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The influence of clear-cut area size on forest regrowth: a case study in the dry tropical forests of Pernambuco, Brazil

Visêldo Ribeiro de Oliveira[1], Andressa Ribeiro[2]✤, Frans Germain Corneel Pareyn[3], Marcos Antônio Drumond[1], Diogo Denardi Porto[1], Lúcia Helena Piedade Kiill[1], Antonio Carlos Ferraz Filho[2]

[1]Embrapa Semiárido, Petrolina, Pernambuco, Brazil
[2]Federal University of Piauí, Bom Jesus, Piauí, Brazil
[3]Associação de Plantas do Nordeste, Recife, Pernambuco, Brazil

FOREST MANAGEMENT

ABSTRACT

Background: Managed Caatinga forests in Northeast Brazil are an important source of wood products, however, successful regeneration and regrowth is important to guarantee sustainability in these forests. The main objective of this study was to evaluate the natural regeneration and forest regrowth ability of a Caatinga forest under varying clear-cut treatments, as well as to estimate the recovery time of stand parameters.

Results: An experiment was set up in Petrolina, Pernambuco state, Brazil, comparing five clear-cut strip widths: 0, 40, 60, 80 and 100 meters. Forest inventory data was gathered before and eight years after harvesting in 19 plots of 10 x 40 m. Tree seedling regeneration (individuals with circumference at breast height < 6 cm and minimum height of 0.5 m) was also monitored in 5 x 5 m sub plots, before harvesting, one, three and eight years after harvesting.

Conclusions: No influence of the clear-cut strip width on regeneration and forest regrowth ability was detected, with all treatments presenting similar growth and tree species diversity and similarity values. The estimated growth rates of the clear-cut plots were of 0.12 $m^2 \cdot ha^{-1} \cdot year^{-1}$ and 0.39 $m^3 \cdot ha^{-1} \cdot year^{-1}$ for basal area and volume, respectively, resulting in recovery times of 35 and 49 years, longer than the 15 years cycles generally adopted in Caatinga forest management plans.

Key words: Forest Management; Forest Regeneration; Seasonally Dry Tropical Forests.

HIGHLIGHTS

Appropriate management of Caatinga forests ensures fast recovery after interventions.
Clear-cut strips between 0 and 100 m did not influence regeneration and forest regrowth.
Species diversity was lower in clear-cut than in control plots after 8 years.
Recovery time after clear-cut for basal area and volume was 35 and 49 years, respectively.

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✤Corresponding author: andressa.florestal@ufpi.edu.br
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INTRODUCTION

The Caatinga biome, located in the Northeast region of Brazil, is composed of a diverse mosaic of vegetation types, ranging from forest formations, deciduous vegetation and thorny shrub vegetation, among others, depending on proximity to water courses, altitude, rainfall patterns and soil type. This vegetation is mainly composed of seasonally dry tropical forests, and it is considered the most altered by human-induced land use and land cover change in Brazil (Souza Júnior et al., 2020). Drylands are ecosystems vulnerable to water shortage, drought, desertification, land-use change, degradation, and climate change impacts, with dangerous implications for food security, livelihood, and wellbeing of their populations (FAO, 2019). Approximately 22 million people live in the Caatinga (Silva et al., 2018), and their impact on the natural environment can be alleviated by adopting sustainable forest management practices in order to supply forest goods, complementary to traditional agricultural practices, labor, and income (FAO, 2019; Riegelhaupt et al., 2010; Garlet et al., 2018).

Concerning the adoption of forest management practices in the Brazilian semiarid region, few records on literature provide scientific information about cutting cycles, mainly from studies involving forest management, biometrics, harvesting and population dynamics (Carvalho et al., 2020). Notable exceptions include the reports by Pareyn et al. (2020; 2022), who demonstrated the close relationship between average precipitation and the wood biomass annual increment of the stand.

In sustainable forest management of the Caatinga (and other forests in Brazil), regulation by area is advocated based on the division of the forest area into annual productive units, and with a minimum harvest cycle of 15 years (Araújo Filho and Carvalho, 1997; Drumond et al., 2004; Riegelhaupt et al., 2010; Matos et al., 2019, Lopes et al., 2020). The commonly adopted cutting cycle for Caatinga forests is established by federal and state legislation, still lacking solid scientific basis. The main objective of forest management plans is production of wood fuel (firewood and charcoal). There is no consensus on appropriate and standardized guidelines on the most appropriate cutting cycles in order to assure the sustainability of wood harvesting. It is fundamental to identify specific technical parameters for the Caatinga in order to ensure its recovery after anthropic interventions (Matos et al., 2019). This was the overall motivation for the Caatinga Forest Management Network (RMFC) to conduct a series of experiments in different areas across the Brazilian Northeast (Riegelhaupt et al., 2010).

Management of tropical dry forests in Brazil expanded 450% in the last two decades; but little is known about the ideal recovery time of the harvested stock after clear cut as well as the growth dynamics of these areas (Lopes et al., 2020). Many aspects regarding sustainability need further investigation, especially potential for recovery of productive capacity and ways to minimize anthropic impacts on vegetation. In order to better understand the Caatinga forest dynamics after disturbance, this study evaluated the natural regeneration and forest regrowth ability of a forest fragment subjected to different schemes of clear-cutting, varying the width of the clear-cut strip, as well as estimating the time needed for basal area and wood volume recovery.

MATERIAL AND METHODS

The study area is located at a research station of the Centro de Pesquisa Agropecuária do Trópico Semiárido (Embrapa Semiárido) in Petrolina, Pernambuco state, Brazil (9º03’53”S and 40º18’49”W). The studied forest has an area of 36 ha, classified as a dense hyper xerophytic deciduous tropical dry forest, preserved for at least 40 years prior to the experiment (Amorim et al., 2014). The local climate is classified, according to Köppen, as hot semiarid (BSh), with altitude of 421 m, 501 mm average annual precipitation and 25 ºC average temperature (Alvares et al., 2013).

