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Scientific Article

Structural dynamics in a seasonally dry tropical forest under different silvicultural systems

Dinâmica estrutural em uma floresta tropical sazonalmente seca sob diferentes sistemas silviculturais

Ana L. da S. Lopes-Nunes[1]*, Alan C. de Holanda[2], Malcon do P. Costa[1], Lucas J. Nunes[1], Maria K. A. G. da Silva[1]

[1]Jundiaí Agricultural School, Universidade Federal do Rio Grande do Norte, Macaíba, RN, Brazil. [2]Department of Agronomic and Forestry Sciences, Universidade Federal Rural do Semi-Árido, Mossoró, RN, Brazil.

ABSTRACT - Considering the importance of evaluating the compatibility between the exploration system usually used in the Caatinga and the vegetation regeneration process, this study aimed to evaluate the feasibility of recovering structural parameters in an experimental unit subjected to different management systems aged 9, 12, 16, 20 and 26 years post-exploitation. The area was subjected to clearcutting (CC) regimes and three types of selective cuttings (SC1 – selective cutting 1, cut of trees with diameter at the base – DAB < 15 cm; SC2 – selective cutting 2, cut of trees with DAB > 10 cm; and SC3 – selective cutting 3, cut of trees with DAB between 5 and 10 cm). In permanent plots of 20 m × 20 m, individuals with a circumference at breast height (CBH) ≥ 6 cm and a total height greater than 1.0 m were measured. Over the years of monitoring, the CC presented the lowest values of density, dominance, and volume, not obtaining a recovery in basal area and volume even after 26 years of regeneration. Treatments SC2 and SC3 stood out regarding recovery of the original woody biomass stock, presenting values higher than the original ones and indicating that the initial data did not correspond to the site's maximum potential. The forest dynamics pointed to the insufficiency of the 15-year clearcutting cycle in terms of recovering this region forest composition and structure.

Keywords: Cutting cycle. Natural regeneration. Sustainable forest management.

RESUMO - Considerando a importância de se avaliar a compatibilidade entre o sistema de exploração usualmente empregado na Caatinga e o processo de regeneração da vegetação, este estudo objetivou avaliar a viabilidade de recuperação dos parâmetros estruturais em uma unidade experimental submetida a diferentes sistemas de manejo com idades de 9, 12, 16, 20 e 26 anos pós-exploração. A área foi submetida aos regimes de corte raso (CR) e três tipos de cortes seletivos (SC1 – corte seletivo 1, de árvores com diâmetro na base – DNB < 15 cm; SC2 – corte seletivo 2, de DNB > 10 cm; e SC3 – corte seletivo 2, de DNB entre 5 e 10 cm). Em parcelas permanentes de 20 m × 20 m, foram mensurados os indivíduos com CAP ≥ 6 cm e altura total superior a 1,0 m. Ao longo dos anos de monitoramento, o CR apresentou os menores valores de densidade, dominância e volume, não obtendo recuperação em área basal e volume mesmo após 26 anos de regeneração. Os tratamentos SC2 e SC3 se sobressaíram quanto à recuperação do estoque original de biomassa lenhosa, apresentando valores superiores aos originais e indicando que os dados iniciais não correspondiam ao potencial máximo do sítio. A dinâmica florestal apontou à insuficiência do ciclo de corte raso de 15 anos quanto à recuperação da composição e estrutura florestal nesta região.

Palavras-chave: Ciclo de corte. Regeneração natural. Manejo florestal sustentável.

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***Corresponding author:**
<analuizaslps@gmail.com>

INTRODUCTION

Widely occurring in Brazil, the Caatinga occupies around 10.7% of the country (912,529 km²) and is the main ecosystem in the Northeast region (SILVA; LEAL; TABARELLI, 2017). It is part of a global biome referred to by some authors as Seasonally Dry Tropical Forest (SDTF), which can be found on the old eroded peaks in the semi-arid core and the western slopes of the Borborema Plateau (DRYFLOR et al., 2016; SILVA; LEAL; TABARELLI, 2017). In addition to the seasonality common to these regions, the SDTF is threatened by the potential worsening of water conditions caused by climate change (CASTANHO et al., 2020).

In Rio Grande do Norte, the Caatinga domain represents 91% of the areas covered by natural forest; there are around 2 million hectares, where steppic-savannah typology predominates (BRASIL, 2018). Although significant, these areas of native vegetation have been the target of indiscriminate deforestation, leading to a reduction in their biodiversity, the expansion of degraded areas, and the generation of risks to the quality of life of the populations within their area of occurrence (RIO GRANDE DO NORTE, 2010). The demand for dendro fuels stands out as the region main driver of extractive exploitation (MEUNIER; FERREIRA; SILVA, 2018).

