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# Recovery of carbon stocks in deforested caatinga dry forest soils requires at least 60 years

Renisson Neponuceno de Araújo Filho[a], Maria Betânia Galvão dos Santos Freire[a,*], Bradford Paul Wilcox[b], Jason Brossard West[b], Fernando José Freire[a], Flávio Adriano Marques[c]

[a] Department of Agronomy, Federal Rural University of Pernambuco, Av. Dom Manoel de Medeiros, Dois Irmãos, Recife, PE 52171-900, Brazil
[b] Department of Ecosystem Science and Management, Texas A & M University, College Station, TX 77843, USA
[c] EMBRAPA Solos, Rua Antônio Falcão, 402, Recife, PE 51020-240, Brazil

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ABSTRACT

Caatinga forests occupy an area of around one million km$^2$ in the semiarid region of northeast Brazil. These landscapes are undergoing rapid change because of accelerated deforestation for cultivation and firewood. The capacity of Caatinga forests to regenerate after clearing determines the magnitude of the carbon (C) sink in the soil, and thus is fundamental information for developing management policies for long-term sustainability. The objective of this study was to investigate C stocks and microbial activity in soils of dry Caatinga forests that had undergone harvesting at different times in the past. Soils were collected from three depths (0–5, 5–10, and 10–20 cm) within seven sites representing a sequence of years since cutting: 0.5, 6, 9, 12, 25, 50, and undisturbed (at least 80 years since cutting). Samples from each depth interval were analyzed for total C concentration and stock, humic substances, labile-C, and microbial biomass C. In addition, indicators of microbiological activity, such as basal respiration, microbial quotient, and metabolic quotient, were determined for the two shallow layers. The results showed that C stocks and microbiological activity were strongly influenced by forest cutting times, and reflect significant C losses associated with this type of management. They also suggest that reaccumulation of C following disturbance is slow. Those areas in which the vegetation has remained undisturbed for longer periods have larger C stocks, indicating that long-term maintenance of vegetation increases C storage in soils. For example, 20 years after cutting the C concentrations in soil and humic fractions had recovered to only about 32% of the presumed maximum found for the 80-year site. The average time for C in soil and humic fractions to return to their initial values at these sites is estimated to be approximately 65 years. Even achieving 50% recovery would require at least 33 years between cutting campaigns. Our findings show that in the context of mitigating climate change on a global scale, forest management entities should restrict cutting intervals in semiarid regions such as the Caatinga to longer than 30 years, to allow these soils to rebuild significant C stocks.

## 1. Introduction

Forests play an important role in mitigating climate change because they store more C than any other terrestrial ecosystem (Dixon et al., 1994). A biome found exclusively in Brazil, the Caatinga forest has not been studied to the extent that Atlantic and Amazonian forests have (Santos et al., 2011). In semiarid northeastern Brazil, Caatinga forests cover an area approximately the size of France and are characterized by deciduous vegetation that is regularly cleared and used for firewood. After clearing, the land is used for itinerant agriculture (Bezerra-Gusmäo et al., 2011). Eventually the land is allowed to go fallow and recovery of the forest begins. This practice has been ongoing since Portuguese settlement; however, the period of time between tree harvests has gradually decreased, from over 50 years to as little as 10–15 years currently. Such intense forest management and harvesting of biomass is expected to significantly affect the C stocks in the soil (Nave et al., 2010), especially in areas like the Caatinga forest, already threatened by other drivers of degradation.

Carbon stores in soils are distributed in several organic-matter pools produced by the decomposition of plant, animal, and microorganism biomass. The accumulation, preservation, and loss of soil organic C constitute an important exchange between the biosphere and the

* Corresponding author at: Dom Manoel de Medeiros Street, Campus Universitário de Dois Irmãos, Recife, Pernambuco CEP: 52070-030, Brazil.
*E-mail addresses:* nepoaraujo@gmail.com (R.N.d. Araújo Filho), mbetaniafreire@uol.com.br, maria.freire@ufrpe.br (M.B.G.d.S. Freire), bwilcox@tamu.edu (B.P. Wilcox), jbwest@tamu.edu (J.B. West), fernando.freire@ufrpe.br (F.J. Freire), flavio.marques@embrapa.br (F.A. Marques).