The experimental design used in this study was randomized blocks. The blocks were characterized by geographical proximity, expecting greater similarity and more homogeneous vegetation within the blocks. Three replications were used, containing five treatments comprising of different clear-cut strip widths: 0, 40, 60, 80 and 100 meters (Figure 1). The 0 m treatment consisted in clear-cutting only the inventory plot (10 x 40 m), leaving the neighboring vegetation undisturbed. The other treatments consisted in clear-cutting different rectangles representing different strip widths, with the inventory plot in the center (Figure 1). Forest inventory data was gathered before (2007) and after (2015) clear-cutting, in nineteen plots with 10 x 40 m dimensions. Fifteen plots and surrounding strips of variable width (0 up to 100 m) where clear-cut in December 2007 (white polygons in Figure 1). Four control plots (10 x 40 m) located between the experimental blocks were left without cutting.

Forest inventory campaigns were carried out before (2007) and after (2015) the clear-cutting following the Protocol of the Caatinga Forest Management Network (Comitê RMFC, 2005). All trees with circumference at 1.30 meters from the soil (CBH) over 6 cm were included in the inventory. Trees were subjected to botanical identification and measured for: CBH, afterwards converted to diameter at breast height (DBH), circumference at ground height (0.3 meters from the ground), also converted to diameter, and total height. Botanic families and scientific names followed the Angiosperm Phylogeny Group classification (APG IV, 2016). The botanical identification of each species (common and scientific names) was made in the field, relying on past botanical identifications developed in forests near the study area (Drumond et al., 2002; Kiill, 2017).

Using the data collected in the forest inventories of 2007 and 2015, we computed the mean and standard deviation for the following metrics: diameter at 0.3 and 1.3 m height; height; base stems, stems and individuals per hectare; number of stems per individual; basal area; and volume per hectare. A form factor of 0.9 was used to estimate individual tree volume from DBH and height values, as is commonly applied to this type of vegetation (Nazareno et al., 2021). Basal area and volume data per hectare were used to evaluate the recovery rate of the clear-cut plots. Diameter and height classes distributions, both in numbers of stems and volume per hectare, were also assessed.

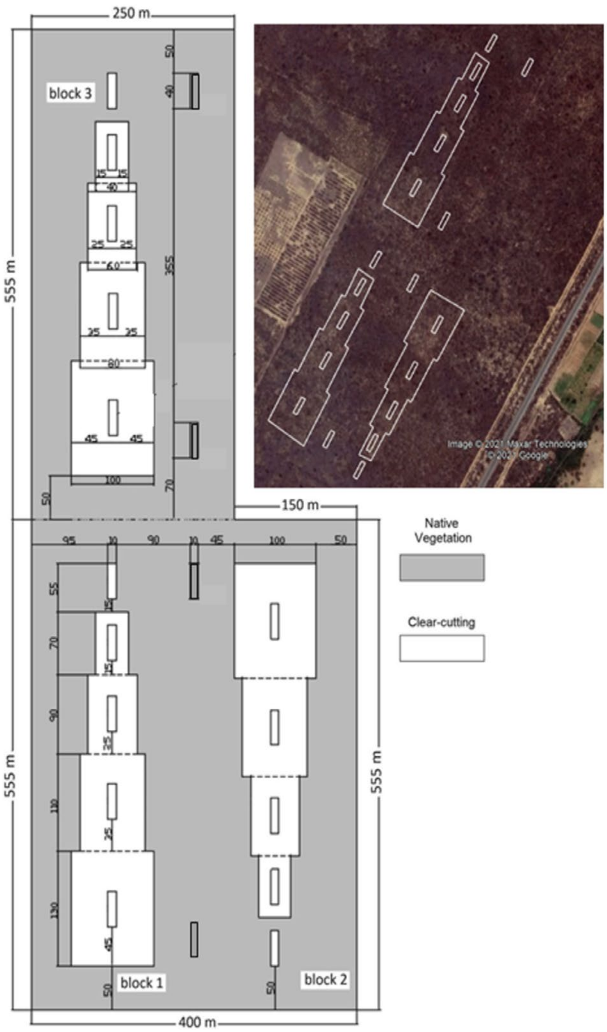

Figure 1. Spatial arrangement of the experimental plots (white rectangles in the upper right panel) and blocks design for this study (Source: Adapted from Amorim et al. (2014) and Google Earth).

The influence of the treatments (clear-cut strip size) on the previously mentioned tree and stand parameters was tested by analysis of variance in a blocked design, using a probability value equal or lower than 0.05 to detect significant differences. This was applied separately to the data of 2007 and 2015, with the former to verify if the area was homogeneous enough to apply the treatments and the latter to check the influence of the treatments in the regeneration and forest regrowth of the stand. In case a significant effect was detected in the analysis of variance, Tukey's honest significant difference test was applied to differentiate between the treatments. Comparisons between clear-cut and control plots were made by means of a two-sample t-test considering equal variances, since the control plots were not included in the blocked design.

Inferences considering the species dominance, diversity and similarity were also made. To check the similarity of tree species occurrence between the plots we used Sorensen's similarity coefficient (Equation 1), which varies from 0 to 1, with higher values indicating higher similarity. This was done with the data of 2007 and 2015. Tree species diversity in the study area was made using Shannon's index (Equation 2), and comparisons between the computed values were made using Hutcheson's test, as presented in Scolforo et al. (2008a). Finally, the importance of each individual tree species was calculated from the relative dominance in basal area, were all species with relative dominance larger than 10% being considered dominant. Where: S = Sorensen's similarity coefficient; a = number of species in both treatments; b = number of species present in treatment 1 and absent in treatment 2; c = number of species present in treatment 2 and absent in treatment 1; H' = Shannon's index; p_i = the proportion of observations in the ith of k species; ln = natural logarithm.

$$S = \frac{2a}{2a+b+c} \tag{1}$$

$$H' = -\sum_{i=1}^{k} p_i \cdot ln\left(p_i\right) \tag{2}$$

Tree seedling regeneration was evaluated in all 19 monitored plots during the forest inventory campaigns of 2007 and 2015. Tree seedling regeneration was also evaluated one and three years after harvesting (in 2008 and 2010), but only in the 15 clear-cut plots. For this, subplots with dimensions of 5 x 5 m were set up in the left corner of each plot. In these subplots, all individuals with CBH < 6 cm and minimum height of 0.5 m had their botanical identification and height collected, being afterwards divided into two classes of regeneration: C1 (height class of 0.5 to 1.0 m) and C2 (height class > 1.0 m and CBH ≤ 6 cm). The origin of each measured seedling was also identified, differentiating between two classes: seedlings from tree stumps (i.e., basal, stool or lateral stump sprouts); seedlings from seeds and root sprouts (suckers).