Among the forms of exploitation, forest management is provided for in Art. 31 of Law 12.651, of May 25, 2012, as a necessary instrument for the use of native forests and should include techniques for management, exploitation, forest replacement, and management compatible with the various ecosystems that the tree cover forms. This management system follows three principles: ecologically correct, economically viable, and socially just (SFB, 2013).

In most of the states in the Northeast, an initial cutting cycle of at least 15 years is used, as stipulated by MMA Normative Instruction nº 1 of June 25, 2009, which assumes an average annual growth rate equivalent to 1/15 of the initial stock. Commonly, the Average Annual Increase (AAI) is estimated based on the initial volumetric stock, considering that the recovery of this stock occurs through natural regeneration, mainly by regrowth of stumps (PAREYN et al. 2015).

According to Scolforo (1997), areas under a harvesting system should have a monitoring program to measure permanent plots before the intervention, identification, and labeling of the stump of all individuals. This proposal highlights the importance of quantifying the impacts caused by logging and identifying the dynamics of natural regeneration in the fragment. Therefore, studying natural regeneration dynamics is fundamental for managing forest resources that prioritize their ecological functioning and forest management (SANTOS et al., 2015).

In the forestry context of Rio Grande do Norte, in addition to the low number of Sustainable Forest Management Plans (SFMP), whose supply of firewood does not meet current energy demand (LOPES-NUNES et al., 2022), a minimum cutting cycle of 15 years has been adopted for the entire state, without considering the growth estimates associated with the site soil and climate aspects. As a result, information and inferences about volumetric stock recovery, structural changes, and forest dynamics in areas under sustainable management are still incipient.

Because of this, this study questions the viability of recovering the area structural parameters when subjected to the management system usually used in the Caatinga, under clearcutting, and in 15-year cycles.

The aim is to characterize the structure of the shrub component 26 years after the application of different silvicultural systems and to evaluate its growth dynamics in a Caatinga fragment located in the Central Potiguar Mesoregion, Rio Grande do Norte, Brazil.

MATERIAL AND METHODS

Study area

The components evaluated in this study are part of an Experimental Unit (EU) of the Caatinga Forest Management Network (CFMN), located in the Venâncio Zacarias Settlement Project in the rural area of Macau, Rio Grande do Norte, at 05°18'51.71" S and 36°29'07.62" W (Figure 1).

