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Scientific Article

Survival and growth of planted and naturally established trees in a degraded caatinga area

Sobrevivência e crescimento de mudas de árvores plantadas e estabelecimento natural em uma área de caatinga degradada

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ABSTRACT - The Semiarid region in the Northeast of Brazil is characterized by Caatinga tropical forests, adapted to 8-to-9 months of annual water stress. Human activities have resulted in environmental degradation due to tree removal and soil exposure to erosion factors; however, planting native trees, such as *Mimosa tenuiflora* and *Cnidoscolus quercifolius*, may accelerate environmental recovery. Tree recovery was evaluated in a degraded areas under a 14-year period of grazing exclusion (2005 to 2019) and planting of *M. tenuiflora* (2005 and 2009) and *C. quercifolius* (2007 and 2009) and under natural regeneration. Data on survival, height, and diameter of planted seedlings, and the number, species, height, and diameter of naturally regenerating trees were collected. The absence of grazing allowed for the establishment of 50.5% and 44.6% of the 204 *M. tenuiflora* and 204 *C. quercifolius* planted seedlings, which presented mean heights of 395 and 355 cm and mean basal diameters of 92 and 76 mm. Naturally regenerated *M. tenuiflora* and *C. quercifolius* totaled 190 and 7 plants, with heights of 95 and 139 cm, and basal diameters of 10 and 26 mm. A naturally established specimen of *Cenostigma pyramidale* with a height of 175 cm and basal diameter of 36 mm was found. This denotes the positive effect of seedling planting on tree cove compared to a nearby continuously grazed area; however, full recovery, especially regarding diversity of the tree community, requires more than 14-year grazing exclusion, tree planting, and natural regeneration.

Keywords: Tropical dry forest. Site recovery. Seedling planting.

RESUMO - A região semiárida do nordeste do Brasil é caracterizada pela floresta tropical Caatinga adaptada a déficit hídrico anual de 7-a-8 meses. As atividades humanas degradam o ambiente pela remoção das árvores e exposição do solo aos agentes erosivos; porém o plantio de árvores nativas, tais como *Mimosa tenuiflora* e *Cnidoscolus quercifolius*, pode acelerar a recuperação ambiental. A recuperação arbórea de uma área degradada foi avaliada considerando 14 anos sem pastejo (de 2005 a 2019), o plantio de *M. tenuiflora* (2005 e 2009) e *C. quercifolius* (2007 e 2009), e a regeneração natural. Foram coletados dados de sobrevivência, altura e diâmetro das mudas plantadas, e a quantidade, espécie, altura e diâmetro dos regenerantes. A ausência do pastejo permitiu o estabelecimento de, respectivamente, 50,5% e 44,6% das 204 *M. tenuiflora* e das 204 de *C. quercifolius*, com médias altura de 395 e 355 cm, e de diâmetro basal de 92 e 76 mm. Foram observados 190 e sete regenerantes de *M. tenuiflora* e *C. quercifolius*, com média de 95 cm e 139 cm de altura, e de 10 mm e 26 mm de diâmetro basal. Foi observado um regenerante de *Cenostigma pyramidale*, com altura de 175 cm e diâmetro basal de 36 mm. Isto mostrou o efeito positivo do plantio de mudas na cobertura arbórea comparada ao cenário ainda observado na área adjacente pastejada continuamente, mas a recuperação completa, especialmente quanto à diversidade da comunidade arbórea, precisa de mais do que 14 anos sem pastejo, plantio de mudas e regeneração natural.

Palavras-chave: Floresta tropical seca. Recuperação de área. Plantio de mudas.

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INTRODUCTION

Caatinga is a tropical biome exclusive to the Northeast region of Brazil, covering 844.453 km^2 across the states of Bahia, Alagoas, Ceará, Pernambuco, Paraíba, Rio Grande do Norte, Piaui, Sergipe, and Minas Gerais (MMA, 2018). It shelters a diverse flora and fauna (MMA, 2018) adapted to a 7-to-8-month annual period of water deficit (DRUMOND et al., 2004). Most of its perennial plants shed their leaves in the dry season, developing exuberant green leaves after the first rains, contrasting to the grayish leafless vegetation during this season; this helps them to withstand adverse environmental conditions, along with bromeliads and cacti that contribute to the local characteristic vegetation (GOMES et al., 2021).

The main economic activities in this region are based on the extraction of minerals and forest products, ranching, and small-scale food crops, such as beans and corn (SOUSA et al., 2016). These activities degrade the environment by removing forest cover and exposing the soil to the direct effects of winds, torrential rains, and solar radiation, resulting in reductions in soil productive capacity and biodiversity loss in ecosystems (SILVEIRA et al., 2015; SOUSA et al., 2016; RABELO, 2017).

Environmental recovery should consider soil properties and the planting of native trees capable of successfully establishing in degraded areas (LIMA et al., 2015a), such as *Mimosa tenuiflora* (Willd.) Poiret, a nitrogen-fixing Fabaceae, and *Cnidoscolus quercifolius* Pohl, a latex-producing Euphorbiaceae (BAKKE et al., 2018a,b; CORDÃO et al., 2016; FREIRES et al., 2020; NUNES, 2012; FIGUEIREDO et al., 2012). According to these studies, these trees protect themselves from herbivory by developing branches with sharp aculeus (*M. tenuiflora*) or leaves and fruits with stinging hairs (*C. quercifolius*); they produce high-calorific woody biomass (*M. tenuiflora*), nutritious forage for ruminants (fresh leaves, thin branches, and mature fruits of *M. tenuiflora;* or senescent leaves, thin branches after chopping and dehydration, and seeds after explosive release from fruits of *C. quercifolius*), and other products such as medicinal extracts from tissues of both species and edible seeds of *C. quercifolius*.