Using the tree seedling data, we computed the following metrics: sprouts·ha^{-1}; individuals·ha^{-1}; sprouts per individual; mean height; percentage of seedlings originating from stumps. As was done for the forest inventory data, we tested possible differences between the treatments using analysis of variance with a blocked design and possible differences between the treatments and control plots using two-way t-test, independently for each measurement date. Similarity of tree species occurrence between the plots was also assessed using Sorensen's similarity coefficient (Equation 1). All statistical data analyses were performed in R (R Core Team, 2022).

RESULTS

A total of 36 tree species were found during forest inventories operations (Table 1). The highest species richness was found in the pre-harvest forest inventory (30), followed by the regeneration plots (23) and 2015 inventory (15). Exempting

Manihot carthagenensis, all species found in the 2015 inventory were also present in 2007. Likewise, exempting the species *Calliandra depauperata*, *Cnidoscolus quercifolius* and *Jacaratia corumbensis*, all species found in the regeneration plots were also present either in the 2007 or 2015 forest inventories.

Forest inventory before and eight years after clear-cut

According to the data before the clear-cut (Table 2), the different plots in the experimental area presented homogeneous tree and stand metrics. With exception of the mean DBH, in the pre-harvest inventory, none of the treatments presented significant differences for all variables presented in Table 2. The mean DBH did not differ between the clear-cut treatments [$F(4, 8) = 0.94$, $p = 0.49$], but a significant difference was detected between the clear-cut plots and the control plots, with mean DBH values of 3.9 versus 3.3 cm, respectively [$t(17) = 2.11$, $p = 0.01$].

Eight years after clear-cutting, none of the clear-cut strip width treatments presented significant differences amongst themselves, except for the mean height [$F(4, 8) = 18.01$, $p = <0.00$]. According to Tukey's honest significant difference test, mean height in the 0 m treatment was greater than all the other treatments, and reached the same mean value as the control plots. None of the clear-cut treatments

Table 1. Family, scientific and popular names of the tree species found in the forest inventories of 2007, 2015 and the regeneration plots.

Species	Family	Popular name	Presence		
			2007	2015	Regeneration
Anadenanthera colubrina (Vell.) Brenan	Fabaceae	angico-de-caroço	x	x	
Aspidosperma pyrifolium Mart. & Zucc	Apocynaceae	pereiro	x		x
Astronium urundeuva (Allemão) Engl.	Anacardiaceae	aroeira	x	x	
Bauhinia cheilantha (Bong.) Steud.	Fabaceae	mororó	x	x	x
Calliandra depauperata Benth.	Fabaceae	carqueja			x
Cenostigma microphyllum (Mart. ex G.Don) Gagnon & G.P.Lewis	Fabaceae	catingueira	x	x	x
Cereus jamacaru DC.	Cactaceae	mandacaru	x		
Chloroleucon dumosum (Benth.) G.P.Lewis	Fabaceae	arapiraca	x		
Chloroleucon foliolosum (Benth.) G.P.Lewis	Fabaceae	espinheiro	x		
Cnidoscolus bahianus (Ule) Pax & K.Hoffm.	Euphorbiaceae	favela-de-galinha	x	x	x
Cnidoscolus quercifolius Pohl	Euphorbiaceae	faveleira			x
Commiphora leptophloeos (Mart.) J.B.Gillett	Burseraceae	imburana-de-cambão	x	x	x
Croton conduplicatus Kunth.	Euphorbiaceae	quebra-faca	x	x	x
Croton echioideus Baill.	Euphorbiaceae	marmeleiro	x		x
Cynophalla flexuosa (L.) J.Presl	Capparaceae	feijão-bravo	x		
Erythroxylum nummularia Peyr.	Erythroxylaceae	rompe-gibão	x		
Handroanthus spongiosus (Rizzini) S.O.Grose	Bignoniaceae	sete-cascas	x	x	x
Helicteres brevispira A.Juss.	Malvaceae	imbira-branca			x
Jacaratia corumbensis Kuntze	Caricaceae	mamãozinho-de-veado			x
Jatropha mollissima (Pohl.) Baill.	Euphorbiaceae	pinhão	x	x	x
Lippia grata Schauer	Verbenaceae	alecrim	x		x
Manihot carthagenensis (Jacq.) Müll.Arg.	Euphorbiaceae	maniçoba		x	x
Mimosa ophthalmocentra Mart. ex Benth.	Fabaceae	jurema-vermelha	x	x	x
Mimosa tenuiflora (Willd.) Poir.	Fabaceae	jurema-preta	x	x	x
Myriopus rubicundus (Salzm. ex DC.) Luebert	Boraginaceae	pau-de-chumbo	x		x
Not identified	Not identified	not identified	x		x
Piptadenia retusa (Jacq.) P.G.Ribeiro, Seigler & Ebinger	Fabaceae	jurema-branca	x		
Pityrocarpa moniliformis (Benth.) Luckow & R.W.Jobson	Fabaceae	angico-de-bezerro	x		
Pseudobombax simplicifolium A.Robyns	Malvaceae	imbiruçu	x	x	x
Sapium glandulatum (L.) Morong	Euphorbiaceae	burra-leiteira	x	x	x
Schinopsis brasiliensis Engl.	Anacardiaceae	baraúna	x	x	x
Senegalia piauhiensis (Benth.) Bocage & L.P.Queiroz	Fabaceae	jurema-rama-de-boi	x		
Senna macranthera (DC. ex Collad.) H.S.Irwin & Barneby	Fabaceae	são-joão	x		
Spondias tuberosa Arruda	Anacardiaceae	umbuzeiro	x		
Varronia leucocephala (Moric.) J.S.Mill.	Boraginaceae	moleque-duro	x		x

were able to achieve the values of the uncut control plots for the following variables: d0.3; DBH; S0.3·ha^{-1}; S·ha^{-1}; N·ha^{-1}; G and V [for all variables, t(17) = > 2.95, p = < 0.01]. The number of stems per tree (S·N^{-1}) was the only variable from Table 2 that did not differ between the clear-cut and control plots [t(17) = 1.17, p = 0.13].