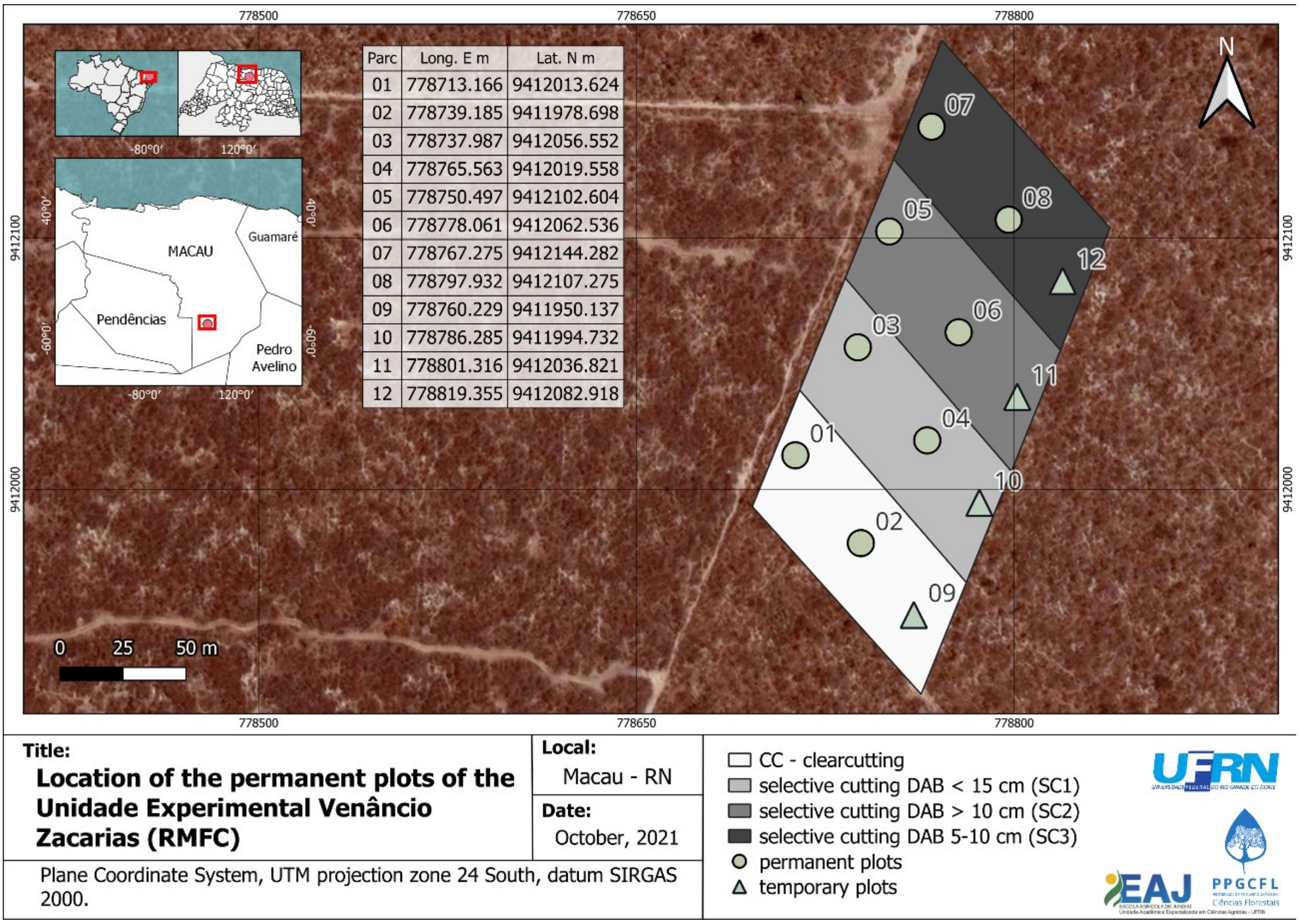

Figure 1. Location map of the study area in Macau, RN, Brazil.

Macau covers a total area of 775.3 km² and is part of the Central Potiguar mesoregion and the Macau microregion. It is bordered by the municipalities of Guamaré, Pedro Avelino, Afonso Bezerra, Alto do Rodrigues, Pendências, Caraúbas, and Porto do Mangue (IBGE, 2017). Macau has a hot semi-arid climate (BSh-type), according to the Köppen classification. The average annual rainfall is 526.2 mm, with a rainy season from March to April, an average annual temperature of around 27.2 ºC, a maximum of 32.0ºC and a minimum of 21.0ºC, and an average annual relative air humidity of 68% (DUBREUIL et al., 2018).

According to Diniz and Pereira (2015), Macau is the driest coastal city in Brazil, with an average annual rainfall of 537.6 mm. It is located on the northern coast of Rio Grande do Norte, considered the driest stretch of the Brazilian coast. The predominant soils in the region are Neossolo Quartzarênico, Gleissolos, and Latossolo Vermelho-Amarelo eutrófico (EMBRAPA, 1971); mostly soils of low fertility, high salinity, and acid pH, i.e., characteristics that determine the quality of the site.

Concerning the edaphic aspects of the study area, according to Riegelhaupt, Pareyn, and Bacalini (2010), the soil is classified as a Latossolo Amarelo Distrófico típico, medium-textured with a depth of more than one meter and an absence of stoniness, presenting predominantly flat relief.

The local vegetation cover can be classified as a Wooded Steppic-Savannah, which generally has a sparse upper shrub layer and a lower grass layer (IBGE, 2012).

Characterization of the Experimental Unit

According to residents, the study area consisted of a large cotton-producing farm called Bela Vista, which closed in the mid-1980s. The farm was later expropriated for land reform and converted into a Settlement Project.

In 1995, CFMN set up the Venâncio Zacarias Experimental Unit on the property, which covers an area of 2.0 ha. This area was divided into four 0.5 ha blocks, each 100 m x 50 m, where the following silvicultural treatments were CC - clearcutting; SC1 – selective cutting 1, cut of trees with diameter at the base – DAB < 15 cm; SC2 – selective cutting 2, cut of trees with DAB > 10 cm; and SC3 – selective cutting 3, cut of trees with DAB between 5 and 10 cm).

Two fixed 20 m x 20 m plots were delimited in each block to obtain the following variables: species, circumference at breast height (CBH) at 1.30 m from the ground, circumference at the base (CAB), and total height. The eight permanent plots were used to determine the phytosociological parameters. To assess the effects of each treatment on the basal area of the individuals and the volumetric stock, in addition to the two existing plots per treatment, a new 20 x 20 m plot was installed, i.e., four additional plots, giving a total of 12 plots for the four blocks.