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atmosphere (Raich and Schlesinger, 1992). Quantification of ecosystem C stocks across disturbance regimes not only helps us understand how a given ecosystem may respond to natural and human disturbances under different management strategies (He et al., 2008), but also enables us to better assess ecosystem potential to sequester C—information that is critical for mitigating global climate change. It is therefore very important to establish a broad database of information on (1) existing C stocks in soils under different plant species and affected by different management strategies, and (2) changes in C stocks over time (Wu et al., 2008).

In addition, changes in the soil environment as a result of disturbance, at both macro and micro scales, affect microbial activity, which affects rates of decomposition of soil organic matter (Anderson and Domsch, 1989). And because microbial biomass can respond more quickly to changes caused by forest management, changes in this biomass can enables us to detect changes in soil C stocks. These changes are also often linked to changes in the chemistry of soil organic C, in particular the proportion of humic substances. In addition to serving as a C reservoir, humic substances improve soil structure, promote soil stability, and regulate soil chemical and biological functions, making them an important contributor to the sustainability of terrestrial ecosystems (Stevenson, 1994).

There have been a few studies addressing the impact of anthropogenic disturbance on Caatinga soil C. Schulz et al. (2016) suggest that grazing causes substantial releases of C from these dry forest soils and argue that better grazing management would lead to higher soil C stocks. Moura et al. (2016) reported that literfall was lowest in recently abandoned pastures, peaked in intermediate regeneration stages, and then slowed in mature (> 50 year old) Caatinga forests. Annual net C accumulation in the ecosystem, however, continued to increase with succession age, as a result of increasing C accumulation in other pools. Althoff et al. (2016) carried out a study of a Caatinga area in Brazil in which tree cutting took place every 10 years at one site, every 15 years at a second site, and every 20 years at a third site, with and without the burning of the residues. They concluded that 50 years was required for C stocks to recover to the levels obtaining before cutting of the vegetation biomass, and therefore the currently recommended cutting cycle of 10–20 years is insufficient.

Given these reported trajectories in ecosystem C fluxes and pools, we hypothesized that following removal of woody vegetation, soil C stocks require over 50 years to recover to their prior levels. The objective this study was to confirm this hypothesis by investigating changes in C content and microbial activity in soils of Caatinga forest areas where woody plant harvesting has taken place at different time intervals.

## 2. 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 (Fig. 1). The climate type of this area is BSh semiarid Brazil, characterized as warm and dry (Alvares et al., 2013), with an average annual temperature of 28°C. The average annual precipitation is 500 mm, typically occurring almost entirely between November and March, and the average annual potential evapotranspiration is 1.646 mm. The relief is flat to gently rolling. We selected this area because of the land management practices already in place there and because it possesses a well-defined sequence of forest cutting times. Within the area, we delineated seven experimental sites:

