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Climate change impacts on the sustainability of the firewood harvest and vegetation and soil carbon stocks in a tropical dry forest in Santa Teresinha Municipality, Northeast Brazil ☆

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ABSTRACT

The Brazilian semi-arid region is characterized by low and erratic rainfall, high temperatures and high potential evapotranspiration. The removal of firewood from the native tropical dry forest, called "Caatinga", can negatively impact important ecosystem services, such as soil conservation, water resources, biodiversity and atmospheric carbon capture, if performed in an unsustainable manner. Most global climate models indicate that Caatinga will experience temperature increases and rainfall decreases in the next few decades. We used the Century model to simulate the impact of climate changes on woody vegetation growth and on vegetation and soil organic carbon stocks in a Caatinga area managed with a single clear cut or cuts every 10 years, 15 years, and 20 years, followed or not followed by the burning of plant residues (leaves and small branches) left after firewood removal. The effects of future climate projections, (LOW, MIDI and HIGH members of the climate scenario SRES A1B, which corresponded to different CO_2 emission predictions, downscaled by the Eta/CPTEC model), were compared to those of the projection of the historical climate. With the current climate, it would take 50 years to regenerate the Caatinga biomass stock to a level close to that before cutting after a single cut, followed or not followed by fire. Therefore, the recommended cutting cycles (10–20 years) were not long enough to allow for the regeneration of a fully mature Caatinga. However, all of these cycles reached sustainable biomass production levels, with similar total productions until the end of the century. Under these conditions, the lower proportions of biomass recovery of shorter cycles would be compensated by more frequent cutting. The model also indicated that burning or not burning the residues would have little effect. On the contrary, if the climate changes as predicted, the biomass of the native Caatinga vegetation and soil organic carbon stock would decrease throughout this century, even without cutting the vegetation. All of the cutting cycles would not provide sustainable firewood production, with reduced production after each consecutive cut. Therefore, if the climate changes as expected, forest management legislation should require longer periods of forest recovery between cutting cycles for sites with environmental conditions (e.g., climate, soil and vegetation) similar to those of the present study.

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1. Introduction

The native tropical dry forest of the semi-arid region of Northeastern Brazil, called "Caatinga", originally occupied an area of nearly 1 million km^2 (Brasil, 2007). Natural fires are rare in the Caatinga vegetation (Sampaio, 1995; Gariglio et al., 2010), but burning is part of the three main production systems: firewood production, cattle production on native pasture and slash and burn

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itinerant agriculture. Firewood production used to occur at the end of the fallow period of the itinerant agricultural system (10–20 years fallow, following 3–5 years of annual crops), but increased consumption and shortening of the fallow periods led to the cutting of firewood in areas not suitable for agriculture. Selective tree and shrub cutting is also increasingly practiced in open native pastures to increase herb production. In all cases, fire is used to clear the plant residues (leaves and small branches) left after firewood is removed. Due to these systems, only approximately half of the original area is currently covered by native vegetation, and mismanagement associated with harsh climatic conditions (e.g., high temperatures and low and erratic rainfall) has caused the degradation of vast areas of the semi-arid region, leading to ecological and socioeconomic problems (Sampaio et al., 2003).

Climate changes projected to occur in the future may cause significant impacts in South America in the present century, and these impacts will be more intense in the tropical region, specifically the Brazilian Amazon and Northeast regions (Baettig et al., 2007; IPCC, 2007). In the semi-arid region of Northeastern Brazil, increased climate variability may result in higher environmental degradation and decreased agricultural and cattle production. Marengo et al. (2014) predicted that the Brazilian semi-arid region would be the most vulnerable to climate changes due to the increased difficulty of accessing water and that these changes, coupled with the current economic situation that is based on subsistence and provides low profit to the farmers, may lead to a social crisis. To increase the accuracy of the climate predictions, we adapted the Eta model, which was implemented at INPE in 1996 and used it to produce climate projections for South America at different time scales (Chou et al., 2012; Marengo et al., 2012) at a specific site considering the present temperature and precipitation of the site (Carvalho et al., 2015; Marengo and Bernasconi, 2015).

