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Adaptation of the century model to simulate C and N dynamics of Caatinga dry forest before and after deforestation

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ABSTRACT

About half of the original one million km^2 originally covered by the tropical dry forest of northeastern Brazil (known as "Caatinga"), has been deforested and replaced by crops and pastures. The remaining forest is constantly subjected to firewood removal. Besides that, pastures and cropping fields are often abandoned after a few years, allowing regeneration of secondary forest patches. These patterns create a mosaic of land use types and dry forest fragments under different regeneration stages, but there is little information about biogeochemical cycling in this ecosystem. Understanding the impacts of these changes, especially on carbon and nitrogen cycling, is important to define appropriate policies to preserve soils and vegetation and to contribute to reduce emissions and remove carbon from the atmosphere. Generating data about these processes require monitoring of large areas for long periods, and the use of models can be useful to improve the understanding of such systems. In the present study, the Century model was calibrated and validated to simulate the carbon (C) and nitrogen (N) dynamics in areas of caatinga vegetation before deforestation and during regeneration after abandonment. Calibration data were obtained in field plots in Paraiba state and validation data from plots Rio Grande do Norte state, both areas closely monitored for at least a couple of decades. Two types of deforestation practices were evaluated: clear cutting and cutting with stump removal followed by residue burning. The model files were prepared and calibration parameters were adjusted to represent observed values in the calibration site. Afterwards, the adjusted model was used to simulate the dynamics in the validation site, changing only the site soil and climate characteristics. In areas of preserved native vegetation, the validated C stock values of the woody vegetation biomass (21.0 Mg ha^{-1}) were similar to the average values observed in the field (20.2 Mg ha^{-1}). The soil organic carbon stock (SOC) (30 Mg ha^{-1}) and its C:N ratio (11) were also satisfactorily validated by the Century model, indicating that the model can represent very closely the dynamics in areas under preserved forest vegetation. In areas under regeneration after deforestation, the model also represented well the C accumulation in the biomass of the secondary vegetation and the SOC dynamics for the different firewood harvest practices. The model is very sensitive to the type of deforestation, since the removal of the stumps slows down tree growth during regeneration, therefore it must be well detailed in the site management history during model runs. It is also important to create two different crop files for the herbaceous vegetation within the preserved forest or in the open deforested areas, because they comprise different vegetation types. The model was very sensitive to the KLAI variable, which controls the buildup of leaves during the young phase of the trees. After the necessary adaptations, the Century model simulated adequately C and N cycling in areas of Caatinga

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vegetation in the semi-arid region of Brazil. The model will now be a useful tool to better understand ecosystem functioning in this region.

1. Introduction

The native tropical dry forest vegetation of the semi-arid Brazilian Northeastern region, known as "Caatinga", has been under increasing human pressure, mainly due to the removal of firewood and establishment of pastures and agricultural fields. Caatinga originally covered an area of nearly 1 million km^2, but only about half of this area is currently covered by native shrub and woody vegetation (Gariglio et al., 2010; Araújo Filho, 2013). The changes in land cover derive from the relatively high population density ($\sim$25 inhabitant km^{-2}) and from the predominance of small farms, which impose strong pressure on natural resources, mainly on native vegetation. The forest biomass is one of the most important energy sources in this region, with a total harvest of about 10 million m^3 of wood per year (Gariglio et al., 2010). As a result, more than 90% of the forest cover area nowadays represent secondary forest vegetation under regeneration as part of the fallow cycle of slash and burn agriculture and as part of the regrowth cycle of firewood production (Gariglio et al., 2010)

The removal of firewood is commonly followed by forest residue burning for the establishment of agricultural fields or pastures (Sampaio, 1995), which intensifies the impacts on carbon and nutrient cycling in these ecosystems (Moura et al., 2016). Due to the great population demand, firewood extraction is often carried in short cycles, which do not allow vegetation recovery and may adversely affect ecosystem processes. Therefore, it is evident that wood extraction practices need to be better studied and regulated to ensure sustainable exploitation. The determination of the time required between each harvest to allow adequate recovery of vegetation and soil carbon stocks still lacks detailed studies.

In addition to supporting management of firewood harvest, a better understanding of the functioning of the C and N dynamics in these ecosystems will also improve estimates of emissions and removals of greenhouse gases in the region. Caatinga vegetation represents one of the largest remaining areas of tropical dry forest in the world (Miles et al., 2006) and may play an important role in regional and global processes derived from the interactions between the biosphere and atmosphere (Moura et al., 2016). The understanding of these processes is still limited because there is very little available data about soil and vegetation carbon and nutrient stocks and fluxes in Caatinga areas (Moura et al., 2016).

The scarcity of data is hard to be fulfilled since determining the effects of forest cutting activities in ecosystems, mainly about soil compartment, comprises a relatively long period, often on the scale of decades. Therefore, models to simulate biogeochemical cycling may be particularly important tools because they can improve the understanding of these ecosystems and thereby support immediate decisions and help define appropriate and sustainable land use practices (Parton, 1987). Among the various models used to simulate biogeochemical cycling in terrestrial ecosystems, the Century Model has been used in various biomes, soil types and climates (Parton et al., 1988; Metherell et al., 1994).

Some studies have been conducted using Century in Brazil, both in tropical (Cerri et al., 2003; Carvalho et al., 2015) and subtropical ecosystems (Lopes et al., 2008; Tornquist et al., 2009; Bortolon et al., 2011). In most of the studies, the model has demonstrated good ability to simulate the effects of different land use systems and management practices.

However, the Century model has not been adjusted with the necessary details to represent the diversity of environmental conditions, management practices and caatinga vegetation types that occur in the semiarid region of Northeast Brazil. The adaptation of the model may bring benefits not only to studies in this region but also in other tropical dry ecosystems of the world. Therefore, the main aim of this study was to calibrate and validate the Century model to simulate the dynamics of C and N stocks and flows in the soil-plant system in native Caatinga vegetation areas submitted to different cutting practices with and without burning in the semi-arid region of Northeast Brazil.