In 2004, the plots were transformed into permanent plots to evaluate the effects of the silvicultural system over the years. So far, monitoring has consisted of five measurements, in 2004, 2007, 2011, 2015, and recently in 2021. These periods are equivalent to 9, 12, 16, 20, and 26 years of post-treatment regeneration.

Data collection and analysis

From the four cutting regimes mentioned above, the variables measured were: the number of individuals per hectare (N), diameter at breast height (DBH), diameter at base (DAB), and total height (H). The individuals measured were labeled with coded numbers and classified according to the APG IV classification system (2016).

The classic phytosociological parameters of density and dominance were calculated according to Mueller-Dombois and Ellemberg (1974). For wood volumetry, the cylindrical volume at breast height was calculated, followed by the actual volume in cubic meters, and the stere volume was estimated, considering a form factor of 0.9 (ZAKIA; PAREYN; RIEGELHAUPT, 1992) and a stacking factor of 3.32 (PAREYN et al., 2015).

To analyze vegetation dynamics, we used data measured in 2004 (9 years of regeneration), 2007 (12 years of regeneration), 2011 (16 years of regeneration), 2015 (20 years of regeneration), and 2021 (26 years of regeneration). Calculating the average annual rates of mortality and recruitment, in number of individuals, and average annual rates of loss and gain, in basal area (SHEIL; BURSLEM; ALDER, 1995; SHEIL; JENNINGS; SAVILL, 2000), according to the equations:

$$M = \left[1 - \left(\frac{N_0 - N_m}{N_0}\right)^{\frac{1}{t}}\right] * 100$$

$$R = \left[1 - \left(1 - \frac{N_r}{N_t}\right)^{\frac{1}{t}}\right] * 100$$

$$P = \left[1 - \left(\frac{BA_0 - BA_m - BA_d}{BA_0}\right)^{\frac{1}{t}}\right] * 100$$

$$G = \left[1 - \left(1 - \frac{BA_r + BA_g}{BA_t}\right)^{\frac{1}{t}}\right] * 100$$

where: M = mortality rate (% year^{-1}); R = recruitment rate (% year^{-1}); L = loss rate (% year^{-1}); G = gain rate (% year^{-1}); N_0 and N_t = initial and final counts of individuals, respectively; N_m and N_r = respectively, the number of dead and recruited trees; BA_0 and BA_t = respectively, initial and final basal area; BA_m and BA_r = respectively, basal area of dead and recruited trees; and BA_d and BA_g = respectively, decrease and increase in basal area of surviving individuals.

To express global dynamics, the turnover rates in the number of individuals (T_N) and basal area (T_{BA}) were calculated using the following expressions (WERNECK; FRANCESCHINELLI, 2004):

$$T_N = \left[\frac{(M + R)}{2}\right] \qquad T_{BA} = \left[\frac{(P + G)}{2}\right]$$

As well as the rates of net change for the number of individuals (Ch_N) and basal area (Ch_{AB}) (KORNING; BALSLEV, 1994):

$$Ch_N = \left[\left(\frac{N_t}{N_0}\right)^{\frac{1}{t}} - 1\right] * 100 \qquad Ch_{BA} = \left[\left(\frac{BA_t}{BA_0}\right)^{\frac{1}{t}} - 1\right] * 100$$

RESULTS AND DISCUSSION

In the survey carried out in 2021, 26 years after the silvicultural treatments were applied, 808 individuals were recorded in the 12 sampling units, distributed among six botanical families: Euphorbiaceae (5), Fabaceae (5), Apocynaceae (1), Burseraceae (1), Nyctaginaceae (1), and Rhamnaceae (1); 14 of which were woody species (Table 1). The species with the highest density in all treatments were *Pityrocarpa moniliformis* (Catanduva - average density of 588 ind. ha^{-1}), *Croton blanchetianus* (Marmeleiro - average density of 558 ind. ha^{-1}), and *Cenostigma pyramidale* (Catingueira - average density of 352 ind. ha^{-1}).

Table 1. List of woody species recognized in a caatinga fragment after 26 years of exploitation at the Venâncio Zacarias Experimental Unit in Macau, RN, Brazil.

