REVEGETATION OF DEGRADED CAATINGA SITES

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FIGUEIREDO JM, ARAÚJO JM, PEREIRA ON, BAKKE IA & BAKKE OA. 2012. Revegetation of degraded Caatinga sites. The Caatinga vegetation covers approximately 0.8 × 10^6 km^2 of Brazil's north-east. It has 300 to 800 mm annual rainfall during the four to five months of wet season. Its vegetation (seasonal herbs, xerophilous cactus, shrubs and trees) has been grazed, cut or removed, resulting in environmental degradation and arrest of tree regeneration in sites where desertification processes are under way. This study examined the two-year survival and growth of native trees, and the effects of tree planting on soil cover in degraded Caatinga sites, Patos, Brazil. Seedlings were planted in a 2 m × 2 m grid, into 40 cm × 40 cm × 40 cm holes enriched with manure and fertilisers, according to randomised block design with five treatments (control, and planting of *Poincianella pyramidalis, Mimosa tenuiflora* and *Cnidoscolus quercifolius* in pure or mixed stands) and five replications. Survival of planted trees ranged from 72.5 to 95.0%. *Mimosa tenuiflora* was the most promising species. Its height, basal diameter and canopy cover averaged 250 cm, 41 mm and 77% respectively. Herb cover reached 53% under its canopy. In adjacent grazed plots in which no seedlings were planted, no tree regenerated and herbs covered 10% of the soil. The results showed that within two years, planted trees could thrive in degraded Caatinga sites and increase soil cover to 93%.

Keywords: *Poincianela pyramidalis*, *Cnidoscolus quercifolius*, *Mimosa tenuiflora*, tropical dry forest, reforestation, restoration, anthropisation, native

FIGUEIREDO JM, ARAÚJO JM, PEREIRA ON, BAKKE IA & BAKKE OA. 2012. Pemulihan tumbuhan di tapak Caatinga yang usang. Vegetasi Caatinga meliputi lebih kurang 0.8 × 10^6 km^2 daripada timur laut Brazil. Jumlah hujan tahunannya ialah antara 300 mm hingga 800 mm ketika musim hujan selama empat bulan hingga lima bulan. Vegetasinya (herba bermusim, kaktus xerofili, pokok renek dan pokok) telah diragut, ditebang atau dibersihkan. Ini menyebabkan kemerosotan alam sekitar dan membantutkan pemulihan pokok di tapak yang sedang bertukar menjadi gurun. Kajian ini menyelidiki kemandirian dan pertumbuhan pokok asli serta kesan penanaman pokok terhadap litupan tanah di tapak Caatinga yang usang di Patos, Brazil selama dua tahun. Anak benih ditanam di dalam lubang berukuran 40 cm × 40 cm × 40 cm yang dibubuh baja asli dan sintetik di atas grid berukuran 2 m × 2 m. Lima rawatan iaitu anak-anak benih kawalan serta *Poincianella pyramidalis, Mimosa tenuiflora* and *Cnidoscolus quercifolius* dalam dirian asli dan campuran mengikut reka bentuk blok rawak dan lima ulangan. Kemandirian pokok yang ditanam berjulat antara 72.5% hingga 95.0%. *Mimosa tenuiflora* merupakan spesies yang paling baik. Ketinggian, diameter pangkal dan litupan kanopinya masing-masing 250 cm, 41 mm dan 77%. Litupan herba mencapai 53% di bawah kanopi *M. tenuiflora.* Tiada pemulihan pokok diperhatikan dan herba meliputi 10% daripada tanah di plot bersebelahan yang diragut dan tiada aktiviti penanaman. Keputusan menunjukkan yang dalam masa dua tahun, pokok yang ditanam boleh hidup di tapak Caatinga yang usang dan telah meningkatkan litupan tanah sehingga 93%.

INTRODUCTION

Environmental degradation becomes widespread since the 19th century and is mostly on tropical dry lands. In general, degradation refers to the decrease of the productive potential of an area caused mainly by inappropriate agricultural practices, overgrazing, logging and fuelwood extraction (Parrotta et al. 1997).