2. Material and methods

2.1. Century model

The Century model simulates carbon (C), nitrogen (N), phosphorus (P) and sulfur (S) dynamics in plants and soils of natural or cultivated systems, using a monthly time step. In our work, we simulated only C and N dynamics. The key Century inputs represent monthly climate variables, soil physicochemical properties, initial soil C and N levels, and plant information and management data. Plant production can be simulated using sub-models of pasture/crop, forest or savanna systems. Land use change can be represented by changing the type of community of the plant during the model runs; for example, start with forest, change to a cultivation system and then to the regeneration phase of the native vegetation. The residue production is divided into structural and metabolic residues with differing decomposition rates and initial lignin to N ratios. Soil texture and climate variables control the decomposition rate and organic N flows follow the C flows (Parton, 1987).

The Century model version 4.5 was used for the calibration and validation procedures. The model developers (https://www.nrel.colostate.edu/projects/century/) provide pre-established parameters for several biomes and major crops around the world (Parton et al., 1994). The savanna sub-model (TSAVAN) was used to simulate the caatinga vegetation, integrating woody and herbaceous vegetation into

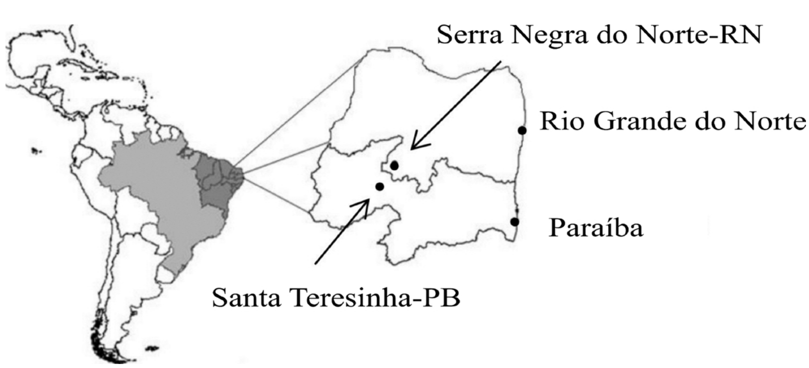

Fig. 1. Location of the areas (indicated by arrows) used for calibration (Santa Teresinha) and validation (Serra Negra do Norte) of the Century model in the present study.

the same environment, adopted to represent the competition for water and nutrients between these vegetation strata.

2.2. Characterization of areas used for model calibration and validation

The area chosen for calibration is within the Tamandua Farm (06°59′13″ and 07°00′14″S and 37°18′08″ and 37°20′38″W), municipality of Santa Teresinha, Paraíba state, Brazil. The area for validation is within the Seridó Ecological Station (ESEC) (06°35′35″S and 37°14′19″W), Serra Negra do Norte municipality, Rio Grande do Norte state. The two sites are about 70 km distant from each other, present the same soil type, and are part of the same climatic isohyet (MME, 2011) (Fig. 1).

The key Century inputs represent monthly climate variables, soil physicochemical properties, plant information and management data (Parton, 1987). Soil and plant nutrient content data for plots used in the calibration procedure were obtained from Moura et al. (2016) and Freitas et al. (2012). Data for plots used in the validation procedure were provided from by "Associação Plantas do Nordeste" (APNE), which is a Non-Government Organization that aims to develop sustainable forest management practices in NE Brazil. Average monthly rainfall distribution in both calibration and validation areas were similar in amount (about 60,7 mm) and season distribution (Fig. 2). The monthly rainfall data of the calibration area was provided by Tamanduá Farm (Santa Teresinha municipality), which keeps rainfall records since 1911. Rainfall data in the validation area (Serra Negra do Norte municipality) were available from 1995 to 2006, but, since they were similar to those of Santa Teresinha, these later data from 1911 to 1994 were used to supplement the precipitation of the RN region.

Monthly air temperature data (maximum and minimum) were estimated for the study areas by the Estima T software (Cavalcanti et al., 2006), which was developed by the Federal University of Campina Grande to be used for air temperature estimates in northeastern Brazil. This software allowed determining the quadratic function coefficients for the monthly maximum and minimum average air temperatures according to local longitude, latitude and altitude coordinates of Santa Teresinha and Serra Negra do Norte. The average minimum and maximum temperatures of the two study areas were around 19 and 28 °C, respectively.

2.3. Model calibration

An important procedure for calibration is acquiring information about C and N stocks to model parameterization, and establishment of land use history. Vegetation and soil data were obtained from plots with two management histories: i) a preserved vegetation area, *i.e.*, no clear cutting or significant human disturbance at least in the previous 50 years before this study; and ii) forest patches under regeneration for 20-years after pasture abandonment. The management histories were obtained from Tamanduá Farm managers. They reported that the regenerating plots had their native vegetation clear cut in 1965, with stump removal and burning of vegetation residues. After forest removal, the area was cultivated with perennial cotton during five years. In 1970, cotton was replaced by Buffel grass (*Cenchrus ciliaris* L.) with intensive grazing, and the pasture was abandoned in 1990 when the vegetation began to regenerate naturally without relevant anthropic disturbances up to 2010. In the modeling study, intensive pasture was simulated during 1965–1990, ignoring the five years of cotton cultivation, due to lack of detailed data on the period of cotton cultivation. This decision followed the proposal of Bortolon et al. (2011) and Brandani et al. (2014), which simulated only main events in a land use history.

The Century model file for site parameterization (SITE.100) *i.e.*, used to characterize the studied site, was adjusted with data describing the local climate (monthly precipitation, maximum and minimum temperatures), soil (density, pH, and texture) and vegetation (C:N ratio, monthly litterfall and maximum leaf area index (MAXLAI). The time series of monthly rainfall from January 1911 to July 2013 was provided by Fazenda Tamanduá (2014). Monthly air temperature data (maximum and minimum) were estimated by the Estima T software (Cavalcanti et al., 2006).