The distribution of stems per diameter classes (Figure 2 A and B) followed the expected behavior of a native Caatinga forest (e.g., Batista et al., 2019; Souza et al., 2020), presenting a negative exponential distribution, where most of the stems and volume occurs in the lower diameter classes (less than 8 cm). The height distribution (Figure 2 C and D) concentrated most stems and volumes per hectare closer to the mean height values, between 3 and 5 meters tall. This behavior is also in accordance with the expected distribution of a native Caatinga forest (e.g., Batista et al., 2019; Souza et al., 2020).

The results from the Sorensen similarity coefficient did not indicate any notable tree species occurrence dissimilarities between the treatment and control plots, either before harvesting or eight years after harvesting (Table 3). The mean value of the Sorensen similarity coefficient before harvesting was 0.77, ranging between 0.65 and 0.88. Considering the area after harvesting, the mean value of the Sorensen similarity coefficient remained similar to the one found in the area before harvesting (0.76), ranging from 0.60 to 0.92.

Given the similarities between the species occurrence across plots (Table 3), we opted to compute and compare the Shannon index considering three scenarios: for the pre-harvest data (2.48 nats·ind^{-1}), for the control plots (2.15 nats·ind^{-1}), and for the clear-cut plots (1.77 nats·ind^{-1}) eight years after harvesting. The results from Hutcheson's t-test indicated that not only were the diversity indices between the control and clear-cut plots in 2015 significantly different [t(611) = 5.81, p = < 0.00], but also that the diversity indices between the control plots in 2015 and the pre-harvest data showed differences [t(440) = 5.76, p = < 0.00], indicating that forest is in a changing environment even without harvesting. While no notable differences were found concerning the occurrence of tree species, either across clear-cut treatments or between the vegetation before and after harvesting (Table 3), the relative importance of tree species changed eight years after harvesting, for both the clear-cut treatments and the control plots (Table 4). The larger part of the relative dominance before harvesting was concentrated in two species, *Mimosa tenuiflora* and *Cenostigma microphyllum*, which together accounted for 55.8% of the relative dominance. A combined relative dominance of 83.5% was achieved by the seven main species in the pre-harvest phase. We found that eight years after harvesting, only *Cenostigma microphyllum* maintained a high relative dominance in the control plots. For these plots, *Mimosa tenuiflora* lost much of its relative dominance, and was substituted by other tree species, mainly *Cnidoscolus bahianus*, *Manihot carthagenensis* and *Pseudobombax simplicifolium*.

We did not detect any clear trend of the relative dominance for the species occurring in the plots that received clear-cut (Table 4). For instance, while *Mimosa tenuiflora* achieved a relative dominance value of 32.2% in the 100 m treatment, this value dropped to 4.9% in the 40 m treatment. However, some general trends can be inferred from Table 4, such as: i) *Cenostigma microphyllum* and *Sapium glandulatum* were negatively impacted by clearcutting, being practically absent in these plots but important in the control plots; ii) *Pseudobombax simplicifolium* only reached a high relative dominance value in the control plots eight years after harvesting, being practically absent in all other monitored plots; iii) the high relative dominance of *Schinopsis brasiliensis* in the clear-cut plots occurred for two reasons, firstly because it is protected from cutting and therefore was not removed in the harvesting operation and secondly because of its natural regeneration and growth in the area.

Table 2. Mean and standard deviation of the evaluated variables by clear-cutting treatment before and eight years after harvesting, where d0.3 is the mean diameter at 0.3 height, DBH is the mean diameter at 1.3 height; h is the mean height; S·N^{-1} is the number of stems per individuals, S is the number of stems, S0.3 the number of base stems, N the number of individuals, G the basal area, and V the volume, all per hectare.