Mimosa tenuiflora and *C. quercifolius* produce abundant seeds and predominate in several inhospitable areas of the Caatinga biome, although the seedling establishment rate can be significantly low in degraded areas (AZEVEDO, et al., 2012; BAKKE et al., 2018a,b; SALES, et al., 2019). However, relatively high rates (approximately 50%) of seed germination and seedling establishment have been reported for *M. tenuiflora* and *C. quercifolius* (BAKKE et al., 2018a,b; FIGUEIREDO et al., 2012; NUNES, 2012; APNE, 2008) by planting seedlings in holes of 30×30×30 cm or wider in soils fertilized by manure or mineral fertilizer applications, indicating that these species respond well to silvicultural practices.

Tree planting can rapidly reestablish trees in degraded areas and minimize soil erosion by water and wind, as established trees increase soil organic matter contents and transport nutrients to upper soil layers, among other benefits, improving soil attributes and recovering sites degraded by agriculture, livestock, mining, and dam construction (LIMA et al., 2015a; MARTINS et al., 2022). This indicates that tree planting in degraded areas may improve the reestablishment and growth of planted seedlings compared to naturally regenerating trees.

Therefore, the objective of this study was to assess the recovery of tree community after 14 years of animal grazing exclusion, by planting *Mimosa tenuiflora* and *Cnidoscolus quercifolius* in the initial four years, in a Caatinga area degraded by recurrent extraction of firewood and continuous cattle grazing for approximately 40 years.

MATERIAL AND METHODS

Field data were collected at the NUPEARIDO Experimental Farm of the Universidade Federal de Campina Grande (07°04'53"S, 37°16'11"W, and 254 meters of altitude), in Patos, Paraiba, Brazil. According to the Köppen classification, the regional climate is BShw, hot and dry, with a high mean annual air temperature (25 °C) and a wide range of annual rainfall depth (300 to 1,500 mm, averaging 700 mm), mostly concentrated in the first five months of the year, irregularly distributed in time and space (ALVARES et al., 2013).

The study site (60 × 70 m) at the experimental farm was in an area where trees were recurrently cut for firewood and had been continuously grazed by cattle, sheep, and goats for approximately 40 years, resulting in eroded soils and incipient regeneration of herbs and shrubs, with no tree recruitment, despite the presence of two adult *M. tenuilfora* and two adult *Neltuma juliflora* (Sw.) Raf. A barbed wire fence was installed around this area in 2005, and no animal has been allowed to graze since then, except for an accidental sheep grazing in August 2006, as reported by Sales et al. (2019). Trees, such as *Sarcomphalus joazeiro* (Mart.) Hauenschild, *Tabebuia aurea* (Silva Manso) Benth. & Hook.f. ex S.Moore, *Piptadenia retusa* (Jacq.) P.G. Ribeiro, Seigler & Ebinger, and *Parkinsonia aculeata* L., were sparsely distributed within a 500-meter radius from the area (SALES et al., 2019).

Sales et al. (2019) and Figueiredo et al. (2012) conducted experiments in this degraded area to assess the survival rate, height, and diameter of some tree species, starting in February or March of several years after planting *M. tenuiflora* and *Cenostigma pyramidale* (Tul.) Gagnon & G.P. Lewis in 2005, *C. quercifolius* in 2007, and *M. tenuiflora*, *C. quercifolius*, and *C. pyramidale* in 2009. *M. tenuiflora*, *C. quercifolius*, and *C. pyramidale* trees were planted, using 204, 204, and 90 seedlings, respectively, to restore the tree cover in experimental plots of 6 × 6 m or 12 × 12 m; however, all 90 seedlings of *C. pyramidale* perished within one year after planting (FIGUEIREDO et al., 2012; SALES et al., 2019). Nunes (2012) extended the analysis of the experiment by Figueiredo et al. (2012) until July 2011. Data collection was resumed in 2018; thus, data collected from 2005 to 2019 were analyzed. In 2019, the age of the planted *M. tenuiflora* ranged from 10 to 14 years, while the age of planted *C. quercifolius* ranged from 10 to 12 years.

The soil texture in the experimental area was classified as loamy sand and its chemical and physical properties, according to Sales (2008) and Figueiredo et al. (2012), are shown in Table 1.

Table 1. Chemical and physical properties and textural classification of the soil of the study area at the NUPEARIDO Experimental Farm, Patos, PB, Brazil.

	Chemical properties									
Reference	pH $CaCl_2$ 0.01M	P µg cm^{-3}	K^+	Na^+	H^+Al^{+3}	Ca^+	Mg^{+2}	SB	CEC	BS (%)
			$cmol_c$ dm^{-3}							
*	5.40	14.61	0.29	0.70	1.60	3.10	1.20	5.29	6.89	76.76

	Physical properties			
Reference	Sand	Silt	Clay	Textural Class – USDA
	g kg^{-1}			
**	820	112	68	Loamy sand

Adapted from *Sales (2008) and **Figueiredo et al. (2012). SB = sum of bases; CEC = cation exchange capacity; BS = base saturation; USDA = United States Department of Agriculture.

The seedlings in the experiment conducted by Sales et al. (2019) were planted in a 3 × 3 m grid in planting holes of 30 × 30 × 30 cm, whose soil was fertilized with a 5-liter mixture of sheep and goat manure. The seedlings in the experiment conducted by Figueiredo et al. (2012) were planted with a spacing of 2 × 2 m in planting holes of 40 × 40 × 40 cm, whose soil was fertilized with 20 L of goat manure, 16 g of simple superphosphate (2.88 g of P_2O_5) and 4.3 g of KCl (2.58 g of K_2O).