The predominant soil type in the area is Lithic Neosol, relatively shallow, with average depth close to 40 cm and usually with low fertility, mainly due to low levels of organic matter (EMBRAPA, 2006). Soil data for the 0–20 cm soil layer of plots with preserved vegetation and vegetation regenerating for 20 years (Table 1) were obtained from Freitas et al. (2012). The C stocks were calculated multiplying the soil organic carbon concentration (g kg^{-1}) of the layer by its density (kg dm^{-3}) and volume (2000 m^3).

The vegetation of the area is classified as shrub-tree hyperxerophilic Caatinga, being characterized by small trees, often with heights less than 7 m with sparse distribution. Data on aboveground biomass of trees and shrubs were obtained from the preserved vegetation plots described by Souza et al. (2012). Within each of the three 50 × 20 m plot, the biomass was calculated from the stem diameter of all plants that had a diameter at breast height (DBH, 1.3 m above round) ≥ 3 cm, measured in 2007 and 2010, based on the allometric equation proposed by Sampaio and Silva (2005). The biomass (48.8 Mg ha^{-1}) was distributed to leaves (5%), twigs (15%) and thick branches and stems (80%) based on the proportions determined by Silva and Sampaio (2008). The data on herb and small plant biomass were obtained from Freitas et al. (2012), who conducted measurements in the same plots. Belowground biomass was obtained from Costa et al. (2014), which also worked in the same plots. For conversion of biomass to C stocks, the value of 45% was adopted (Chazdon, 2012).

Following adjustments in the Century files to the climate and soil data, 1800 years spin ups were performed to allow stabilization of the simulated C distribution in the different compartments of vegetation

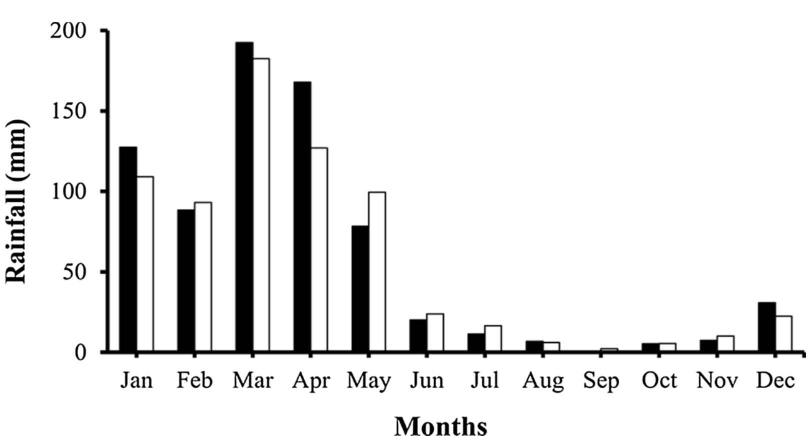

Fig. 2. Monthly average rainfall distribution for the period 1995–2006 at the Tamanduá Farm, Santa Teresinha, PB (black bars) and Serra Negra do Norte, RN (white bars).

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Table 1
Soil characteristics in the 0–20 cm layer in areas under caatinga vegetation, measured in 2010, in the municipality of Santa Teresinha, PB.

Type of vegetation	C	N	Sand	Silt	Clay	pH	Density
	$g\ kg^{-1}$					Water	$kg\ dm^{-3}$
Preserved[a]	11.62	1.06	648	123	229	6.41	1.37
Regeneration[b]	8.61	0.78	645	117	239	5.94	1.34

[a] Preserved caatinga vegetation without severe disturbances for over 50 years.
[b] Caatinga vegetation under regeneration for 20 years after pasture abandonment.

and soil in the preserved plots. In this modeling step, stabilization is achieved when the carbon stocks in the plant biomass and in soil show values relatively stable over time. The stabilization occurs when there is a balance between C inputs through photosynthesis and C losses (deposition of litter and soil and plant respiration). These data were used to represent preserved vegetation establishing the initial N and C values.

The parameters calibrated for a dynamic equilibrium in the preserved areas were then used to assess C and N flows and stocks in the regenerating plots. Due to the link between N and C dynamics in ecosystem functioning, Century model developers recommend adjustments of N inputs, including tree biological N fixation and deposition. Variable SNFXMX (2) evaluates the N input by biological N fixation (BNF) by the forest tree component (TREE.100), which was adjusted based on data from Souza et al. (2012). Variable SNFXMX (1) (CROP.100), corresponding to the BNF of the herb layer, was adjusted according to data from Freitas et al. (2012), who conducted experiments in the same plots. Tree and shrub symbiotic N fixation in the preserved areas were set at 6 $kg\ ha^{-1}\ year^{-1}$ and herb fixation was set at 2.22 $kg\ ha^{-1}\ year^{-1}$. The areas under regeneration were set at 6.3 $kg\ ha^{-1}\ year^{-1}$, obtained from a study by Costa (2017) in a 15-year regenerating site in an area with environmental conditions similar to those of our site. Herb fixation was set at 0.22 $kg\ ha^{-1}\ year^{-1}$. Table 2 shows the changes of parameters with major adjustments to adapt the model to the environment of this study.

Non-symbiotic N fixation by free-living soil microorganisms and N atmospheric deposition values necessary to parametrize the model were considered to be the same for both preserved and regenerating plots. Non-symbiotic fixation was fixed at 2 $kg\ N\ ha^{-1}\ yr^{-1}$, within the range from 1 to 5 $kg\ ha^{-1}\ yr^{-1}$, defined by Boring et al. (1988), in the absence of data for the region. Atmospheric deposition was set at 5 $kg\ N\ ha^{-1}\ yr^{-1}$, based on data from Marin and Menezes (2008) and Deusdará et al. (2016), both conducted in semi-arid NE Brazil.