	Treatment	d0.3 (cm)	DBH (cm)	h (m)	S·ha^{-1}	S0.3·ha^{-1}	N·ha^{-1}	S·$^{N-1}$	G (m²·ha^{-1})	V (m³·ha^{-1})
Pre-harvest	0 m	5.8 ± 0.4	4.0 ± 0.2	3.7 ± 0.2	5292 ± 1347	3433 ± 983	2050 ± 681	2.6 ± 0.3	8.8 ± 2.4	36.5 ± 10.5
	40 m	5.6 ± 0.7	4.2 ± 0.5	3.7 ± 0.3	5533 ± 2022	3750 ± 1470	2017 ± 700	2.7 ± 0.2	9.8 ± 2.5	42.5 ± 13.1
	60 m	5.0 ± 0.3	3.6 ± 0.3	3.5 ± 0.1	3750 ± 740	2650 ± 378	1600 ± 214	2.4 ± 0.4	6.1 ± 1.4	23.2 ± 4.2
	80 m	5.4 ± 0.4	4.0 ± 0.4	3.8 ± 0.3	5000 ± 993	3392 ± 539	1867 ± 238	2.7 ± 0.2	8.2 ± 2.2	37.1 ± 12.6
	100 m	5.4 ± 1.2	3.7 ± 0.5	3.7 ± 0.3	5425 ± 672	3692 ± 1039	2025 ± 799	3.0 ± 1	8.0 ± 1.2	32.9 ± 6.5
	Control	4.9 ± 0.4	3.3 ± 0.2	3.4 ± 0.2	5288 ± 1370	3269 ± 997	1969 ± 621	2.7 ± 0.2	6.3 ± 1.9	24.2 ± 8.7
	Pre-harvest mean	5.4	3.8	3.6	5048.0	3364.3	1921.3	2.7	7.9	32.7
8 years after clear-cut	0 m	4.2 ± 0.3	3.1 ± 0.6	3.7 ± 0.1	1533 ± 690	1117 ± 350	567 ± 238	2.7 ± 0.4	1.0 ± 0.2	3.6 ± 0.4
	40 m	4.6 ± 0.8	3.0 ± 0.5	3.1 ± 0.3	1808 ± 538	1233 ± 357	783 ± 202	2.3 ± 0.1	1.5 ± 0.8	5.8 ± 4.6
	60 m	4.1 ± 0.1	2.6 ± 0.1	2.6 ± 0.1	1600 ± 402	1067 ± 292	633 ± 101	2.5 ± 0.5	1.0 ± 0.2	3.0 ± 0.8
	80 m	4.4 ± 0.5	2.9 ± 0.6	2.6 ± 0.2	1667 ± 846	1017 ± 322	642 ± 181	2.5 ± 0.6	1.3 ± 0.7	5.1 ± 4.8
	100 m	4.0 ± 0.4	2.6 ± 0.1	2.8 ± 0.2	2200 ± 740	1375 ± 468	783 ± 325	3.2 ± 1.7	1.2 ± 0.3	3.5 ± 1.2
	Clear-cut mean	4.3	2.8	3.0	1761.6	1161.8	681.6	2.6	1.2	4.2
	Control	5.1 ± 0.4	3.5 ± 0.3	3.7 ± 0.4	3663 ± 886	2288 ± 691	1731 ± 506	2.2 ± 0.3	4.4 ± 1.5	19.1 ± 10.9

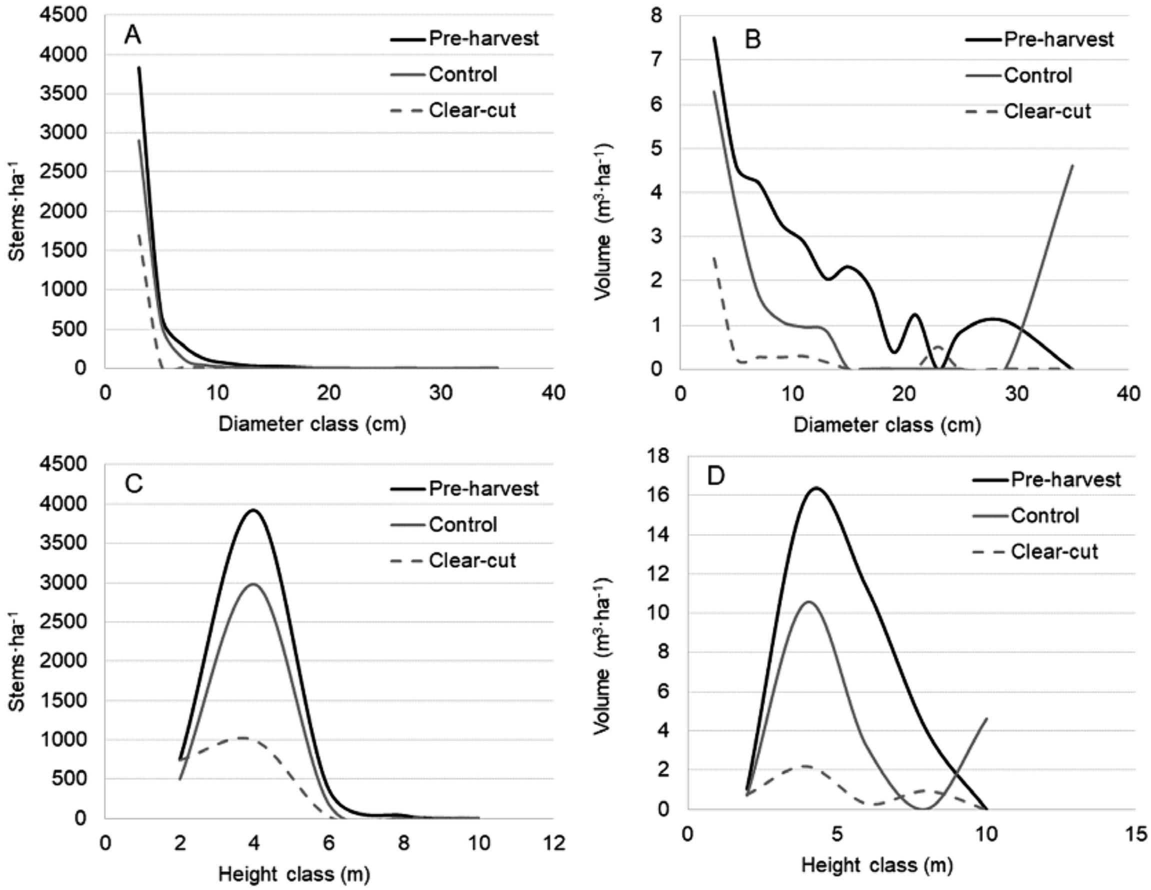

Figure 2. Number of stems and volume per hectare by diameter (A and B) and height classes (C and D) before harvesting, and eight years after with and without clear-cut in a Caatinga forest fragment in Petrolina, Brazil.

Table 3. Tree species occurrence similarity as measured by the Sorensen similarity coefficient for the different treatments and control plots, where the values under the dashed line refer to the area before harvesting and the values above the dashed line eight years after harvesting.