1. The R (reserve) site (08°36.423′S, 37°59.290′W) is an 80-ha parcel that has not been subjected to any kind of anthropogenic interference in the last 80 years. The soil is classified as Haplustepts (Soil Survey Staff, 2014) and the vegetation is dominated by five tree species (a total of 2288 individuals), in the following order of abundance: 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.); and 4.98% Pinhão Brabo (*Jatropha mollissima* (Pohl) Baill.) (CPRH, 2000, 2008).
2. The 50-year site (08°30.970′S and 37°59.025′W) is a parcel of 60 ha that has undergone harvesting of forest products for domestic use. The soil class is Haplustepts (Soil Survey Staff, 2014) and the vegetation is dominated by five tree species (a total of 1032 individuals), in the following order of abundance: 34.3% Catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 11.9% Jurema de Embira (*Mimosa ophthalmocentra* Mart. ex Benth.); 6.4% Pereiro (*Aspidosperma pyrifolium* Mart.); 5.6% Faveleira Braba (*Cnidoscolus bahianus* (Ule) Pax & K. Hoffm.); and 5.3% Angico (*Anadenanthera* colubrina var. cebil (Griseb.) (Altschul) (Alves Júnior et al., 2013).
3. The 25-year site (08°33.416′S and 37°56.548′W) is a 60-ha parcel. This site underwent removal of all vegetation (cutting), and was then abandoned, 25 years before sampling. The soil class is Haplustepts (Soil Survey Staff, 2014), and the five tree species dominating the vegetation (a total of 544 individuals) are as follows: 37.1% Catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 21.1% Jurema de Embira (*Mimosa ophthalmocentra* Mart. ex Benth); 8.9% Pinhão Brabo (*Jatropha molíssima* (Pohl) Baill.); 5.3% Quipembe (*Pityrocarpa moniliformis* (Benth.) Luckow & R. W. Jobson); and 2.4% Sipaúba (*Thiloa glaucocarpa* (Mart.) Eichler) (Ferraz et al., 2014).

   The four sites cut more recently were treated somewhat differently from the three older sites. Rare trees, protected by law, were preserved. These include: Aroeira *(Myracrodruon urundeuva* Allemão), Baraúna (*Schinopsis brasiliensis* Engl.), Umbuzeiro (*Spondias tuberosa* Arruda), Quixabeira-Braba (*Erytroxylum* sp.), and Imburana de Cambão (*Commiphora leptophloeos* (Mart.) J. B. Gillett). Trees growing along creek and stream borders were preserved as well, as were species not useful for charcoal production and species having a stem diameter of less than 2 cm. All information about these sites comes from existing forest management plans (CPRH, 2000, 2008). Their regeneration has taken place through seed germination and resprouting.
4. The 12-year site (08°35.940′S and 37°59.409′W) is 90 ha. The vegetation at this site was shallow-cut 12 years before sampling. The soil class is Haplustalfs (Soil Survey Staff, 2014), and the five tree species dominating the vegetation (a total of 261 individuals) are as follows, in order of abundance: 25.7% Catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 11.01% Jurema de Embira (*Mimosa ophthalmocentra* Mart. ex Benth.); 9.29% Maniçoba (*Manihot glaziovii* Müll. Arg.); 8.08% Quebra Faca Branca (*Croton rhamnifolius* Willd.); and 7.41% Aroeira (*Myracrodruon urundeuva* Allemão).
5. The 9-year site (08°35.485′S and 37°59.351′W) is 90 ha. The vegetation at this site was shallow-cut 9 years before sampling. The soil class is Haplustalfs (Soil Survey Staff, 2014), and the five tree species dominating the vegetation (a total of 196 individuals) are as follows, in order of importance: 29.7% Catingueira [*Poincianella bracteosa* (Tul.) L. P. Queiroz]; 8.31% Jurema de Embira (*Mimosa ophtalmocentra* Mart. ex Benth.); 8.1% Quipembe [*Pityrocarpa moniliformis* (Benth.) Luckow & R. W. Jobson]; 7.3% Quebra Faca Branca (*Croton rhamnifolius* Wild.); and 6.02% Aroeira (*Myracrodruon urundeuva* Allemão).
6. The 6-year site (08°34.665′S and 38°00.910′W) is 90 ha. The vegetation at this site was shallow-cut 6 years before sampling. The soil class is Haplustepts (Soil Survey Staff, 2014), and the five tree species dominating the vegetation (a total of 131 individuals) are as follows, in order of abundance: 36.31% Catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 10.69% Jurema de Embira (*Mimosa ophthalmocentra* Mart. ex Benth.); 9.7% Pinhão Brabo (*Jatropha mollissima* (Pohl) Baill.); 5.08% Aroeira (*Myracrodruon urundeuva* Allemão); and 5.02% Pereiro (*Aspidosperma pyrifolium* Mart.).
7. The 0.5-year site (08°35.518′S and 37°59.741′W) is 90 ha. The