The model was calibrated to simulate the carbon stocks of forest patches under regeneration for 20 years in the same area. Field data on the aboveground biomass in the regenerating plots were estimated as described for the preserved plots. In the simulation process, it was found that the tree vegetation biomass did not regenerate as fast as the data observed in the field. So, it was necessary to assess the reason for the limitation in the early forest regeneration to adjust the behavior. The dynamics of biomass accumulation for most different Caatinga species is poorly understood. It is known that differences in the functional characteristics of each area largely depend on the successional status and history of human disturbance, and also on other important factors such as soil and climate (Dirzo et al., 2011).

During the calibration activities, we observed that a very important aspect of the calibration step to simulate the regeneration of caatinga vegetation after tree removal was the adjustment of the mass of coarse wood ($g\ C\ m^{-2}$) with which half of the theoretical maximum leaf area (MAXLAI) would be achieved, that is labelled as the KLAI parameter. According to White et al. (2000), in dry forests, the mean maximum leaf area is around 2. In the present work, the best value for the variable (MAXLAI) was 1.9. The default value for KLAI in Century is set at 2000, which was adjusted for a forest at a moist temperate forest. However, the default value needs to be adjusted for each type of vegetation and site conditions during the calibration process. After a detailed test of possible values, it was found that, for the simulation to satisfactorily represent the regeneration of caatinga biomass after wood harvest under the conditions of this study, the value of the KLAI variable had to be set at 39.6. Most of the parameters controlling the C flow in the system come with default values (FIX.100) but they can be altered to simulate soils to a greater depth or control the C pool structure.

Another interesting aspect was the calibration of the herbaceous vegetation. During the model adaptation process, there was a need to create two types of herbaceous vegetation to reproduce the herbaceous traits in the preserved and regenerating caatinga plots. This difference may result from the different species composition in the two successional stages, with species adapted to the shaded understory conditions in the preserved site and species adapted to more solar radiation in the regenerating site.

Table 2
Modified parameters in the Century model from the original default values which correspond to those of Forest Coweeta (North Carolina, USA) for the TREE.100 file and Konza tallgrass (Kansas, USA) for the CROP.100 file.

Parameters	Default	Modified
TREE.100 file		
PRDX (2)-maximum gross forest production (g biomass m^{-2} $month^{-1}$)	0.5	0.2
SNFXMX (2) − symbiotic N fixation maximum for forest (g N fixed g^{-1}C net production)	0.0	0.00435
DECW (1) − decomposition rate for wood1 (dead fine branch) per year	1.5	4.5
DECW (2) − decomposition rate for wood2 (dead large wood) per year	0.5	3.8
DECW (3) − decomposition rate for wood3 (dead coarse root) per year	0.6	4.0
MAXLAI − theoretical maximum leaf area index achieved in a mature forest	20	1.9
KLAI − large wood mass ($g\ C\ m^{-2}$) at which half of theoretical maximum leaf area (maxlai) is achieved	2000	39.6
CROP.100 file (Herbaceous)		
Preserved plots		
PRDX (1) − potential aboveground monthly production for crops ($g\ C\ m^{-2}$)	0.3	0.418
RDR − root death rate at very dry soil conditions (fraction $month^{-1}$)	0.07	0.72
SNFXMX (1) − symbiotic N fixation maximum for grass/crop (g N fixed g^{-1} C net growth)	0.0	0.00077
Regeneration plots		
PRDX (1)	0.3	0.5
RDR	0.07	1.0
SNFXMX (1)	0.0	0.000035
FIX.100 file		
DEC 3 (1) − decomposition rate of surface organic matter with active turnover	6.0	7.0
DEC 3 (2) − decomposition rate of soil organic matter with active turnover	7.3	6.5
DEC 4 − decomposition rate of soil organic matter with slow turnover	0.0045	0.007
DEC 5 − decomposition rate of soil organic matter with passive turnover	0.2	0.25

2.4. Model validation process

Independent datasets, obtained with APNE, were used for model validation, but changes in SITE.100 file were necessary to adjust traits such as temperature, precipitation and soil (Table 3). Since 1989, APNE has monitored the production of firewood in field plots at the Seridó Ecological Station, Serra Negra do Norte, RN. In this experiment, plots with different types of caatinga firewood harvest were established to assess the regeneration time of Caatinga firewood stocks. In our study, two types of harvest practices for removal of firewood were included: i) clear cut harvest followed by stump removal and residue burning (four plot replicates); and ii) clear cutting without stump removal and burning (three replicates). Each of the plots with these treatments had an area of 1600 m^2 (40 × 40m). Tree and shrub biomass stock measurements, using allometric equations (Sampaio and Silva, 2005), were made 15 and 18 years after firewood removal in each plot. Since herb measurements were not made and they represent a small proportion of the total biomass, we assumed that the herb biomass was the same as in the calibration plots in Santa Teresinha, PB, previously described.

Model performance was verified by evaluating model error (the difference between observed and validated C stocks) through lack of fit (LOFIT), and root mean square error (RMSE) tests, according to Smith et al. (1997). To test the association between observed and validated values and to evaluate if the trend of observed values was correctly simulated, we used the coefficient of determination (r^2) and Pearson correlation coefficient (r). Another evaluation of the performance of the Century model was done by calculating the efficiency index "E" proposed by Nash and Sutcliffe (1970) and the index of agreement "d" proposed by Willmot (1981).

3. Results and discussion

3.1. Century model calibration for the native Caatinga vegetation (biomass and soil)

Careful adjustment of nitrogen inputs during model calibration is very important to obtain a good model performance, contributing to improve knowledge about the effects of firewood management on C stocks. In our simulation, calibrated N inputs by the model had the values as those measured in the preserved Caatinga plots, and very close (8% difference) to those in the regenerating Caatinga plots (Table 4).