The Caatinga biome covers more than 8.4 × 10^5 km^2 in north-eastern Brazil (PROBIO/MMA 2004). The Caatinga vegetation is dominated by trees and shrubs, while herbs develop during the 4- to 5-month-long rainy season. Although some authors classify this vegetation as steppic savannah, Melo et al. (2004) consider this term inappropriate as savannah corresponds to an open field dominated by herbs with few scattered trees. This tropical dry biome stretches from 3° to 17° S and from 35° to 45° W. It has vegetation characterised by herbaceous seasonal species, cactus and particularly thorny deciduous retorted shrubs and trees, comprising 4322 identified seed plant species,

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744 of them endemic to the biome (Forzza et al. 2010).

Annual mean precipitation in this biome ranges from 300 to 800 mm. In Cabaceiras province, it may be as low as 279 mm. In Paraíba, the average value is 800 mm which fluctuates depending on local topography and predominant air currents (Bezerra et al. 2004). Rains are torrential, irregular in time and space, and heavier during the three to four months of the five-month-long rainy season. This resulted in it displaying some characteristics of semiarid regions such as negative water balance for eight to nine months of the year. Torrential rains may cause soil erosion especially due to removal of the permanent protection provided by tree canopy and root system.

This region is one of the most populated semiarid regions (more than 20 inhabitants/km^2). About 55% of the original Caatinga vegetation was cut and removed, resulting in negative environmental effects (PROBIO/MMA 2004). Many areas show environmental degradation. Attention is needed to avoid desertification. Less than 20% of the Caatinga forest cover is in pristine condition while 40% has been cut for firewood or removed for agriculture or cattle raising activities and 15% shows high levels of degradation (Silva et al. 2004).

In sites with high levels of degradation, plant species such as *Sida* and *Aristida* predominate. Predomination of *Sida* species indicates that plant succession may remain in the initial phases (herbs and shrubs) for a long time, characterising the process of regressive succession, as opposed to progressive succession when the expected climax is close or equal to the original (Araújo Filho & Carvalho 1996).

Two of the provinces of this biome, Ceará and Paraíba, showed respectively 30 and 50% of the area classified as highly degraded (Silva et al. 2004). These authors reported that the main causes of environmental degradation in the Caatinga biome were firewood extraction, overgrazing and shifting cultivation. Moreover, wood provides most of the energy used by some industries (ceramic and gypsum) (Campello et al. 1999). Economic, social and environmental sustainability are at risk if no actions are taken to address this issue of environmental degradation.

Some authors consider tree planting beneficial to the re-establishment of species richness of degraded tropical areas. For instance, Galvão and Porfírio-da-Silva (2005) stated that sustainability could be recovered in the semiarid region of north-east Brazil by the re-establishment of tree species. Appropriate revegetation techniques such as planting of native tree species and non-destructive systems of production such as proper grazing must be developed. Environmental recovery begins with the temporary cessation of degrading factors such as overgrazing and shifting cultivation with short or no fallow periods. Planting fast-growing native trees adapted to degraded sites and localised soil amelioration may be necessary to accelerate environmental recovery, increase biodiversity and allow the re-establishment of later successional tree species. Native tree species were successfully re-established in Malaysia where vegetation and top soil were removed during rains (Nussbaum et al. 1995). In the conditions of the remaining subsuperficial compacted soil, these authors reported that fertiliser addition to 20 cm × 20 cm × 20 cm planting holes restored growth of six-month-old seedlings of two pioneer and two dipterocarp indigenous trees to levels similar to those observed in areas with preserved forest soil.