0 m	-	0.8	0.7	0.8	0.9	0.7
40 m	0.7	-	0.7	0.7	0.7	0.8
60 m	0.7	0.8	-	0.9	0.8	0.6
80 m	0.6	0.7	0.9	-	0.8	0.8
100 m	0.8	0.8	0.7	0.8	-	0.6
Control	0.9	0.8	0.7	0.8	0.8	-
	0 m	**40 m**	**60 m**	**80 m**	**100 m**	**Control**

Seedling regeneration

The regeneration dynamics varied over the years (Tables 5 and 6 and Figure 3), but not between the clear-cut treatments. Considering all evaluated years (pre-harvest, 1, 3 and 8 years after cutting) and all variables (sprouts·ha^{-1}, individuals·ha^{-1}, mean height and percentage of seedlings from stumps), the only significant difference occurred for the sprouts·ha^{-1} one year after harvesting [$F(4, 8) = 22.77$, $p = 0.02$]. For this variable, the treatment 0 m presented a smaller amount of sprouts·ha^{-1} compared to treatments 80 m and 100 m (95,200 versus 180,000 sprouts·ha^{-1}) and was equal to treatments 40 m and 60 m. Given the small effect of clear-cut on the regeneration metrics, we opted for presenting the data grouping all clear-cut treatments, differentiating only between these and the control plots (Table 5). The regeneration in the clear-cut areas increased considerably up to 3 years after harvesting, both in number of individuals and number of sprouts per hectare (Table 5). However, after eight years, regeneration metrics reached values similar to the control plots [for all variables, $t(17) = < 1.97$, $p = > 0.07$].

Table 4. Relative dominance (%), ordered by importance in the pre-harvest phase, of tree species present in the pre-harvest inventory and per treatment eight years after harvesting, values in bold present the most important species, with values above 10%. Only species with relative values above 1% are included.

Species	Pre-harvest	Control	0 m	40 m	60 m	80 m	100 m
M. tenuiflora	**32.6**	7.2	**29.6**	4.9	**28.2**	**10.7**	**32.2**
C. microphyllum	**23.1**	**22.1**	0.0	0.8	0.0	0.0	0.0
C. bahianus	8.7	**15.4**	**16.0**	**13.1**	**13.8**	**10.4**	**21.8**
S. glandulatum	4.9	5.9	0.0	0.0	0.0	0.0	0.0
M. carthagenensis	4.8	**14.7**	**27.6**	**12.3**	**15.7**	**19.0**	**26.5**
H. spongiosus	4.8	5.4	0.5	1.3	0.0	0.0	0.8
C. conduplicatus	4.6	2.8	0.0	0.9	0.0	0.0	0.0
A. pyrifolium	2.1	0.0	0.0	0.0	0.0	0.0	0.0
S. brasiliensis	2.0	0.4	**23.2**	**48.5**	**14.7**	**29.2**	3.7
C. echioideus	1.7	0.0	0.0	0.0	0.0	0.0	0.0
J. mollissima	1.6	6.4	1.7	6.3	**18.1**	**21.9**	**15.0**
A. colubrina	1.5	0.0	0.0	8.5	0.0	0.0	0.0
M. ophthalmocentra	1.4	0.6	0.0	0.0	0.0	0.0	0.0
S. tuberosa	1.4	0.0	0.0	0.0	0.0	0.0	0.0
C. leptophloeos	1.0	5.1	0.0	2.3	3.7	8.8	0.0
P. simplicifolium	0.1	**13.5**	1.5	1.1	0.0	0.0	0.0
A. urundeuva	0.1	0.0	0.0	0.0	5.9	0.0	0.0

Table 5. Number of individuals ($N \cdot ha^{-1}$) and sprouts per hectare for the most important regenerating tree species in the study area for the different measurement dates. Species are ranked according to the number of individuals in the last measurement.

	Species	$N \cdot ha^{-1}$				$Sprouts \cdot ha^{-1}$			
		2007	2008	2010	2015	2007	2008	2010	2015
Control	*C. depauperata*	2,300	-	-	500	12,600	-	-	1,400
	B. cheilantha	1,000	-	-	400	2,200	-	-	1,500
	C. microphyllum	900	-	-	200	2,700	-	-	200
	M. carthagenensis	300	-	-	200	400	-	-	200
	C. conduplicatus	0	-	-	100	0	-	-	1,100
	V. leucocephala	1,700	-	-	100	4,700	-	-	300
	L. grata	100	-	-	0	300	-	-	0
	Total control	**6,300**	**-**	**-**	**1,500**	**22,900**	**-**	**-**	**4,700**
Clear-cut	*C. conduplicatus*	987	2,000	3,600	693	4,027	37,813	40,720	2,187
	B. cheilantha	1,413	3,253	5,093	667	3,333	25,147	21,813	1,493
	J. mollissima	160	80	1,200	560	160	320	1,333	933
	C. microphyllum	507	880	1,387	320	1,040	12,640	11,867	480
	V. leucocephala	2,347	1,147	2,240	320	10,080	25,707	26,293	640
	C. bahianus	0	160	613	160	0	720	1,707	213
	C. depauperata	773	667	1,387	133	2,453	18,000	16,187	533
	A. pyrifolium	27	213	267	107	53	3,520	2,267	800
	H. spongiosus	373	427	560	107	667	4,693	4,400	213
	M. tenuiflora	0	160	507	80	0	1,920	3,547	107
	P. simplicifolium	27	80	133	80	27	507	373	80
	Remaining	560	1,547	2,533	133	773	12,080	10,133	293
	Total clear-cut	**7,173**	**10,613**	**19,520**	**3,360**	**22,613**	**143,067**	**140,640**	**7,973**

We found that clear-cutting was able to increase the number of regenerating species eight years after harvesting, with the number of species increasing from six in the control plots to twenty-three in the clear-cut plots. While some species were an important part of the regeneration stratum, regardless of the area being harvested or not (e.g., *Bauhinia cheilantha*; *Calliandra depauperata*; *Cenostigma microphyllum*), other species regenerated better in clear-cut plots, especially *Croton conduplicatus and Jatropha mollissima*.