Studies have reported that the removal of forest cover interrupts the flow of nutrients between litter and the live plant component, making nitrogen one of the most limiting factors for natural regeneration (Vitousek and Howarth, 1991). As the availability of N acts as an important mechanism in the natural succession process, biological N fixation (BNF) by woody legume could be the main source of N, allowing plant recolonization and increasing biodiversity (Siddique et al., 2008). This process also contributes to soil recovery (Nardoto et al., 2008) and SOM stabilization (Lavelle, 2000). Nitrogen input via tree BNF was responsible for the highest N input to the area used for calibration (40% of N input in preserved plot and almost 50% of N input in regeneration plot), and it was adequately simulated by the Century model in the calibration procedure.

Average aboveground woody vegetation biomass C stocks in the preserved Caatinga plots (21.99 Mg C ha^{-1}), measured in 2007 (21.7 ± 4.5 Mg C ha^{-1}) and 2010 (22.25 ± 6.3 Mg C ha^{-1}), were almost perfectly matched to those obtained during calibration (Table 5). Average biomass C stocks in the regenerating Caatinga plots were slight underestimated during calibration, the largest difference (8%) corresponding to twigs (Table 5). The total simulated aboveground C stocks differed by 10% in 2007 and 1% in 2010 (Fig. 3).

The model also represented well the woody vegetation biomass regeneration in plots subjected to wood harvest followed by stump removal and burning (Fig. 4). In this case, the differences between observed and simulated values during calibration were 6.3% and 5%, in 2004 and 2007, considering the observed values of 6.7 and 8.8 Mg ha^{-1} of woody biomass carbon accumulation and the validated values of 7.15 and 9.3 Mg ha^{-1}, respectively. The practice of stump removal and burning is unusual in forest management, but the simulation of this system was useful to check the model performance to simulate woody vegetation recovery after fire occurrence and after establishment of crop fields, when stimp removal is common.

Soil organic carbon (SOC) calibration was also satisfactory since there was consistency between simulated values and those measured in the field. When simulating the harvest and removal of firewood, the model was robust and represented well the soil C dynamics during regeneration of the woody vegetation (Fig. 3). Harvest followed by stump removal and burning was also well represented, with an initial increase of SOC due to the decomposition of roots, a subsequent decrease over the period of land use with pasture and recovery since the beginning of caatinga regeneration in 1990.

In the preserved caatinga plots, the observed SOC stock was 31.85 Mg ha^{-1}, while the soil C stock simulated in the calibration procedure was 31.75 Mg ha^{-1} (1% difference). In the regenerating caatinga plots, simulated SOC was close to the observed SOC stock in 2010 (23.2 and 23.1 Mg ha^{-1}, respectively) with 1% difference. The difference between preserved and regenerating plots shows that secondary caatinga forests, even after 20 years of regeneration, still have nearly 30% less soil carbon than a caatinga left uncut. Besides total soil C, the correct C distribution into soil organic pools is important to study long-term effects of management. Distribution of soil C stocks into active, slow and passive pools, as estimated by the Century model was 3, 67 and 30%, respectively, in the preserved caatinga plots and 3, 54 and 43%, in the regenerating plots. SOM stabilization increases with the increase in clay + silt content (Six et al., 2002), but the soils in our calibration area are rather sandy, with 64% of sand. As a result, a higher proportion of soil C would be expected on the slow pool, as it was observed. It also makes sense to see a decrease in the proportion of C in the slow pool after deforestation, since this soil compartment is susceptible to management, due to higher rates of decomposition than the passive pool. Finally, the C:N ratio of the soil simulated in the calibration procedure was around 11:1 and agreed with data found by Freitas et al. (2012). The soil C:N ratio in the regenerating plots, which averaged 9.3:1, was 15% lower than that reported by Freitas et al. (2012).

Freitas et al. (2012) measured slightly higher herb biomass production in the regenerating plots used for calibration (3.95 Mg ha^{-1}, equivalent to 1.75 Mg ha^{-1} of carbon stock) than in the preserved plots (3.35 Mg ha^{-1} or 1.5 Mg C ha^{-1}), which is a well-documented pattern in this ecosystem (Moura et al., 2016; Menezes et al., 2002). In the preserved area, the higher tree density limits development of the herbaceous layer due to increased competition for resources, such as water and light. In regenerating plots, the herbaceous layer shows the typical development of open fields in some patches, with less competition for light, water and nutrients, accumulating more biomass. Along the regeneration process, herb biomass tends to decrease due to as tree and shrub biomass increases, having decreased after 20 years of

Table 3
Soil characteristics in the 0–20 cm layer in plots of caatinga preserved for more than 50 years (measured in 1989) and caatinga regenerating for 20 years (measured in 2010), after clear cutting (CC) or clear cutting followed by stump removal and burning in Serra Negra do Norte, RN.

Treatment	C	Sand	Silt	Clay	pH	Density
	g kg^{-1}				Water	kg dm^{-3}
Preserved	10.65	673	135	192	5.9	1.41
CC	8.57	677	147	176	6.1	1.45
CC + stump removal and burning	9	686	147	167	5.6	1.42

Table 4
Nitrogen inputs observed in the field and simulated by the Century model during calibration in preserved Caatinga vegetation plots (more than 50 years without disturbances) and caatinga plots under regeneration for 20 years after pasture abandonment, in Santa Teresinha, PB.

Nitrogen inputs	Observed	Calibrated	Difference
	Kg N ha^{-1} yr^{-1}		(%)
Preserved plots			
Non-biological fixation[a]	2	2	0
Atmospheric deposition[b]	5	5	0
Herbaceous biological fixation[c]	2.2	2.2	0
Tree biological fixation[d]	6	6	0
Total	15.2	15.2	0
Regeneration plots			
Non-biological fixation[a]	2	2.16	7.4
Atmospheric deposition[b]	5	5.37	7
Herbaceous biological fixation[c]	0.22	0.22	0
Tree biological fixation[e]	6.3	6.9	9
Total	13.92	14.8	7.8

[a] Jeffries et al. (1992).
[b] and Menezes (2008).
[c] Freitas et al. (2012).
[d] Souza et al. (2012).
[e] Costa (2017).