Species	Popular name	Habit	CC	SC1	SC2	SC3
APOCYNACEAE						
Aspidosperma pyrifolium Mart.	Pereiro	Arb	x			
BURSERACEAE						
Commiphora leptophloeos (Mart.) J.B.Gillett	Imburana-de-cambão	Tre	x	x	x	x
EUPHORBIACEAE						
Cnidoscolus quercifolius Pohl	Faveleira	Arb/Shr				x
Croton blanchetianus Baill.	Marmeleiro	Arb/Shr	x	x	x	x
Croton nepetifolius Baill.	Marmeleiro-branco					x
Jatropha mollissima (Pohl) Baill.	Pinhão-bravo	Arb		x	x	x
Manihot glaziovii Müll.Arg.	Maniçoba	Arb	x	x	x	x
FABACEAE						
Bauhinia cheilantha (Bong.) Steud.	Mororó	Arb				x
Cenostigma pyramidale (Tul.) Gagnon & G.P. Lewis	Catingueira	Arb	x	x	x	x
Mimosa ophthalmocentra Mart. ex Benth.	Jurema-vermelha	Arb		x	x	x
Pityrocarpa moniliformis (Benth.) Luckow & R.W. Jobson	Catanduva	Arb	x	x	x	x
Piptadenia retusa (Jacq.) P.G. Ribeiro, Seigler & Ebinger	Jurema-branca	Arb	x	x	x	x
NYCTAGINACEAE						
Guapira laxa (Netto) Furlan	João-mole	Arb/Shr	x	x		
RHAMNACEAE						
Sarcomphalus joazeiro (Mart.) Hauenshild	Juazeiro	Arb/Shr		x	x	

Legend: CC - clearcutting; SC1 - selective cutting of trees with diameter at base (DAB) < 15 cm; SC2 - selective cutting of trees with a DAB > 10 cm; and SC3 - selective cutting of trees with a DAB between 5 and 10 cm. Arb – Arboreal habit; Shr – Shrubby habit.

The occurrence of greater richness and dominance of species from the Fabaceae and Euphorbiaceae families in the study area is a common characteristic of the Brazilian semi-arid region (LIMA; COELHO, 2018; SOUZA et al., 2020). Due to their morphological and physiological attributes, species from the Fabaceae family are abundant in SDTF areas and can withstand low water availability and high temperatures. An example is the association between certain legumes and bacteria of the *Rhizobium* genus, which promotes greater nitrogen fixation capacity in the soil, making soil conditions more favorable to macrofauna and microfauna (FREITAS et al., 2011).

Structure

Based on the structural dynamics of the vegetation (Figure 2), it can be seen that the area subjected to CC did not recover its initial volumetric stock over 26 years. Although it showed a population decline and consequent reduction in its wood yield from 2015 onwards, SC1 exceeded the original data at 16 years (2011), which indicates its suitability for continued management in 15-year cycles (considering the replacement of the pre-cut volume as a requirement and parameter).