Survival, height, and basal diameter of planted *M. tenuiflora* and *C. quercifolius* trees were assessed based on data collected by Sales et al. (2019), Figueiredo et al. (2012), and Nunes (2012), and data collected in 2018 and 2019, totaling a 14-year data collection. Recruiting trees of each species were counted and measured (height and diameter) for determining the qualitative and quantitative potential of natural regeneration of tree species in degraded Caatinga areas protected from grazing.

The survival of planted seedlings was calculated for each species by dividing the number of surviving plants in June 2019 by the total number of seedlings planted in 2005, 2007, and 2009 (SALES et al., 2019; FIGUEIREDO et al., 2012). Surviving seedlings were those exhibiting any visible living structure above the ground in June 2019. Survival rates between species were not compared.

Tree height was measured with a graded rod: precision was 1 cm in measurements conducted by Sales et al. (2019), Figueiredo et al. (2012), and Nunes (2012), whereas the precision was 5 cm in measurements taken in 2018 and 2019. Height refers to the length of the longest branch of each plant.

Basal diameter (5 cm above the soil surface) was measured with a digital caliper, with a precision of 0.01 mm by Sales et al. (2019), Figueiredo et al. (2012), and Nunes (2012), whereas measurements taken in 2018 and 2019 were indirectly estimated using a measuring tape (1 cm precision) to determine basal circumference (cm); the circumference results were divided by π = 3.1416.

Plants with "I" bifurcations (I = number of bifurcations ≥ 1) at the base in 2018 and 2019 had the "I" circumferences measured, and the respective basal diameters (di) were calculated. These values were used to calculate the equivalent diameter (Deq) of each plant, following the recommendation of Soares, Paula Neto, and Souza (2006), according to Equation 1:

$$D_{eq} = \sqrt{\sum_1^I d_i^2} \quad (1)$$

Height (cm) and basal diameter (mm) data of naturally established trees within the fenced area were collected, including those eventually observed in the experimental plots. These unplanted specimens were classified into 4 classes (I, II, III, and IV) of height (H) and basal diameter (BD), based on the data collected in 2019 (Table 2).

Table 2. Class intervals for height and basal diameter of recruiting trees in the study area.

Class	Class intervals	
	Height (cm)	Basal diameter (mm)
I	$30 < H_I \leq 50$	$1 < BD_I \leq 11$
II	$50 < H_{II} \leq 100$	$11 < BD_{II} \leq 21$
III	$100 < H_{III} \leq 150$	$21 < BD_{III} \leq 31$
IV	$150 < H_{IV} \leq 200$	$31 < BD_{IV} \leq 41$

Absolute density (DAi) and relative density (DRi) of naturally established trees of each species were estimated. DAi is the quotient between the number (Ni) of recruiting trees of the i-th species and the total sampled area in hectares (A) (i.e. $DA_i = \frac{N_i}{A}$); DRi is the ratio between the number (Ni) of naturally established trees of the i-th species multiplied by 100 and the total number (TN) of naturally established trees of all species (or equivalently $DR_i = \frac{DA_i * 100}{DT}$, considering $DT = (\sum_1^I N_i / A)$ = total density) (MUELLER-DOMBOIS, ELLEMBERG, 1974).

The height (cm) and basal diameter (mm) dependent variables Y of planted *M. tenuiflora* and *C. quercifolius* were related to age (X = months after planting), considering September 2004 as X = 0 for the data collected by Sales et al. (2019), and September 2008 as X = 0 for data collected by Figueiredo et al. (2012). Regression analysis was carried out for data collected between 2006 and 2011 (SALES et al., 2019; FIGUEIREDO et al., 2012; NUNES, 2012) and those collected in the present study (December 2018 and June 2019). Polynomial regression models were chosen by the General Stepwise Regression module, Best subset subroutine of the Statistica 5.0 software package, considering a 5% significance level. Heteroscedasticity was detected and, thus, the data were log-transformed before estimating regression parameters.

RESULTS AND DISCUSSION

Considering the data collected in 2019, the survival rates for *Mimosa tenuiflora* and *Cnidoscolus quercifolius* were 50.5% and 44.6%, respectively, corresponding to 103 10-to-14-year-old plants of *M. tenuiflora* and 91 10-to-12-year-old plants of *C. quercifolius* that remained alive in June 2019. These surviving trees withstood the adverse conditions of the degraded area without any post-planting treatment other than protection from grazing and a weed control treatment around each planting hole carried out in the middle of the first growing season after planting the seedlings.

These low survival percentages denote the challenges for tree establishment in degraded Caatinga areas. However, they also denote a relative success in revegetating degraded areas when considering the number of recruiting trees, as will be discussed below.

Annual rainfall depths ranged from 169.8 mm in 2012 to 1,595 mm in 2009 (Table 3). Probably, mortality was lower in years with higher rainfall depths and higher in drier years, especially in consecutive dry years.

Table 3. Annual and monthly cumulative rainfall depths (mm) from 2005 to 2019 at the NUPEARIDO Experimental Farm, Patos, PB, Brazil.