As was the case for the inventory data (Table 3), the results from the Sorensen similarity coefficient did not detect any notable dissimilarities of occurrence between the seedlings found in the treatment and control plots, either before harvesting or eight years after (Table 6). However, the similarity coefficient values were lower for the regeneration data than for the inventory data, presenting an overall mean of 0.60 for the former, versus 0.76 for the latter. The mean value of the Sorensen similarity coefficient for the seedlings before harvesting was 0.61, ranging between 0.46 and 0.77. Considering the area after harvesting, the mean value of the Sorensen similarity coefficient remained equal to the one found in the area before harvesting (0.61), ranging from 0.38 to 0.78.

Table 6. Seedling species occurrence similarity as measured by the Sorensen similarity coefficient for the different treatments and control plots, where the values under the dashed line refer to the area before harvesting and the values above the dashed line eight years afterwards.

0 m	-	0.6	0.4	0.8	0.6	0.7
40 m	0.8	-	0.6	0.7	0.5	0.5
60 m	0.7	0.8	-	0.6	0.5	0.6
80 m	0.7	0.6	0.7	-	0.7	0.7
100 m	0.6	0.7	0.5	0.5	-	0.5
Control	0.7	0.5	0.5	0.5	0.5	-
	0 m	**40 m**	**60 m**	**80 m**	**100 m**	**Control**

We found that clear-cutting had an important effect on the origin of the regenerating seedlings and on the number of sprouts per individuals, but not on the overall mean height of the seedlings, with an overall mean of 1 m (Figure 3). Before harvesting, 75% of the seedlings were either originated from root sprouts or from seeds. One year after cutting, almost all seedlings (98%) were coppice sprouts, originating from the stumps of the harvested trees. This value decreased to 73% three years after harvesting and returned to pre-harvesting levels (25%) eight years after clear-cutting. The number of sprouts per individual followed a similar behavior, presenting 3.3 sprouts per individual before harvesting, increasing to 13.9 one year after harvesting, decreasing to 7.6 three years after harvesting, and returning to pre-harvesting levels (3.1 sprouts per individual) eight years after harvesting.

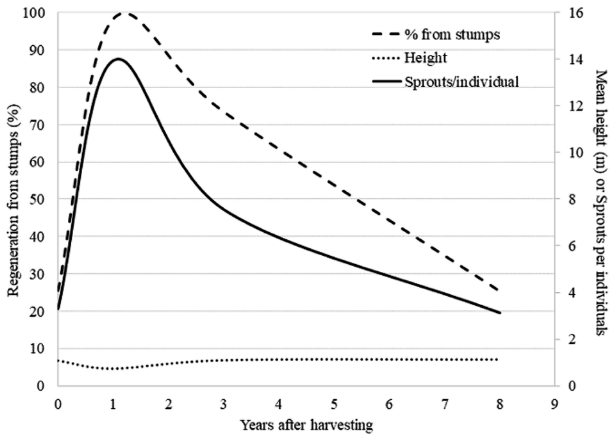

Figure 3. Regeneration dynamics before and up to eight years after clear-cutting, presenting the mean seedling height (dotted line), the number of sprouts per individual (solid line) and the percent of individuals originating from the stumps (dashed line).

DISCUSSION

Limiting the size of the area to be submitted to clear-cut is expected to be an effective way to mitigate the possible negative impacts of this kind of forest exploitation (Boston and Bettinger, 2006). For instance, Gomide et al. (2012) suggest clear-cut in strips as the recommended option for the sustainable management of the Cerrado, also a tropical dry forest. In this case, clear-cut is applied in strips no larger than half the total managed area, alternating between equal sized cut and uncut strips. The authors cite as advantages of this methodology a greater environmental protection from degradation, as well as the possibility of seed dispersal in the cleared area, promoting natural regeneration. Eight years after clear-cut, we found little evidence to suggest that the width of the clear-cut strips influenced the dynamics of the regeneration and forest regrowth of the study area. However, these findings are limited to the distances tested in this study, up to 100 m.

The experimental area is a controlled environment, and thus suffered little human interference 40 years prior to the installation of the experiment. Its vegetation can be described as a typical Caatinga forest, with low volume and basal area per hectare, and a high dominance of a few species concentrated in the smaller diameter classes (Tables 2, 4 and Figure 2). The relative homogeneity between the plots prior to the treatments helps to guarantee that any possible effects of the treatments on the regeneration and forest regrowth of the vegetation were properly ascertained.

Before harvesting, we found that only two species (*Mimosa tenuiflora* and *Cenostigma microphyllum*, both Fabaceae, Table 4) were responsible for 55.8% of the relative dominance of the vegetation. Both are widespread in region and typically present high dominance values wherever they occur (Calixto Júnior and Drumond, 2011; Reis et al., 2022; Souza et al., 2020). According to Calixto Júnior and Drumond (2011) and Santana et al. (2021), *Mimosa* *tenuiflora* occurs in the whole Brazilian Northeast region, as well as in other countries of South and Central America, and can be considered opportunistic and secondary, rapidly establishing itself in anthropized and degraded areas. The concentration of the relative dominance, either in terms of basal area or number of individuals per hectare, in two to five species, is common in the Caatinga vegetation (e.g., Calixto Júnior and Drumond, 2011; Reis et al., 2022). The Shannon Index of 2.48 nats·ind^{-1} found in the area before harvesting can be considered above average for this type of vegetation (Santana et al., 2021), which usually presents values around 2.00 nats·ind^{-1} or lower (Calixto Júnior and Drumond, 2011; Ferraz et al., 2014; Reis et al., 2022; Souza et al., 2020) but can reach values of up to 3.71 (Scolforo et al., 2008a).