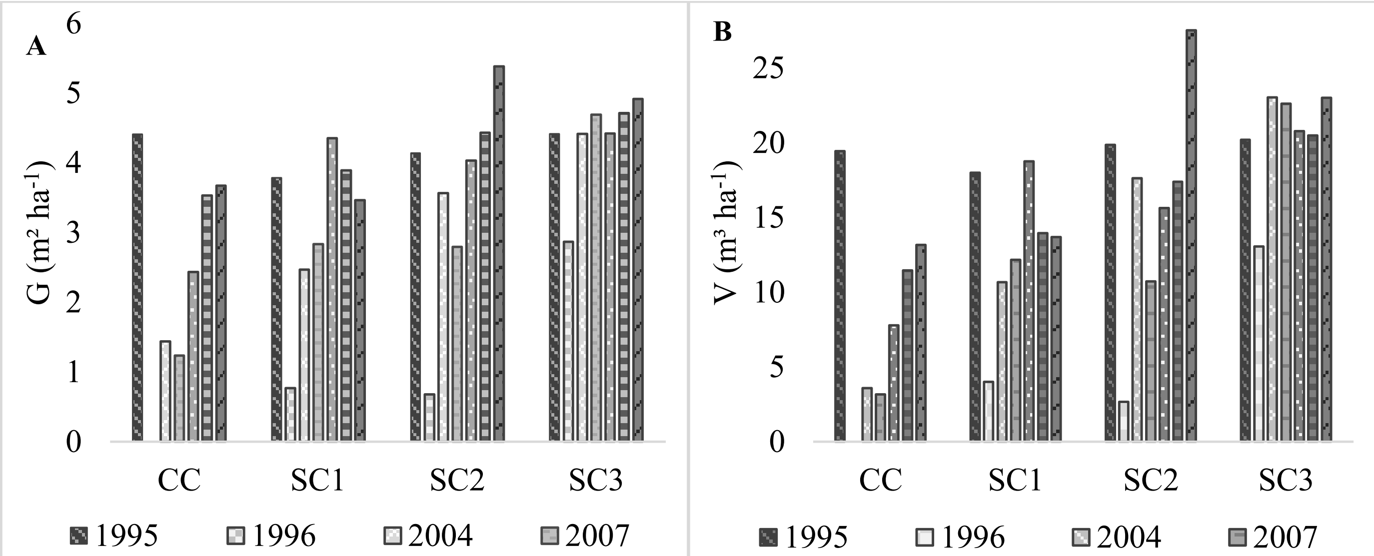

Figure 2. Basal area (A), in m² ha^{-1} and volume (B), in m³ ha^{-1} of each treatment in the years of monitoring at the Venâncio Zacarias Experimental Unit, in Macau, RN, Brazil.

In the SC2 treatment, the results for 2021 exceed the 1996 data by an average of 1.4 times. This confirms the finding by Lopes et al. (2020) that the original stocks of woody biomass do not correspond to the maximum potential exploitable shrub and tree biomass. In this regard, Riegelhaupt, Pareyn, and Bacalini (2010) had already questioned the exclusive use of this criterion, given, for example, the lack of parameters to certify that the initial average stock found in a certain area corresponds to the maximum stock that the site can reach.

Evaluating an area of SDTF under management with clearcutting in Ceará, Lopes et al. (2020) found that the vegetation reached the average stock of original biomass at 8 years of regeneration in a location with a hot semi-arid climate and average annual rainfall of 744 mm. However, although the initial stock was recovered seven years before the cutting cycle, the vegetation cover was still quite young, with most of the biomass occupying the first diameter class (2 -5.99 cm). According to the authors, at this stage, harvesting would result in low-quality biomass with a high presence of thin stems, causing losses in energy efficiency (YAN; XU; HE, 2018).

On the other hand, in this study, the expression of the vegetation subjected to clearcutting, when compared to the development in treatments SC2 and SC3, denotes the local unfeasibility of this system in 15-year cutting cycles and sites similar to this one.

Carvalho et al. (2020), in a similar study in a Caatinga area, estimated a clearcutting cycle of 17.3 years in a region located in Agreste Potiguar with a dry sub-humid climate (IDEMA, 2022). This result highlights the phytosociological plurality in the Caatinga biome due to climatic factors promoting its individuals' heterogeneous growth between locations.

When analyzing the farm's productive past, the 1980s is the final milestone for the crops at the farm - also a reflection of the crisis caused by the boll weevil in the Northeast, which culminated in a sharp reduction in cotton production at the end of the 1980s (BUAINAIN et al., 2007). In this way, it can be inferred that the native vegetation measured in 1995 consisted of secondary vegetation cover with no more than 15-20 years of regeneration.

Therefore, if the initial stock sampled corresponded to vegetation that was still regenerating and whose stability/ maturity had probably not been reached, why use it as a condition to be achieved? From an economic point of view, the annual yield would be based on a flawed criterion. Because of this, Lopes et al. (2020) suggest that the definition of cutting cycles should also be supported by an assessment of biodiversity and the occurrence of biomass in the upper diameter classes.

In the study unit, even after 26 years of regeneration, the average stock recovered during clearcutting was equivalent to 82.8% and 67.4% of the original dominance and volume (Table 2). In contrast, the initial average density of the treatment had been recovered nine years after logging.

In quantitative terms, SC1 is similar to CC in that it resulted in the felling of 95.5% of the woody individuals and around 77.7% of the woody stock. However, the impact of these managements on the vegetation generated different responses throughout regeneration. After 16 years, for example, SC1 had a woody volume proportional to 104% of the original value, while this proportion in CC was 40%. In this case, the permanence of matrices (individuals with DAB above 15 cm) in the SC1 area may have made it possible to increase the recruitment rate through seed dispersal, which, added to the gain in the basal area of the remaining trees, may have favored the gradual recovery of the treatment.

Table 2. Changes over 26 years of regeneration in the parameters of density (ind./ha), dominance (m² ha^{-1}), and volume (m³ ha^{-1}) of the treatments at the Venâncio Zacarias Experimental Unit in Macau, RN, Brazil.