Year	Cumulative rainfall depth												
	Annual	Monthly											
		Jan.	Feb.	Mar.	April	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
2005	771.3	27.8	68.3	384.3	47.5	20.7	40.1	0.0	2.5	0.0	0.0	0.0	180.1
2006	867.5	0.0	168.8	244.1	202.4	128.8	23.4	0.2	0.0	0.0	15.3	1.3	83.2
2007	594.2	16.6	264.7	50.1	112.5	43.1	8.3	2.9	1.2	0.0	0.0	0.0	94.8
2008	1365.7	27.4	227.1	491.6	216.9	187.4	14.0	15.6	2.2	3.7	0.0	0.0	179.8
2009	1595.0	96.0	177.0	304.0	620.0	273.0	35.0	14.0	31.0	0.0	15.0	11.0	19.0
2010	363.8	82.0	46.2	25.4	26.2	0.4	43.2	1.2	0.4	0.0	44.4	1.2	93.2
2011	851.4	270.7	119.0	118.5	116.8	137.2	8.0	32.4	2.8	0.0	19.2	26.8	0.0
2012	169.8	21.2	103.2	17.2	3.2	4.8	18.4	1.8	0.0	0.0	0.0	0.0	0.0
2013	394.0	108.0	2.4	30.0	0.6	6.2	87.8	11.6	0.2	0.0	0.0	26.2	121.0
2014	849.4	16.8	55.8	428.4	123.4	108.2	9.4	6.0	6.4	1.6	13.0	19.8	60.6
2015	499.1	23.9	174.1	148.0	117.2	3.7	5.9	14.1	3.2	0.0	0.0	0.0	9.0
2016	528.0	142.5	83.0	214.7	50.6	22.2	13.6	0.0	0.2	0.0	0.0	0.0	1.2
2017	490.2	41.8	136.2	136.0	118.4	22.4	19.8	10.6	0.0	0.0	0.0	2.6	2.4
2018	543.4	59.8	127.2	88.6	187.0	23.2	1.2	0.0	0.0	0.0	4.4	12.6	39.4
2019	661.3	128.4	198.2	126.5	116.7	70.7	4.0	16.8	-	-	-	-	-
Mean	702.9	70.9	130.1	187.2	137.3	70.1	22.1	8.5	3.6	0.4	8.0	7.3	63.1

Source: INMET (2019).

These results are confirmed when correlating annual rainfall data with number of dead trees per year (Table 4): cumulative rainfall depth in 2010 was low (363.8 mm), and number of dead individuals was high (37; 9 *M. tenuiflora* and 28 *C. quercifolius*). No annual mortality data were collected between 2012 and 2018; however, 40 out of the total 101 dead *M. tenuiflora* (approximately 40% of the total mortality) and 71 out of the total 113 dead *C. quercifolius* (approximately 63% of the total mortality) were recorded in this period, despite the expected increased resistance of plants compared to the initial years of seedling development.

Table 4. Annual number of dead trees of *Mimosa tenuiflora* and *Cnidoscolus quercifolius* from 2005 to 2019.

Year	*Mimosa tenuiflora*	*Cnidoscolus quercifolius*
2006	14	-
2007	9	-
2008	23	0
2009	5	9
2010	9	28
2011	1	5
2012 to July 2018	40	71
July 2018 to July 2019	0	0
Total number of dead trees in the period	101	113

The high mortality of developed plants of both species from 2012 to 2018 may be attributed to low annual rainfall depths (< 400 mm) in 2012 and 2013 (Table 3). This is consistent with the mortality found between July 2018 and July 2019 (zero), when annual rainfall depths exceeded 543 mm. These results denote a significant impact of years with low rainfall (2010, 2012, and 2013) on the survival of 1-to-6-year-old plants in degraded areas.

Additionally, the annual rainfall is concentrated in 3 to 4 months, with little or no rainfall during 8 to 9 months (Table 3). Therefore, the effects of water deficit on plant survival were more pronounced during years with rainfall depths bellow 400 mm, such as in 2012. In these years, monthly total rainfall depths were low, generally 0 to 20 mm, even during the supposedly rainy season (January to May), which was particularly stressful for plants when occurring in two consecutive years, as in 2012 and 2013. Furthermore, water deficit was aggravated by other climate factors, such as average temperatures above 25 °C and 2,800 hours of solar radiation per year, as well as topographic-edaphic factors, such as undulating relief and shallow soils, that increase evapotranspiration rates and water deficit (LIMA, 1996).

The mortality of *M. tenuiflora* plants found from 2012 to July 2018 may also be attributed to the pruning of thin branches (Ø < 1 cm) carried out by Nunes (2012) on 80 plants in 2011, which was a year with a rainfall depth of 851.4 mm (Table 3). According to this author, pruning is carried out to promote the development of the herbaceous stratum and estimate tree forage production; the data collected by this author revealed that plants died after pruning, accounting for 87.5% of the mortality found for *M. tenuiflora* plants after 2011 (35 out of 40) and 34.7 % of the total mortality (35 out of 101).

Pruning of thin branches may significantly stress *M. tenuiflora* plants, probably because the recovery of their reserves depends on the rainfall depth in the following year or years, which is difficult to predict in the region. Annual rainfall depths in the years following pruning, 169.8 and 394,0 mm in 2012 and 2013, respectively, were not sufficient for the plants to recover reserves, resulting in a high mortality rate for pruned plants. Tree mortality may also have been affected by accidental sheep grazing in the area in August 2006, which caused significant damages to many seedlings of this species, as reported by Sales et al. (2019). This partially explains the mortality of this species after 2006, despite the significant rainfall depths in the two subsequent years: 594.2 mm in 2007 and 1,365.7 mm in 2008 (Table 3). Further studies should be conducted to identify an adequate pruning or grazing intensity for *M. tenuiflora* and other Caatinga trees.

Relatively few studies on survival rate of native trees planted in degraded Caatinga areas have been published. According to Medeiros and Aloufa (2015), 87% of *C. quercifolius* seedlings survived for up to 60 months in an area affected by extensive grazing but without cutting and burning of vegetation for 60 years. Lima et al. (2015b) reported survival rates of 20.5%, 36.9%, 48.8%, 51.2%, 55.5%, and 82.2% for *Hymenaea courbaril* L., *Anadenanthera colubrina* (Vell.) Brenan, *C. pyramidale*, *Libidibia ferrea* (Mart. ex Tul.) L.P. Queiroz, *Schinopsis brasiliensis* Engl., and *Myracrodruon urundeuva* (Allem.), respectively. These rates refer to 12 months after seedling planting in fertilized planting holes in a degraded Caatinga area in a region with annual rainfall depths of 700 to 850 mm. The comparison of these survival data (20.5% to 87.0% survival from 12 to 60 months after planting) with those obtained in the present study (45% to 50% from 10 to 14 years after planting) indicates that planting seedlings in holes fertilized with manure and soil fertilizers and delaying grazing (SALES et al., 2019; FIGUEIREDO et al., 2012) provided similar or higher long-term survival rates compared to those reported for several Caatinga trees planted in areas with higher annual rainfall depths, potentially accelerating the revegetation process in degraded areas.