Eight years after harvesting, we found that species diversity was significantly lower in the areas submitted to clear-cut when compared with the control plots, presenting a Shannon Index of 1.77 nats·ind^{-1} versus 2.15 nats·ind^{-1}. On the other hand, the similarity of species occurrence did not appear to be affected by the clear-cut treatments (Table 3). Ferreira et al. (2016) and Ferraz et al. (2014), studying forest management in Pernambuco state, found equal diversity between preserved and harvested areas, 30 and 22 years after clear-cut, respectively. So, we expect that the tree species diversity from the clear-cut plots will eventually increase and reach the values found in the control plots. The effect of clear-cut was also observed in the species' relative dominance (Table 4), where *Mimosa tenuiflora* was able to maintain a high importance in both the control and clear-cut plots, but *Cenostigma microphyllum* was restricted to the control plots. In the clear-cut plots, other species were able to reach high relative dominance values, such as *Manihot carthagenensis*, *Cnidoscolus bahianus*, and *Jatropha mollissima*, indicating that these species were able to take advantage of the modified environment. *Schinopsis brasiliensis* also reached high relative dominance values in the clear-cut plots, but this was due in part to the fact that this species is legally protected from cutting (Carvalho, 2008), and so, had not been harvested in 2007.

The sprouting ability of Caatinga tree species is an important factor to the success of its regeneration after clear-cut (Gomide et al., 2012; Lima et al., 2021). Our results show how the regeneration dynamics change over time, with a notable increase in the number of individuals and sprouts up to three years after harvesting, and returning to pre-harvest levels after eight years (Table 5). The seedlings' architecture (expressed as the number of sprouts per individual) and origin (percentage from harvested stumps) also confirm that the regeneration of the harvested area was able to reach values similar to pre-harvest levels after eight years (Figure 3).

Sustainable forest management requires that social, ecological, and economic services that forest ecosystems provide to society be maintained. Economic sustainability requires that the current use of the forests should not compromise future harvest levels, maintaining the forest's capability to generate economic returns (Pukkala, 2021). In this respect, one of the key indicators of forest management sustainability is the ability of the harvested areas to produce wood in a similar fashion to pre-harvest levels. We found a mean basal area of 1.2 m^2·ha^{-1} and wood volume of 4.2 m^3·ha^{-1} eight years after clear-cut, generating growth values of 0.15 m^2·ha^{-1}·year^{-1} and 0.52 m^3·ha^{-1}·year^{-1}, respectively. Discounting the pre-harvest values of *Schinopsis brasiliensis* (uncut tree species) from the values found in 2015, these growth values were adjusted to 0.12 m^2·ha^{-1}·year^{-1} and 0.39 m^3·ha^{-1}·year^{-1} for basal and wood volume, respectively. Considering the mean reference values of the control plots in 2015 (4.4 m^2·ha^{-1} and 19.0 m^3·ha^{-1}), a cutting cycle of 35 years for basal area and 49 years for volume would be needed in order to reach the initial pre-cut values.

Generally, Caatinga forests are managed applying the legally established minimum cutting cycle of 15 years. However, this restriction does not always guarantee sustainability (Lopes et al., 2020; Pareyn et al., 2020). The cutting cycles of 35 to 49 years estimated in our study are in accordance with other studies on hyper xerophytic Caatinga forests, such as Calixto Júnior and Drumond (2011), Ferraz et al. (2014) and Ferreira et al. (2016). These authors reported basal area growth values ranging from 0.11 to 0.24 m^2·ha^{-1}·year^{-1}, from stands 22 to 30 years after clear-cutting. Ferraz et al. (2014) reported that it would require more than 40 years to restore the forest to the original structure. Likewise, Araújo Filho et al. (2018) recommend cutting cycles in semiarid regions to be longer than 30 years, estimated as the time required to recover 50% of soil carbon stocks in forests that had undergone harvesting in the past. Even higher cutting cycles were reported by Scolforo et al. (2008b), who estimated basal area recovery time to be 108 years for Caatinga forests in Minas Gerais, attributing this long period to the low growth rate.

According to Barros et al. (2021), the recovery rate of managed forests can be linked to the speed at which forest attributes reach old-growth forests values and can also be considered a measurement of resilience. In this study we calculated the recovery rates using as reference the values of the control plots in 2015 (19.0 m^3·ha^{-1}) instead of the ones found in the pre-harvest inventory (32.7 m^3·ha^{-1}). A reduction of about 40% was detected in the volume and basal area values of the control plots between 2007 and 2015. This reduction in the stand parameters occurred mostly because of stem mortality, and not by individual tree death (Table 2, Figure 2). This was probably caused by the rainfall pattern during the study period. Mean annual precipitation from 1991 to 2020 in the area is 419 mm·year^{-1} (Instituto Nacional de Meteorologia, 2022). According to data provided by Embrapa Semiárido (http://www.embrapa.br/semiarido), during the first three years after harvesting, there was higher than average annual precipitation (627 mm·year^{-1}). However, the period between 2011 and 2015 was extremely dry, with annual rainfall around 255 mm. The effect of rainfall on expected recovery rates has been studied by Pareyn et al. (2020), who estimated that in regions with annual rainfall of 419 mm·year^{-1} (i.e., the climate normal in the area) forest growth rates are estimated at 0.89 m^3·ha^{-1}·year^{-1}, about twice the observed values in this study (0.39 m^3·ha^{-1}·year^{-1}). Growth value of managed Caatinga forests present large variation between sites, ranging from 0.3 to 11.0 m^3/ha/year (Pareyn et al., 2022). Therefore, we expect that the recovery rates computed here (35 to 49 years) can be shortened in case rainfall returns to average historical patterns.

CONCLUSIONS

Eight years after exploitation, tree species occurrence was similar in clear-cut and control plots, but with lower diversity values for clear-cut plots. The expected recovery times of stand parameters in the clear-cut areas to return to unharvested levels was estimated at occurring between 35 to 49 years. The width of the clear-cut strip (0 to 100 m) did not influence the regeneration and forest regrowth capacity of the harvested areas. We suggest that monitoring of the experimental area continues in order to evaluate the growth trends over time, especially if rainfall patterns return to historical average precipitation values.

AUTHORSHIP CONTRIBUTION

Project Idea: VRO, FGCP

Funding: VRO, FGCP

Database: VRO, AR, FGCP, MAD, DDP, LHPK, ACFF

Processing: VRO, AR, FGCP, ACFF

Analysis: AR, FGCP, ACFF

Writing: VRO, AR, FGCP, ACFF

Review: VRO, AR, FGCP, MAD, DDP, LHPK, ACFF

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