	1995 pre-cut	1996 post-cut	2004 9 years	2007 12 years	2011 16 years	2015 20 years	2021 26 years
N (ind./ha)							
CC	1000	sd	1225	1225	1175	1638	1513
SC1	1100	50	1550	1963	1988	2788	1813
SC2	950	338	1475	1525	1638	1963	1475
SC3	1088	838	1525	1625	1438	1813	1638
DoA (m² ha^{-1})							
CC	4.41	sd	1.44	1.23	2.44	3.53	3.65
SC1	3.78	0.77	2.47	2.84	4.35	3.89	3.46
SC2	4.14	0.68	3.57	2.79	5.01	4.43	5.38
SC3	4.42	2.87	4.42	4.69	4.42	4.71	4.91
V (m³ ha^{-1})							
CC	19.44	sd	3.6	3.16	7.8	11.48	13.11
SC1	18.02	4.02	10.69	12.19	18.76	13.97	13.69
SC2	19.86	2.67	17.65	10.72	20.32	17.41	27.54
SC3	20.2	13.08	23.04	22.63	20.78	20.5	23.02

Legend: N - density; DoA - dominance; V - real volume; sd - no data due to lack of measurable stems.

From a broader perspective, the maintenance of mother trees in the selective cutting system can also benefit the direct and indirect relationships of the soil plant system. Matos, Barreto-Garcia, and Scoriza (2019), when analyzing the influence of different types of forest management on edaphic macrofauna in an area of arboreal Caatinga, with an average annual temperature of 23°C and annual rainfall between 596 and 679 mm, in Contendas do Sincorá, Bahia, observed the absence of the Blattodea group in an area under clearcutting, even in the rainy season. This is because these insects usually take shelter in damp places (such as bark and leaf litter), and removing the vegetation cover led to more sunlight on the ground and a lack of continuous leaf litter. On the other hand, in the areas under selective cutting by diameter and species, Matos, Barreto-Garcia, and Scoriza (2019) estimated greater richness. The authors attribute these results to the maintenance of soil cover and better temperature and humidity conditions, favoring the dynamics of edaphic organisms.

Under certain conditions, as we have seen, the total removal of woody cover can impact soil dynamics beyond yield aspects. For example, studies suggest that disturbances to the woody vegetation of the Caatinga can affect the production of litter and, consequently, alter the dynamics of nutrient cycling (ARAÚJO et al., 2020). This is because the woody component is responsible for the differentiated accumulation of litter, promoting soil heterogeneity (REYNOLDS et al., 1999; ARAÚJO et al., 2020).

Dynamic

In the legislative context of Rio Grande do Norte, where sustainable management implies replacing the pre-cut volume extracted, SC1, SC2, and SC3 would be fit for the second harvesting cycle, and CC would be unfit. It is clear, however, that there was a 26.58% drop between 2011-2015 in SC1, which was maintained in the next measurement. This decline may be linked to the mortality of remaining older individuals, which can consequently cause significant losses in woody biomass. This can be seen in the marked negative change in basal area calculated for this treatment in the respective period (Figure 3C); with intense mortality in the subsequent interval (Figure 3D).

As for the CC and SC2 treatments, although the density in the 2004-2007 period was unchanged, there was a negative change in their basal area values associated with greater losses than gains (Figure 3). Between 2007-2011, the CC and SC3 treatments suffered from higher mortality rates and losses in density, but the gains in basal area, especially in CC, were significant.

Between 2011 and 2015, only CC showed positive changes in density and basal area, given that although recruitment was high in all treatments, mortality and loss rates were higher. The marked changes in the treatments observed during this period, with an increase in mortality and recruitment rates, may be related to the age of the remaining individuals (selective cuttings) and the opening of clearings that favor population entry.

According to Lambers, Chapin, and Pons (2008), the dynamics of species recruitment and establishment in a given area are influenced by three filters: historical, related to the dispersal syndromes that lead to the arrival or not of the propagule; physiological; and biotic, associated with the species ability to germinate, grow, reproduce, compete, and occupy the area. These filters are constantly changing and interacting.