Poincianella pyramidalis (Fabaceae—Caesalpinoideae), *Mimosa tenuiflora* (Fabaceae—Mimosoideae) and *Cnidoscolus quercifolius* (Euphorbiaceae) are native Caatinga xerophilous pioneer trees known to colonise inhospitable sites in the Caatinga biome (Lima 1996, Sampaio et al. 1998, Maia 2004). Although having unpalatable fresh leaves (*P. pyramidalis* and *C. quercifolius*), thorns (*M. tenuiflora*) or stinging hairs (*C. quercifolius*), these trees can be used to re-vegetate degraded Caatinga sites because they provide forage (fresh or senesced leaves, fruits or seeds) to livestock, and wood for human and industrial use. These species are especially important because they are known to rapidly colonise disturbed and degraded Caatinga sites, and prepare the sites to, and be substituted by, more demanding tree species along the process of ecological succession by providing soil cover and shade, and biologically fixing atmospheric nitrogen (*M. tenuiflora* only). In addition, they shelter and produce forage for native and domestic fauna in sites where other trees hardly survive or do not thrive as pioneer species.

This study examined the first two-year survival and growth of three native trees planted in fertilised planting holes. It also estimated the effects of tree planting on soil cover in Caatinga sites affected by deforestation and overgrazing in order to develop a protocol for re-establishing soil plant cover in degraded sites.

MATERIALS AND METHODS

Study sites

This study was carried out from August 2008 till March 2011 at two deforested sites approximately 500 m apart, in the UFCG/NUPEARIDO (Universidade Federal de Campina Grande/ Núcleo de Pesquisa para o Semi-Árido) Experimental Station, 6 km south of Patos. Site 1 is located 07° 04' S, 37°16' W, 254 m above sea level (asl) while site 2, 07° 04' S, 37° 16' W and 262 m asl.

Soil samples (0–20 cm deep) were collected from five points in each plot, 1 m apart from the centre of five planting holes in the plots in which trees were planted or in five randomly chosen points in each one of the control plots (Figure 1). Each set of five soil samples were mixed together thoroughly. About 0.5 kg of soil was taken to the laboratory for chemical (pH, electric conductivity (EC), P, Ca, Mg, K, Na, H + Al contents, cation exchange capacity (CEC), sum of bases (SB) and saturation by bases (V)) and physical (sand, silt and clay contents) tests (Table 1). Total depth in some plots reached 40 cm but was not attained in other plots due to the presence of shallow D soil horizon. The soil at both sites was classified as LUVISSOIL Ortic cromic.

For pH determination, the potentiometer electrode was immersed in soil: $CaCl_2$ 0.01 M solution (1:2.5, v:v). EC was determined in soil: distilled water solution (1:5, v:v) by means of a conductivimeter. Content of P was determined by colorimetry using Mehlich extractor (1:10, soil:extractor, v:v), Ca and Mg by titulometry using KCl 1N as the extractor (1:10 soil: extractor, v:v), K and Na by flame photometry using Mehlich extractor (1:10, soil:extractor, v:v), H + Al by means of a potentiometer and the same soil:$CaCl_2$ mixture used for pH determination plus 5 mL of SMP buffered solution. CEC and SB were obtained respectively by summing up concentration values for Ca + Mg + K + Na + (H + Al) and Ca + Mg + K + Na, and V by expressing SB as percentage of CEC (EMBRAPA 1997).

Precipitation totalled 92 mm from September till December 2008, 1595 mm in 2009, 364 mm in 2010 and 508 mm from January till March 2011. February and March data were based on precipitation and temperature values collected respectively during the first 19 and the last 28 days of the month due to equipment problem (Figure 2). The data were obtained according to