Table 5
Woody above and belowground biomass C stocks observed in field studies and simulated during calibration by the Century model, in preserved Caatinga vegetation plots (more than 50 years without disturbances) and caatinga plots under regeneration for 20 years after pasture abandonment in Santa Teresinha, PB, Brazil.

C stocks	Observed	Calibrated	Difference
	Mg C ha^{-1}		(%)
Preserved plots			
Leaves[a]	0.69	0.69	0
Twigs[b]	3.30	3.29	0
Thick branches[a]	18.00	18.02	0
Roots[b]	14.27	14.27	0
Total	36.26	36.28	0
Regeneration plots			
Leaves[a]	0.65	0.65	0
Twigs[b]	2.44	2.24	8
Thick branches[a]	7.99	7.63	5
Roots[b]	2.53	2.45	3
Total	13.61	12.97	4.7

[a] Datas from Moura et al. (2016).
[b] Costa et al. (2014).

regeneration to about half the biomass observed in plots without trees. These herbaceous C stocks with the different land uses were well represented by the Century model during calibration, with differences between calibrated and observed values ranging from 1% to 3%.

Considering the small differences of all simulated values in relation to those observed in the field, the model was considered calibrated to simulate carbon and nitrogen cycling in the soil-plant system after firewood removal from caatinga vegetation for the soil and climatic conditions of the study area.

3.2. Validation of the model to simulate the production of aboveground woody biomass and soil organic carbon

During the validation runs, the Century model also represented well the aboveground woody biomass carbon stock of preserved plots in Serra Negra do Norte, RN. The difference between the simulated value during the validation process (21.05 Mg C ha^{-1}) and the observed value (20.25 Mg C ha^{-1}) in 1989 was less than 4%. In the same date, the soil organic carbon stock (0–20 cm of depth) in preserved Caatinga plots was on average 30 Mg ha^{-1}, while the stock simulated by the Century model was 29.6 Mg ha^{-1}, a good model performance with only 1.7% difference (Fig. 4).

In 2010, the soil organic carbon stock (0–20 cm of depth) in these same plots was on average 26.8 Mg ha^{-1} (± 2), while the stock simulated during the Century model validation was around 26.55 Mg ha^{-1}, a difference of 1%.

In the plots with wood harvest through clear cutting the difference between simulated and observed wood vegetation biomass values was higher than in the plots which had also been burned and had the stumps removed (Fig. 4). In 2004, the difference was 16%, and the simulated value (9.65 Mg C ha^{-1}) overestimated the observed value (8.1 Mg C ha^{-1}), while in 2007, the difference was reduced to 12%, the simulated value still overestimated the observed value. The soil C stock was also overestimated, by about 7.5% (26.75 and 24.85 ± 3.15 Mg C ha^{-1}).

Regeneration of woody vegetation in the initial phase is usually faster in areas where clear cutting is not followed by stump removal and burning, due to the maintenance of the root system. Many species are capable of sprouting from roots and/or stems after forest cutting and burning (Kammesheidt, 1999) and this characteristic is common to most Caatinga species (Sampaio et al., 1998). The vigorous growth of sprouts gives a competitive advantage during the early stages of forest succession. Sprouting is a particularly important recruitment mechanism in dry tropical forests, where the seedling establishment rates can be reduced by desiccation (Alvarez-Yépiz et al., 2008). However, even with the good adaptation of Caatinga species to resprout, a certain degree of mortality may occur, and this may explain why the Century slightly overestimated forest growth during regeneration in our model validation runs. Since we do not have mortality data for this site, this hypothesis remains to be tested in future studies.

According to Araújo Filho and Crispim (2002), the average biomass production of vegetation in the semi-arid region of Northeast Brazil is around 2 Mg ha^{-1} yr^{-1}. However, production varies with different soil types and climatic conditions. The soil in both areas selected for the calibration and validation procedures is particularly shallow and rocky, therefore we would expect vegetation productivity to be below the regional average. Biomass production in areas with wood harvest followed by stump removal and residue burning was lower at the beginning of regeneration due to the time required to restore roots and shoots. Thus, in 2004, after 15 years of regeneration, the average biomass production of vegetation was 1 Mg ha^{-1} yr^{-1}, equivalent to 0.45 Mg C ha^{-1} yr^{-1} (Table 6), while in 2007, the average production increased only to 1.06 Mg ha^{-1} yr^{-1} (0.47 Mg C ha^{-1} yr^{-1}). In the clear-cutting treatment, the biomass accumulation was slightly higher, with an average of 1.2 Mg ha^{-1} yr^{-1} (0.54–0.55 Mg C ha^{-1} yr^{-1}) during the regeneration period. These data demonstrate that firewood removal practices should not include stump removal, mainly due to the actual global efforts to mitigate carbon emissions into the atmosphere, once this type of management constrains forest regeneration and reduces C sequestration.

The fact that both calibration and validation areas have shallow, rocky soils, high potential evapotranspiration rates and are in the higher part of the rainfall range (300–1000 mm yr^{-1}) registered in the extensive caatinga region may limit application of the model to other areas within the region (Menezes et al., 2012). Therefore, validation should be tested in other areas and a survey is currently on the way to find sites where reliable field data are available.