The height of planted *M. tenuiflora* and *C. quercifolius* increased significantly up to 14 and 12 years after planting, according to second-degree polynomial models (Figures 1A and 1B), with $R^2 \geq 55\%$. This is highlighted by height values with no logarithmic transformation in Figures 1C and 1D. Increases in height were relatively higher in the initial development phase in the field, probably due to adequate soil moisture contents and nutrient availability resulting from annual precipitation ≥ 594 mm from 2005 to 2009 (Table 3) and the manure and soil fertilizers applied to the planting holes.

The results indicated a growth stabilization in height for both species (Figure 1). The decrease in height of *C. quercifolius* plants (Figure 1D) at the end of the study period may be due to relatively less favorable initial environmental conditions for some *C. quercifolius* seedlings at planting. Analysis of the adopted protocols showed that the seedlings described in Sales et al. (2019) were older than those planted by Figueiredo et al. (2012), as they were planted earlier and in smaller planting holes (30 × 30 × 30 cm vs. 40 × 40 × 40 cm) that received less manure (5 L vs. 20 L) and chemical fertilizers (no fertilizer vs. 2.88 g of P_2O_5 and 2.58 g of K_2O). This denotes the possibility of including and testing additional independent variables in the regression model, such as planting hole dimensions and the amount of manure and soil fertilizers applied to planting holes, to estimate the height of *C. quercifolius* plants.

The pattern observed in plant height for *C. quercifolius* was similar for basal diameter of both species (Figure 2): faster initial increases and sustained growth until 13 years after planting in the degraded area, although with decreasing rates and lower diameters at the end of the study period. This pattern is consistent with that discussed for the apparent decrease in height of *C. quercifolius* trees.

A sequence of rapid initial growth, decrease, and resumption of growth in height and basal diameter was reported by Nunes (2012), who attributed this pattern to effects of a dry season between two rainy seasons; thus, the collected data fitted cubic regression models. However, when considering the perspective of an age range from 4 to 159 months, the collected data fitted second-degree polynomial models, with $R^2 \geq 67\%$.

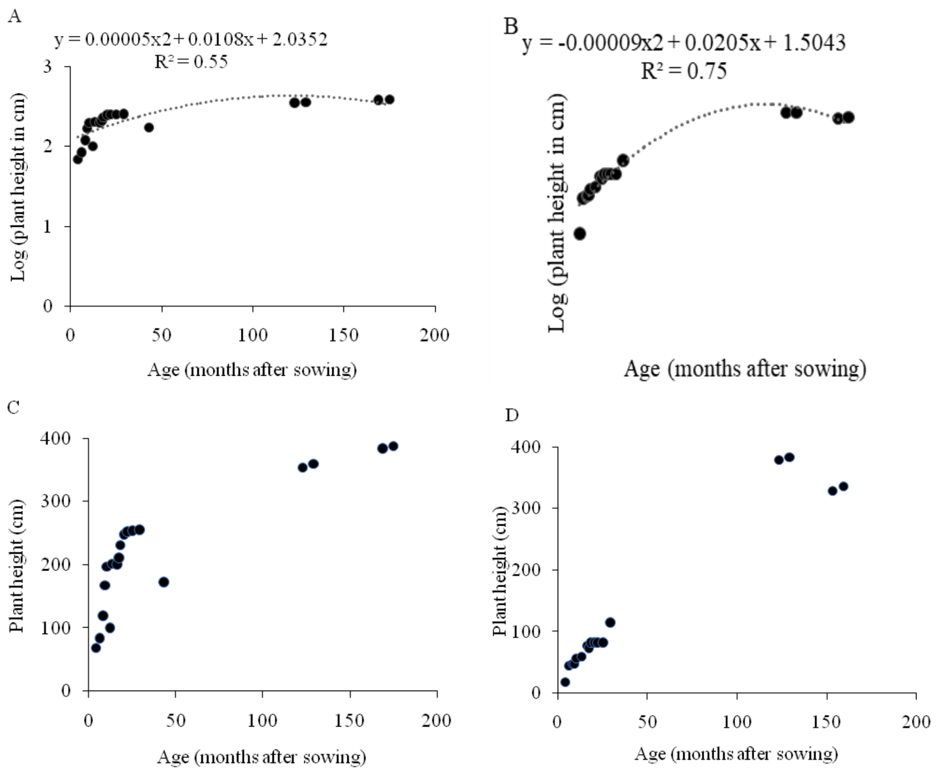

Figure 1. Estimated coefficients of determination (R^2) and regression equations correlating the height logarithm with plant age for *Mimosa tenuiflora* (A) and *Cnidoscolus quercifolius* (B) trees, and height × age relations (C and D, respectively) with no log transformation, in a degraded Caatinga area, Patos, PB, Brazil.