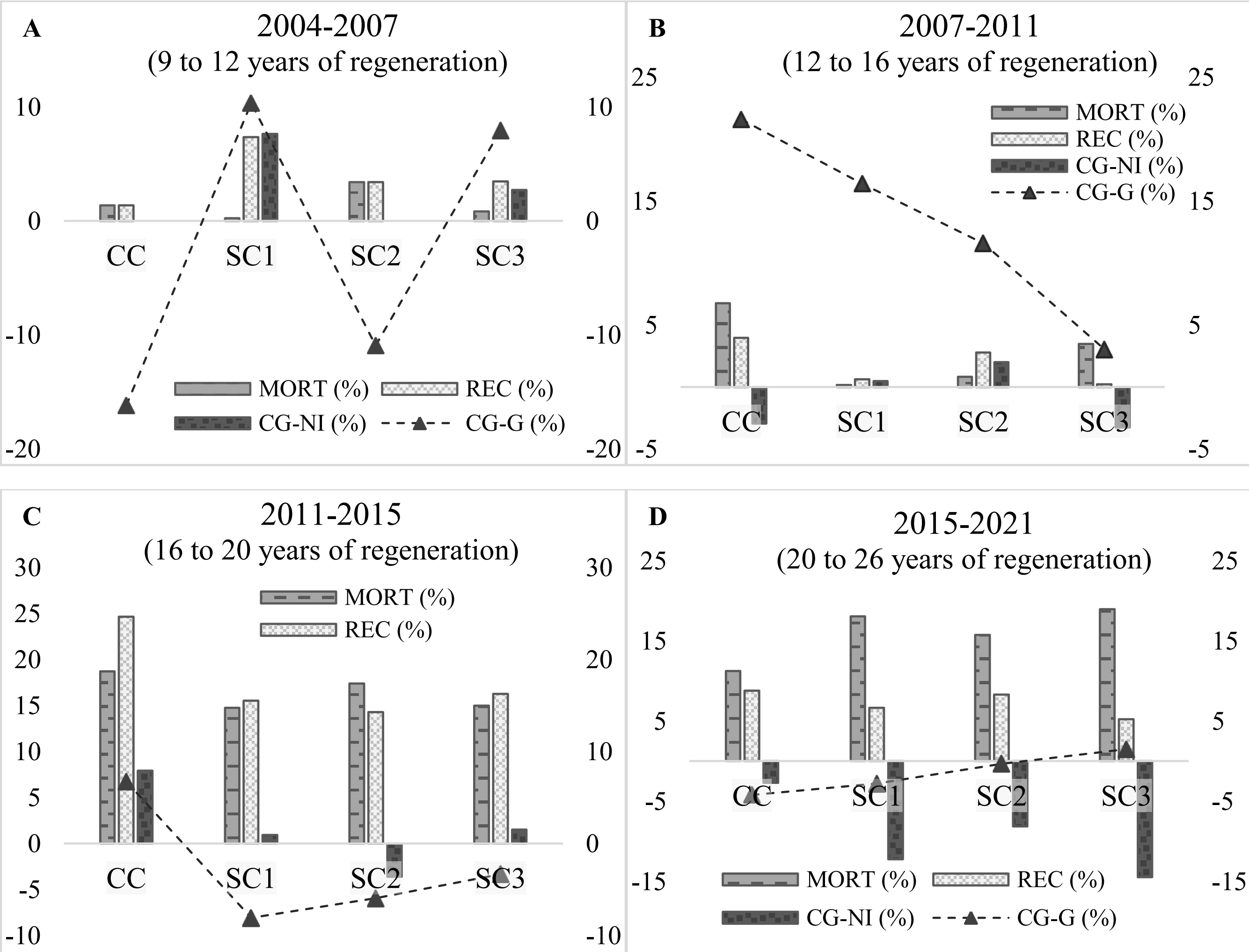

Figure 3. Rates of mortality (MORT), recruitment (REC), and change in the number of individuals (CG-NI), combined with the rate of change in basal area (secondary axis - CG-G), for each period, from 9 to 26 years after application of the treatments (CC, SC1, SC2, and SC3) at the Venâncio Zacarias Experimental Unit, in Macau, RN, Brazil.

For this reason, as mentioned by Lucena, Silva, and Alves (2016), it is essential to know the impacts generated by different silvicultural systems on the production and quality of litter, the condition of soil seed banks, edaphic characteristics, and how management can affect the community capacity for regeneration; especially about the forest resources of the Caatinga, given the advanced process of degradation of its physiognomies.

Forest dynamics point to the insufficiency of the 15 year cutting cycle when clearcutting is applied, which is common in SFMPs in Rio Grande do Norte regarding recovering forest cover in this region.

Considering the pre-cut vegetation prematurity and assuming the original stock recovery as a deficient criterion (when isolated), estimating the appropriate cutting cycle for the site conditions was impossible.

CONCLUSIONS

The Caatinga area was found to be still regenerating, indicating, from the parameters examined, that different management types have different effects on the vegetation being exploited, which can limit or stimulate its regenerative process.

Given the effect of clearcutting on the structural aspects of the vegetation, the application of selective cutting management showed better yield potential in the study area, especially in treatments SC2 and SC3.

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