The Nash and Sutcliffe (1970) test of efficiency for data on the preserved and regenerating plots of the validation procedure reinforces that the model has good performance, especially for aboveground C stocks, which had an E value of 0.96 (Table 7), close to the perfect fit value of 1.0 (Krause et al., 2005). The E value for soil C stock, although lower (0.63), fell in the upper part of the range considered of an acceptable fit (Baltokoski et al., 2010). The index of agreement, proposed by Willmot (1981), confirms the good performance of the model, the

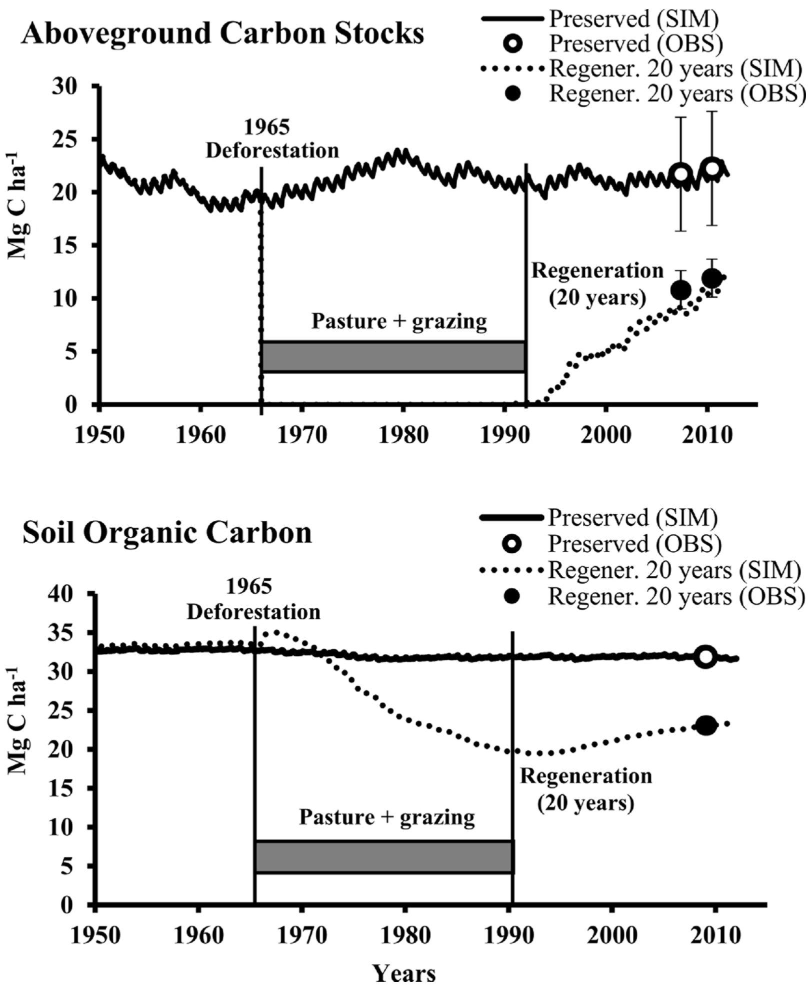

Fig. 3. Carbon stocks of the aboveground woody vegetation biomass and in the soil observed in field studies (OBS) and simulated during calibration by the Century model (SIM), in preserved Caatinga vegetation plots (more than 50 years without disturbances) and caatinga plots under regeneration for 20 years after pasture abandonment (Regener.), in Santa Teresinha, PB.

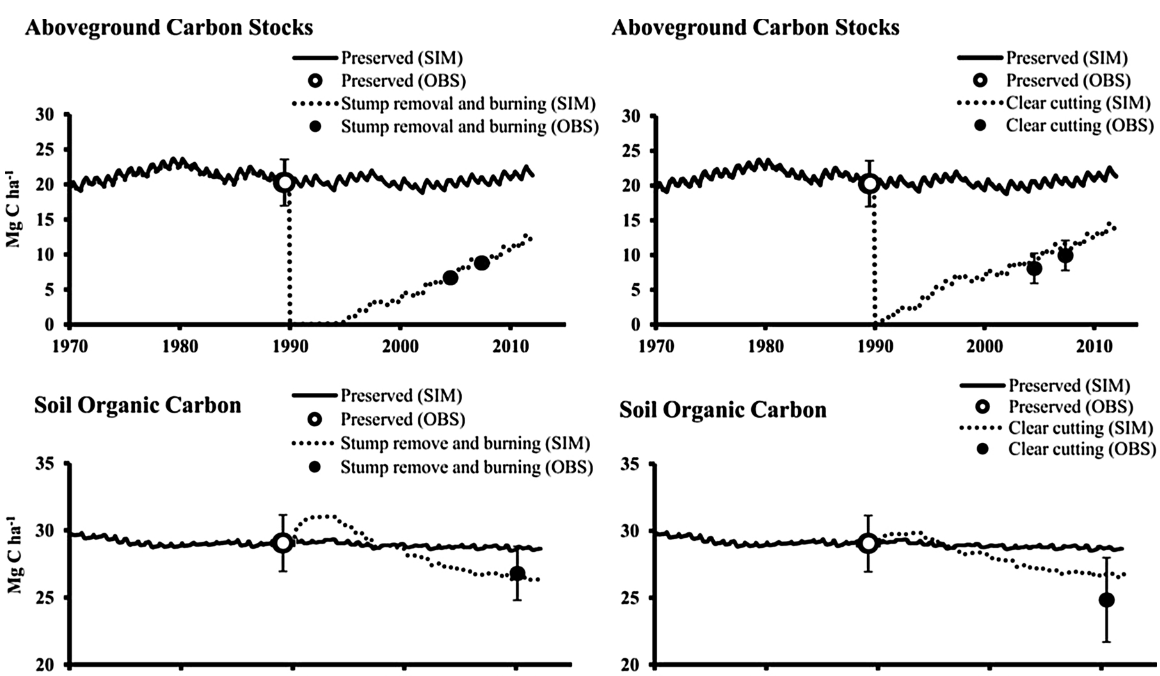

Fig. 4. Carbon stocks of the aboveground woody vegetation biomass and in the soil observed (OBS) and simulated (SIM) by the Century during validation procedure in plots of preserved caatinga and plots regenerating for 18 years after clear cut followed or not by stump removal and burning, in Serra Negra do Norte, RN.