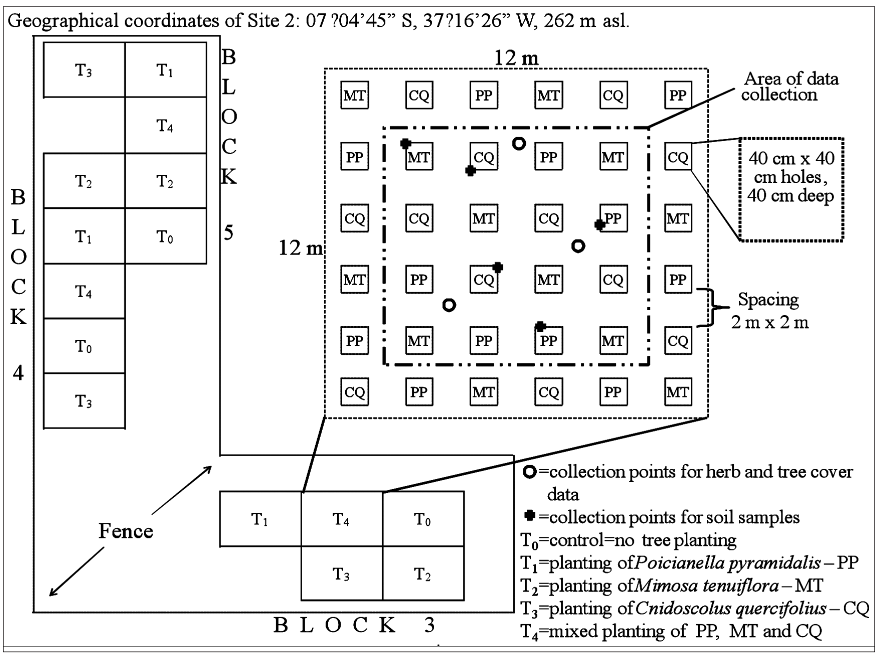

Figure 1 Geographical coordinates of site 2 and layout of blocks 3, 4 and 5 showing details of total and inner plot size, planting treatment in each plot, planting hole size, spacing, points of collection of data on soil and herb soil cover as well as tree species arrangement in one of the plots receiving the three species mixed stand treatment

Table 1 Chemical and physical attributes of soil (0–20 cm) averaged from data collected from five plots of each experimental treatment in October 2008

Treatment	pH $CaCl_2$ 0.01M	EC ($dS\ m^{-1}$)	P ($\mu g\ cm^{-3}$)	Ca	Mg	K	Na	H + Al	CEC	SB	V (%)
				←		($cmol_c\ dm^{-3}$)				→	
T_0	5.05	0.025	6.7	2.0	1.6	0.27	0.51	2.1	6.48	4.38	67.6
T_1	4.92	0.026	3.4	2.4	1.8	0.33	0.68	1.8	7.01	5.21	74.3
T_2	4.82	0.022	3.7	2.0	1	0.31	0.6	2.1	6.01	3,91	65.1
T_3	5.05	0.024	5.2	2.0	1.6	0.29	0.6	2	6.49	4.49	69.2
T_4	4.96	0.022	4.1	2.2	1.4	0.32	0.57	1.9	6.39	4.49	70.3

Treatment	Depth of planting hole (cm) (thickness of each soil horizon and total soil depth)				Soil particle			Soil textural class
	A	B	C	Total	%			USDA
					Sand	Silt	Clay	
T_0	2.9	11.8	24.9	39.6	82.0	11.2	6.8	Sandy loam
T_1	3.0	5.5	16.3	24.8	83.6	10.0	6.4	Sandy loam
T_2	5.7	12.2	18.6	36.5	81.6	10.0	8.4	Sandy loam
T_3	6.9	11.8	12.1	30.8	84.4	8.8	6.8	Sandy loam
T_4	5.8	8.3	13.1	27.2	80.8	10.0	9.2	Sandy loam

T_0 = control, T_1 = planting of *Poincianella pyramidalis*, T_2 = planting of *Mimosa tenuiflora*, T_3 = planting of *Cnidoscolus quercifolius*, T_4 = planting of the three tree species in mixed stand; EC = electric conductivity, P = phosphorus, Ca = calcium, Mg = magnesium, K = potassium, Na = sodium, H + Al = hydrogen + aluminum, CEC = cation exchange capacity, SB = sum of bases, V = saturation by bases