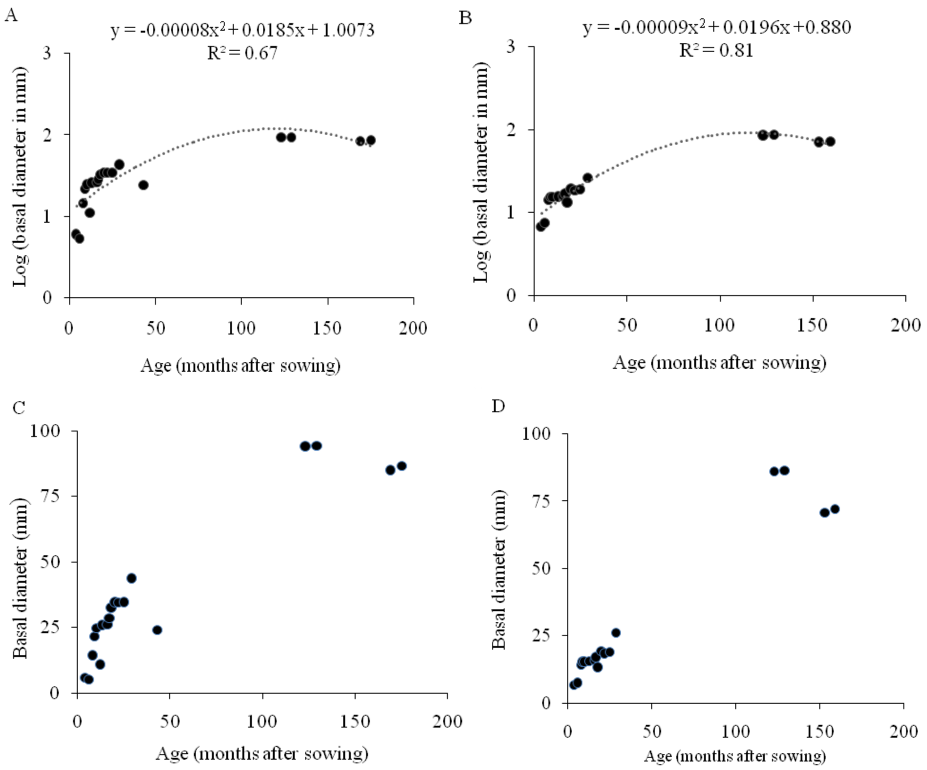

Figure 2. Estimated coefficients of determination (R^2) and regression equations correlating basal diameter with plant age for *Mimosa tenuiflora* (A and C, with and without log transformation, respectively) and *Cnidoscolus quercifolius* (B and D, with and without log transformation) in a degraded Caatinga area, Patos, PB, Brazil.

Variability in height and basal diameter data often differs between species and affects the explanatory power of regression models. The R^2 values associated with the estimated regression equations for *M. tenuiflora* were lower than those estimated for *C. quercifolius*: $R^2 = 0.55$ and $R^2 = 0.75$ for height, and $R^2 = 0.67$ and $R^2 = 0.81$ for basal diameter, respectively. This indicates a greater variability for *M. tenuiflora* than for *C. quercifolius*. However, part of the variability in *M. tenuiflora* data can be explained by the accidental sheep grazing in the area in August 2006 and the pruning of thin branches in May 2011. Considering the high palatability of thin branches of *M. tenuiflora* and the toxicity and presence of stinging hairs on leaves and thin branches of *C. quercifolius*, the accidental grazing negatively and minimally affected *M. tenuiflora* and *C. quercifolius*. Additionally, pruning was carried out on some *M. tenuiflora* plants (80 plants), whereas no *C. quercifolius* plants were subjected to pruning. Thus, the combined effect of grazing and pruning disproportionately increased data variability, experimental error, and explanatory power of the estimated regression equations for *M. tenuiflora*.

These species appear to withstand adverse conditions in degraded Caatinga areas with low rainfall depths, accidental grazing, and pruning. In July 2019, surviving *M. tenuiflora* plants presented mean height and basal diameter of 393.8 cm and 92.0 mm, respectively, while surviving *C. quercifolius* plants had means of 354.7 cm and 76.4 mm, respectively.

Pure stands of 36-month-old *M. tenuiflora* plants grown under similar environmental conditions and subjected to annual pruning of thin branches had mean heights and basal diameters of 127 and 107 cm and 33 and 29 mm for thorny and thornless plants, respectively (BAKKE et al., 2007). Thorny *M. tenuiflora* plants grown in a non-degraded area with deep soil, planted in grids varying from 1.5 × 3 m to 3 × 3 m, in Limoeiro do Norte, Ceara, Brazil, showed mean heights of 320, 360, and 420 cm at 36, 48, and 60 months of age, respectively (APNE, 2008). The better environmental conditions in Limoeiro do Norte may explain the mean heights equal to or greater than 360 cm in plants aged 36 to 60 months. Contrastingly, the performance of *M. tenuiflora* plants in the degraded area evaluated in the present study indicates the ability of this species to develop reasonably well in inhospitable locations of the biome in response to silvicultural treatments, such as planting holes subjected to application of manure combined or not with chemical fertilizers.

C. quercifolius responded relatively well to cultural treatments. According to the regression model, the estimated mean height for 60-month-old plants of this species was 257.2 cm (Figure 1). Medeiros and Aloufa (2015) reported a mean height of 55 cm for plants of the same age in São José do Serido, Rio Grande do Norte, Brazil, which had been planted in 2009; they attributed this performance to low annual rainfall depths in 2012 and 2013 (112 and 234 mm, respectively). These rainfall depths were lower than those in Patos, Paraiba, in those years (169 and 394 mm, respectively) (Table 3); however, other factors may have promoted plant growth, such as soil fertilization by applying manure and soil fertilizers to planting holes, which was not carried out in the study by Medeiros and Aloufa (2015).

The study area exhibited no trees in 2005, except for two *M. tenuiflora* and two *Neltuma juliflora*, along with some *Sida cordifolia* L. shrubs. No tree recruitment was found, and the herbaceous stratum was incipient or absent in parts of the area due to overgrazing and soil erosion (SALES et al., 2019).