Studies on biogeochemical cycling are important to better understand the response of vegetation to climate changes and anthropic disturbances, such as the cutting of plants to produce firewood, introducing domestic animals to forage in the area and practicing slash and burn agriculture. Predicting how the Caatinga vegetation will adapt to future climate scenarios is essential to establish proper management protocols and sustainable conservation strategies to obtain firewood. These protocols and strategies must be specific for each soil type and climate conditions. Therefore, studies that evaluate the long term impacts of different management practices on these areas are urgent (Gariglio et al., 2010). Examples of questions that need to be answered are: (1) What is the time required for the regeneration of the firewood stock in a certain area?; (2) after the regeneration of the firewood stock, has the soil recovered the organic matter content present at cutting?; (3) to what extent does burning the residues that are left after firewood removal affect soil organic matter and nutrient availability and, ultimately, vegetation regrowth?; (4) considering the firewood stock, biodiversity and soil recovery, what is the cutting and regrowth cycle that produces the most firewood and still maintains a sustainable forest management in any particular site?; and (5) how will the climate projected for the future affect all of these processes?

These questions are difficult to answer based on experimental data due to the long amount of time and resources required to conduct representative surveys throughout the Caatinga large and diverse area and considering its high rainfall variability from one year to another (Sampaio, 1995; Marengo et al., 2011). This complexity renders it difficult to design and monitor sustainable land use systems and may explain the actual scarcity of long-term studies regarding possible management systems in the Caatinga region (Gariglio et al., 2010). Studies relating current management systems to possible climate changes are virtually non-existent, and they are needed to formulate future sound environmental, social and economic policies.

Modeling is a flexible and rapid technique that provides basic data to investigate the impacts of future environmental changes. The Century model is one of the models that is most widely used throughout the world to study changes in nutrient cycling, soil stocks and vegetation growth under different conditions (Parton et al., 1987). It has already been used in several studies conducted in Brazil (Cerri et al., 2003; Leite et al., 2004; Tornquist et al., 2009; Bortolon et al., 2011; Carvalho et al., 2015), but it was not tested in the semi-arid region of Northeast Brazil. Recently, the Century model was calibrated and validated to simulate changes in soil and vegetation after different periods of vegetation regeneration following clear cutting, with or without burning the residues, in the Caatinga of the semi-arid area of Northeast Brazil (Althoff, 2015).

The predicted future climate scenarios may affect the regeneration of the Caatinga and hence the firewood production and the fallow period of the itinerant agricultural system. Therefore, the aim of this study was to adapt the climate scenarios to a specific site and to use the Century model to simulate the impact of these scenarios (Metting et al., 1999) on vegetation growth and on carbon stocks in a Caatinga site with different cutting managements from 2015 to 2100. More specifically, the cutting managements included a single cutting in 2015 followed by regeneration until the end of the century and cuttings every 10 years, 15 years or 20 years. These cutting scenarios are similar to those that are presently used, which correspond to one eventual cutting or systematic cuttings with intervals from 10 years to 20 years (Gariglio et al., 2010), with or without the use of fire to burn the residues left after cutting and wood removal. We hypothesized that increased temperatures and decreased rainfall volumes, as expected in future scenarios, could lead to four different outcomes for Caatinga vegetation: (1) smaller vegetation biomass and soil C accumulations, in all of the cutting cycles, compared to the predictions based on the present climate; (2) smaller vegetation biomass and soil C accumulation in sites where residues are burned after cutting the trees compared to the sites where the residues are left in the field; (3) smaller vegetation biomass and soil C accumulation in climate scenarios with higher CO_2 emissions; and (4) shorter cutting cycles (every 10 years and 15 years) under the more severe future climate scenarios are not sustainable.

2. Material and methods

The area chosen for the calibration and simulation of the Century model was within the Tamanduá Farm (06°59′13″ and 07°00′14″S and 37°18′08″ and 37°20′38″W), municipality of Santa Teresinha, Paraíba state. The area chosen for the validation of the model was the Seridó Ecological Station (ESEC) (06°35′35″S and 37°14′19″W), municipality of Serra Negra do Norte, Rio Grande do Norte state. These areas were chosen because they had climate data available for the last few decades, and data for vegetation and soil changes were collected from sites with a known management history since the middle of the last century. The predominant soil type in both areas was Lithic Neosol (Entisol in the American classification), shallow (approximately 40 cm), stony and of low fertility (EMBRAPA, 2006). The native vegetation, called Caatinga, was characterized by an open stratum of shrubs and small trees, mostly less than 7 m tall, and a stratum of herbs, which thrived only in the rainy season (Souza et al., 2012; Freitas et al., 2010). Both of the areas were subjected to the same climate (MME, 2014) and had the same soil type. The mean minimum and maximum temperatures, 21 °C and 33 °C, respectively, were estimated using the Estima T software, specifically developed by the Federal University

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