |
| Na <sup>+</sup>  | 0-5            | 29.95                 | 35.94 | 41.93 | 47.92 | 53.91 | 59.90  |
| Na <sup>+</sup>  | 5-10           | 27.60                 | 33.12 | 38.64 | 44.16 | 49.68 | 55.20  |
| Na <sup>+</sup>  | 10-20          | 32.78                 | 39.33 | 45.89 | 52.44 | 59.00 | 65.55  |

Continuation.

| Variables  | Depths<br>(cm) | Recovery Time (Years) |       |       |       |       |       |
|------------|----------------|-----------------------|-------|-------|-------|-------|-------|
|            |                | 50%                   | 60%   | 70%   | 80%   | 90%   | 100%  |
| CAF        | 0-5            | 31.58                 | 37.89 | 44.21 | 50.52 | 56.84 | 63.15 |
| CAF        | 5-10           | 30.67                 | 36.80 | 42.93 | 49.06 | 55.20 | 61.33 |
| CAF        | 10-20          | 35.00                 | 42.00 | 49.00 | 56.00 | 63.00 | 70.00 |
| CAH        | 0-5            | 32.37                 | 38.84 | 45.31 | 51.78 | 58.26 | 64.73 |
| CAH        | 5-10           | 28.88                 | 34.65 | 40.43 | 46.20 | 51.98 | 57.75 |
| CAH        | 10-20          | 27.20                 | 32.64 | 38.08 | 43.52 | 48.96 | 54.40 |
| HUM        | 0-5            | 31.34                 | 37.60 | 43.87 | 50.14 | 56.40 | 62.67 |
| HUM        | 5-10           | 31.48                 | 37.77 | 44.07 | 50.36 | 56.66 | 62.95 |
| HUM        | 10-20          | 30.13                 | 36.15 | 42.18 | 48.20 | 54.23 | 60.25 |
| Est C      | 0-20           | 32.24                 | 38.68 | 45.13 | 51.58 | 58.02 | 64.47 |
| Est CAF    | 0-20           | 29.42                 | 35.30 | 41.18 | 47.06 | 52.95 | 58.83 |
| Est CAH    | 0-20           | 32.07                 | 38.48 | 44.90 | 51.31 | 57.73 | 64.14 |
| Est HUM    | 0-20           | 30.66                 | 36.79 | 42.92 | 49.06 | 55.19 | 61.32 |
| Labile     | 0-5            | 29.26                 | 35.11 | 40.96 | 46.81 | 52.66 | 58.51 |
| Labile     | 5-10           | 32.25                 | 38.70 | 45.15 | 51.60 | 58.05 | 64.50 |
| Labile     | 10-20          | 25.38                 | 30.45 | 35.53 | 40.60 | 45.68 | 50.75 |
| Est Labile | 0-20           | 27.18                 | 32.61 | 38.05 | 43.48 | 48.92 | 54.35 |
| Est MBC    | 0-10           | 36.50                 | 43.80 | 51.10 | 58.40 | 65.70 | 73.00 |



Continuation.

| Variables        | Depths<br>(cm) | Recovery Time (Years) |       |       |       |       |       |
|------------------|----------------|-----------------------|-------|-------|-------|-------|-------|
|                  |                | 50%                   | 60%   | 70%   | 80%   | 90%   | 100%  |
| LOM              | 0-5            | 31.78                 | 38.13 | 44.49 | 50.84 | 57.20 | 63.55 |
| LOM              | 5-10           | 32.08                 | 38.50 | 44.91 | 51.33 | 57.74 | 64.16 |
| LOM              | 10-20          | 30.83                 | 37.00 | 43.16 | 49.33 | 55.49 | 61.66 |
| C-MBC            | 0-5            | 32.72                 | 39.26 | 45.80 | 52.34 | 58.89 | 65.43 |
| C-MBC            | 5-10           | 32.90                 | 39.47 | 46.05 | 52.63 | 59.21 | 65.79 |
| qMIC             | 0-5            | 31.75                 | 38.10 | 44.45 | 50.80 | 57.15 | 63.50 |
| qMIC             | 5-10           | 30.90                 | 37.08 | 43.26 | 49.44 | 55.62 | 61.80 |
| BR               | 0-5            | 38.13                 | 45.75 | 53.38 | 61.00 | 68.63 | 76.25 |
| BR               | 5-10           | 43.75                 | 52.50 | 61.25 | 70.00 | 78.75 | 87.50 |
| qCO <sub>2</sub> | 0-5            | 29.69                 | 35.63 | 41.57 | 47.50 | 53.44 | 59.38 |
| qCO <sub>2</sub> | 5-10           | 27.39                 | 32.86 | 38.34 | 43.82 | 49.29 | 54.77 |
| Média            |                | 32.58                 | 39.09 | 45.61 | 52.12 | 58.64 | 65.16 |

C soil: soil carbon; N soil: soil nitrogen; EC: electric conductivity; Ca<sup>2+</sup>: Calcium; Mg<sup>2+</sup>: Magnesium; K<sup>+</sup>: potassium; Na<sup>+</sup>: sodium; CAF: fulvic acid carbon; CAH: humic acid carbon; HUM: humin carbon; Est C: storage carbon soil; Est CAF: storage fulvic acid carbon; Est AH: storage humic acid; Est HUM: storage humin carbon; Labile: labile carbon; Est Labile: storage labile carbon; LOM: light organic matter carbon; C-MBC: microbial biomass carbon; qMIC: microbial quotient; BR: basal respiration; qCO<sub>2</sub>: metabolic quotient.

## 5. CONCLUSIONS

- Exchangeable  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^+$ , and CEC increased as a function of time in all studied depths along Caatinga forest chronosequence;
- The main factors influencing exchangeable cations and CEC were pH and C;
- It is necessary long periods of time, to be recovered 100% of the values of the chemical and soil carbon. For recovery of at least 50% is required at least 33 years before a new cut of the Caatinga.
- There was an initial rapid increase of C content after Caatinga cutting, reaching an equilibrium along Caatinga forest chronosequence
- The Humins were the predominant fraction of humic substances in soil;
- The carbon biomass of soil microbial and microbial quotient showed great sensitivity to increased levels of degradation;
- Caatinga forest clearcutting resulted in decline of C storage in soil, humic fractions, labile-C and microbial biomass-C;
- The omission of Caatinga cutting for more than six decades can promote the soil recovery to the nearest stable condition with C stocks;
- At climate change mitigation context in a global scale, the time between vegetation consecutive cuts for a long time favors significant C storage in these soils under Caatinga.

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