In 2019, after 14 years of grazing deferment (2005 to 2019) and planting of *M. tenuiflora* (2005 and 2009) and *C. quercifolius* (2007) seedlings, established trees originated from seeds were found in the 60 m x 70 m study site: 190 *M. tenuiflora*, 7 *C. quercifolius,* and one *C. pyramidale* (Table 5). This indicates that the planted *M. tenuiflora* and *C. quercifolius* seedlings developed, dispersed propagules, and improved the soil seed bank. Contrastingly, the presence of only one regenerating specimen of *C. pyramidale* denotes limitations in seed dispersal by the trees surrounding the study area and the difficulty in tree establishment in degraded Caatinga areas. Birds and rodents eventually attracted to the area due to the development of planted seedlings and the action of winds may have contributed to the seed bank with propagules from surrounding trees, such as *Sarcomphalus joazeiro* and *Libidibia ferrea*. However, improvement in the soil seed bank from external sources proved to be practically insufficient for the establishment of a significant number of tree species other than those already thriving and producing seeds in the area.

Table 5. Number (N_i) of naturally established trees and their respective absolute density (DA) and relative density (DR) in the study area at the NUPEARIDO Experimental Farm, Patos, PB, Brazil.

Specie	N_i	DA (plant ha^{-1})	DR(%)
Mimosa tenuiflora	190	452.381	96.0
Cnidoscolus quercifolius	7	16.667	3.5
Cenostigma pyramidale	1	2.381	0.5
Total	198	471.429	100.0

Low species richness in tree recruitment was previously reported by Andrade et al. (2005) in an area degraded by overgrazing in Sao Joao do Cariri, Paraiba, after 30 years of recovery, with identification of four families and six species. Species richness in tree recruitment can also be low in anthropized Caatinga areas. Holanda et al. (2015) reported six tree species in an area that had been subjected to clear-cutting for firewood extraction and slash-and-burn agriculture, and two years of sheep grazing, after 10 years of regeneration. Andrade et al. (2005) found 12 woody species from 8 families after a 50-year regeneration period. Similarly, Fernandes, Oliveira, and Fernandes (2017) reported 12 species from 8 families in a degraded area in Gilbues, Piaui, Brazil, although without information on regeneration time.

These values are low compared to the tree species richness in more preserved Caatinga areas: 21 tree species from 11 families were reported for the Reserva Particular do Patrimônio Natural (RPPN) at Fazenda Tamandua in Santa Terezinha, Paraiba (GUEDES et al., 2012), whereas 22 tree species from 12 families were identified at the Estaçao Ecologica do Serido, in Serra Negra do Norte, Rio Grande do Norte (SANTANA; SOUTO, 2006).

The dominance of *M. tenuiflora* in the naturally established tree community indicates its pioneer characteristic and ability to colonize degraded Caatinga areas. A total of approximately 6,700 species of the family Fabaceae are widespread in Brazil due to, among other factors, the production of a high number of tiny seeds and, especially, the rapid growth of the root system in the first months after germination (AZEVEDO et al., 2012). According to Pereira et al. (2001), anthropized environments tend to have many plants of few species, which gradually give way to other species and a more qualitatively balanced plant community along with area recovery.

The 198 naturally established plants of the three tree species found were distributed into four height classes: 28 in Class I (30 < $H_I \leq$ 50 cm), 78 in Class II (50 < $H_{II} \leq$ 100 cm), 77 in Class III (100 cm < $H_{III} \leq$ 150 cm), and 15 in Class IV (150 < $H_{IV} \leq$ 150 cm) (Figure 3). *M. tenuiflora* was distributed across all classes and *C. quercifolius* in Classes II, III and IV, while *C. pyramidale* was distributed only in Class IV.

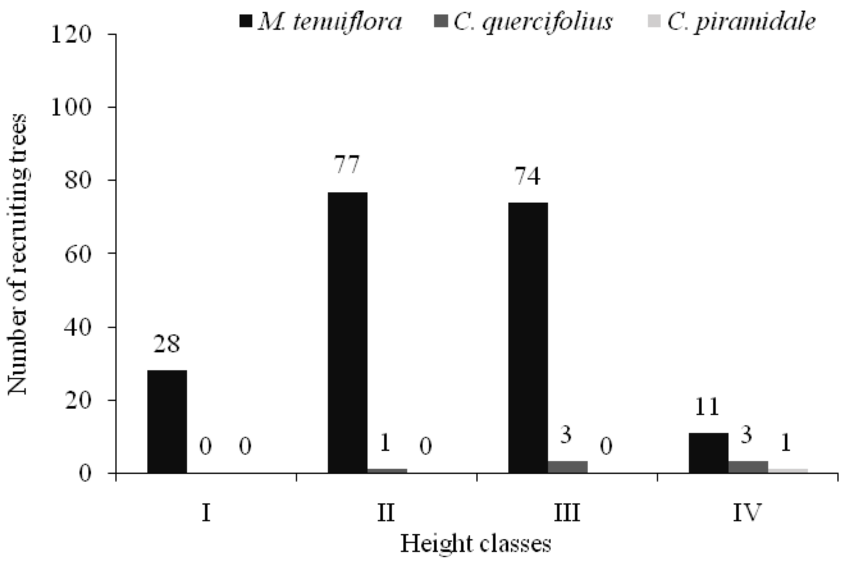

Figure 3. Distribution, in height classes, of naturally established trees in a degraded Caatinga area after 14 years of grazing exclusion: Class I (30 < $H_I \leq$ 50 cm), Class II (50 < $H_{II} \leq$ 100 cm), Class III (100 cm < $H_{III} \leq$ 150 cm), and Class IV (150 < $H_{IV} \leq$ 150 cm). Patos, PB, Brazil.

The 190 naturally established *M. tenuiflora* plants in the 4,200 m^2 of the study area were distributed in height classes as follows: 28 (14.74%) in Class I, 151 (79.47%) in Classes II and III, and 11 (5.79%) in Class IV. The number of plants in Class I was relatively low compared to those in Classes II and III; the distribution in Class IV showed that a significant percentage of naturally established plants reached the reproductive stage. Probably, grazing exclusion and seedling planting contributed to the establishment of new trees, as few young trees were found in the adjacent grazed area.