Table 6
Average annual C accumulation in the aboveground biomass and C stocks observed and simulated during the model validation after 15 and 18 years of caatinga regeneration, in Serra Negra do Norte, RN.

	Observed	Validated	Observed	Validated
	15 years		18 years	
	Mg C ha^{-1}			
Cutting with stump removal and burning				
Annual accumulation	0.45	0.47	0.48	0.51
C stocks	6.7 (± 0.44)	7.15	8.8 (± 0.56)	9.3
Clear cutting				
Annual accumulation	0.54	0.64	0.55	0.62
C stocks	8.1 (± 2.1)	9.65	9.95 (± 2.2)	11.2

Table 7
Statistical parameters to evaluate the fitness of the model simulated data to the field observed data.

Statistical tests	Aboveground woody C biomass	Soil organic carbon
E = Efficiency index[a]	0.96	0.63
d = index of agreement[b]	0.99	0.87
RMSE = Root mean square error of model[c]	9.1%	4.7%
LOFIT = Lack of Fit[c]	15.31	23.37
F = MSLOFIT/MSE	0.02	0.05
$F_{(criticalat5\%)}$	3.16	3.41
r = Pearson correlation coefficient[c]	0.99	0.86
r^2 = Coefficient of determination[c]	0.99	0.75

[a] Nash and Sutcliffe (1970).
[b] Willmot (1981).
[c] Smith et al. (1997).

agreement between observed and predicted aboveground C stocks having a d value of 0.99, also very close to the perfect fit of 1.0, while the index of agreement of the soil C stock was 0.87. This later descriptive statistic is not a measure of correlation or association in the formal sense but rather a measure of the degree to which a model's predictions are error free (Willmot, 1981).

The model root mean square error (RMSE) for the aboveground C stocks, also for data on the preserved and regenerating plots of the validation procedure, was equivalent to 9.1% (Table 7). The lack of fit (LOFIT; 15.31) was not significant, comparing the observed and critical F values (Table 7). The Pearson correlation coefficient (r) and coefficient of determination (r^2) were both very high, above 0.99 (Smith et al., 1997). All these statistical results indicate that the estimates of the Century during the model validation process described well the trends of the observed field data. Figs. 4 and 5 show simulations of systems with harvest through clear cutting and stump removal and burning, where the close similarity between validated and observed values are observed. For the soil C stocks, the RMSE was equivalent to 4.7%, the lack of fit (LOFIT; 23.37) was not significant and the Pearson correlation coefficient (r) and the coefficient of determination (r^2) were also high (0.86 and 0.75, respectively) when using the whole data set (Fig. 5; Table 7).

The good performance of the Century model to simulate these management practices will be helpful to increase our understanding of the biogeochemical changes after deforestation in this ecosystem.

4. Conclusions

The results observed during the adaptation of Century demonstrated that the model was able to simulate the dynamics of C stocks in the aboveground biomass and the soil organic matter (SOM) in areas of Caatinga vegetation under regeneration after cutting, with and without the occurrence of fire. However, the adaptation of Century to represent these systems, particularly when simulating deforestation and forest regeneration, requires detailed attention to a few aspects. First, the model is very sensitive to the type of deforestation, in particular if there is stump removal and fire. Therefore, these management practices must be well detailed in the site history during model runs. We also observed the need to create two different crop files for the herbaceous vegetation within the preserved forest and in the open deforested areas, otherwise the simulation will not adequately represent herb growth dynamics. Another important aspect is the high sensitivity of the model to the KLAI variable, which controls the buildup of leaves during the young phase of the trees. Therefore, after the necessary adaptations, the Century model simulated adequately C and N cycling in areas of Caatinga vegetation in the semi-arid region of Brazil. The model will now be a useful tool to better understand ecosystem function in this region, but further studies should be carried out to adapt the model for a comprehensive application, like other vegetation types and environmental conditions in Northeast Brazil and other tropical dry forests in the world.

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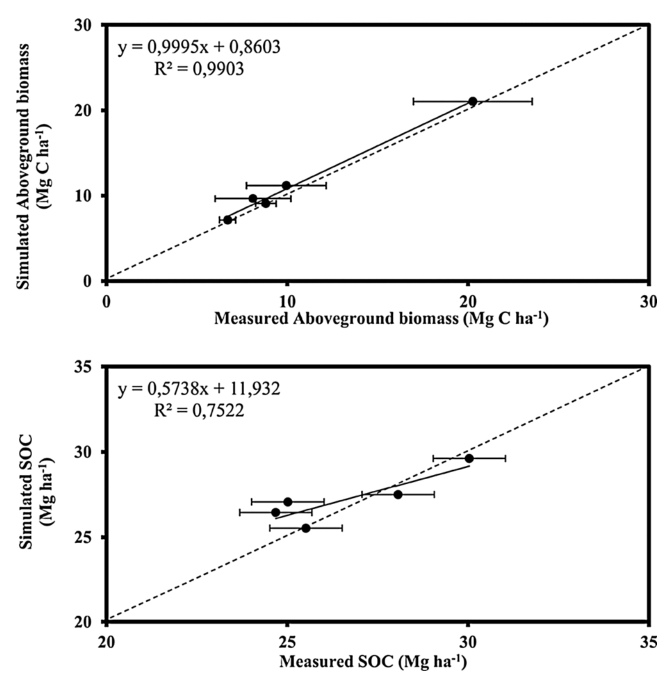

Fig. 5. Linear regression of data for validation of Century model simulations of: a) woody vegetation biomass production in Caatinga areas; b) soil organic carbon stocks in Caatinga areas under regeneration for 15–18 years after wood harvest followed by stump removal and burning or clear cutting in the municipality of Serra Negra do Norte, RN.

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