According to the class distribution, the mean heights of the 198 naturally established trees were 97 cm for all three tree species combined and 95, 139, and 175 cm for *M. tenuiflora*, *C. quercifolius,* and *C. pyramidale* (one plant), respectively. These means were lower than the current mean heights of the surviving plants that were planted in experiments by Sales et al. (2019), Figueiredo et al. (2012), and Nunes (2012): 395 cm for *M. tenuiflora* and 355 cm for *C. quercifolius*. This difference may be due to variations in age and developmental conditions between naturally established and planted specimens: the age of naturally established plants ranged from 1 to 14 years, depending on when they were established, whereas the age of planted specimens ranged from 10 to 14 years; and these naturally established plants resulted from seeds germinating in the field with no application of manure or soil fertilizers, whereas the experimental seedlings were planted in planting holes fertilized with manure and chemical fertilizers.

Similarly, the basal diameters of the 198 naturally established trees (2 to 40 mm) were smaller than those found for planted *M. tenuiflora* and *C. quercifolius,* which ranged from 76 to 92 mm. The mean basal diameter of these plants was 11 mm for the three tree species and 10, 26, and 36 mm for *M. tenuiflora*, *C. quercifolius,* and *C. pyramidale*, respectively. The basal diameter of most naturally established plants was distributed in Class I (1 mm < $BD_I \leq$ 11 mm) and Class II (11 mm ≤ $BD_{II} \leq$ 21.1mm): 113 and 70, respectively, all *M. tenuiflora*, except one *C. quercifolius* classified as Class II (Figure 4).

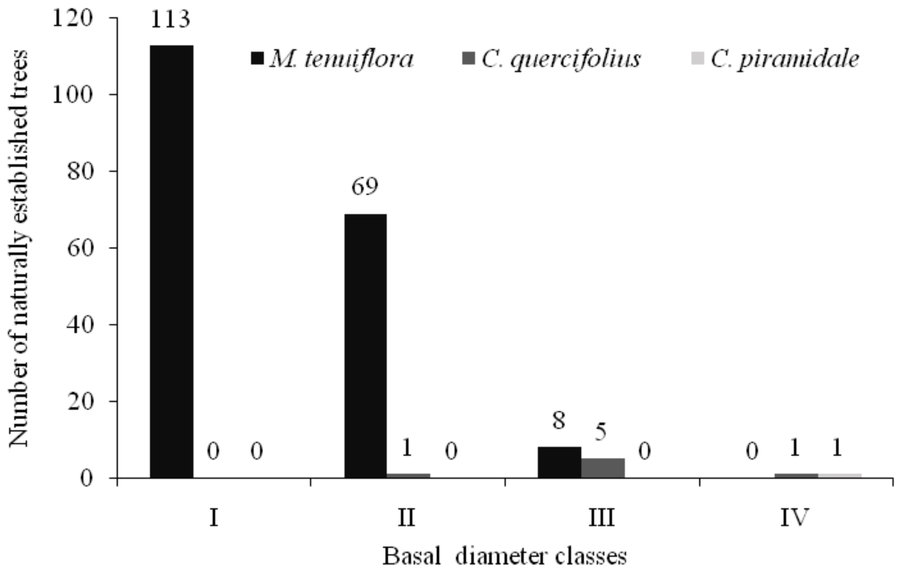

Figure 4. Distribution, in basal diameter classes, of naturally established trees in a degraded Caatinga area after 14 years of grazing exclusion: Class I (1 mm < $BD_I \leq$ 11mm), Class II (11 mm < $BD_{II} \leq$ 21 mm), Class II (21 mm < $BD_{III} \leq$ 31 mm), and Class IV (31 < $BD_{IV} \leq$ 41 mm). Patos, PB, Brazil.

Most of the 197 naturally established *M. tenuiflora* and *C. quercifolius* plants may have originated from seeds of planted seedlings that reached maturity, indicating a positive effect of the reintroduction of tree species combined with grazing exclusion. In addition, the seed bank composition is significantly dependent on the presence of mature trees in the area. Disregarding one specimen of *C. pyramidale* that naturally established in the area, no new plants of any other tree species naturally established in the area during 14 years, despite the presence of some other trees near the study area, such as *S. joazeiro*, *L. ferrea*, and *N. juliflora*.

Planting tree seedlings in degraded and grazing-protected sites provides advantages such as the possibility of choosing the species that will establish in the area, a faster plant succession process, and a balanced and simultaneous establishment of more than one tree species. Additionally, the probability of a successful establishment for a planted seedling is higher than that for a seed germinating directly in the field, as the addition of the equivalent of millions of seeds per hectare was insufficient for the establishment of a new tree (SALES et al., 2019). However, the findings of the present study show that 194 plants (103 *M. tenuiflora* and 91 *C. quercifolius*) out of 408 planted seedlings (204 of each species) were alive after a 10-to-14-year period in the field. This indicates a faster tree revegetation in degraded areas through seedling planting and grazing exclusion due to an interactive process in which planted seedlings developed and produced seeds, which are dispersed throughout the area; this contributed to change a degraded Caatinga area with few trees 14 years ago to an area currently yielding 392 established trees (194 adult individuals from planted seedlings and 198 naturally established individuals), while an adjacent area remains at a relatively higher stage of environmental degradation.

CONCLUSIONS

The analysis of data collected over 14 years revealed that planted tree seedlings had a higher growth compared to naturally regenerating plants. Grazing exclusion and seedling planting had a positive effect on tree recovery in degraded areas compared to a nearby area continuously degraded by grazing; however, the recovery of the tree community is partial, especially regarding diversity.

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