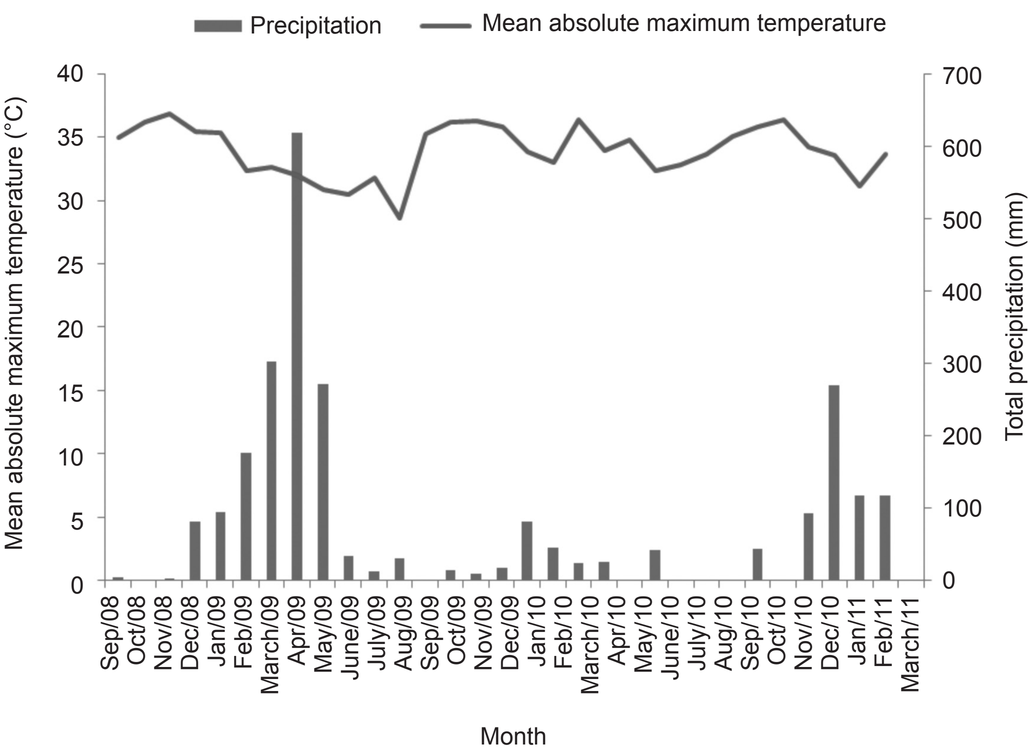

Figure 2 Mean absolute maximum temperature and monthly precipitation from September 2008 till March 2011

the automatic meteorological station positioned between sites 1 and 2, controlled by the Brazilian Institute of Meteorology (INMET 2011). Mean absolute maximum temperature for each month ranged from 28.6 to 36.9 °C and tended to be lower in 2009 than in 2010.

History of sites

According to the local people and observation of nearby forest remnants, a mixed Caatinga forest stand comprising *M. tenuiflora*, *P. pyramidalis* and *C. quercifolius* and other tree species predominated both sites before the area was deforested 30 years ago. Some scattered trees of *M. tenuiflora* trees were left uncut. After clear cutting and collection of stakes and firewood, sheep and goats foraged herbs and tree sprouts. Sprouting stumps perished and only the uncut trees survived. No natural tree regeneration is currently observed under tree canopy. Deforestation and overgrazing had especially localised negative effect on sites 1 and 2. These sites, each with size approximately 5×10^3 m^2, were fenced with commercial metallic net against small ruminants. No grazing was allowed since March 2005 in site 1 (blocks 1 and 2) and since August 2008 in site 2 (blocks 3, 4 and 5), corresponding to 46 and 5 months before planting tree seedlings respectively. At the moment of fencing, both sites showed scattered furrows of soil erosion, laminar soil erosion detected by the exposition of subsuperficial soil horizon at some points, low level of herb (an average of 10% soil cover) and almost no tree soil cover (one or two *M. tenuiflora* plants remaining in each site), low plant species diversity (one and five mono- and dicotyledonous herb species respectively) and predominantly three indicator species of degraded areas (*Aristida* and *Sida* species). Most of the biomass which had accumulated in the herbaceous layer of site 1 since it was fenced in March 2005 was consumed by two horses from September till November 2008, prior to the beginning of the experiment.

Seed cleaning, break of seed dormancy, seed germination and seedling production

In mid-September 2008, seeds of *P. pyramidalis* and *C. quercifolius* were disinfected by immersion in diluted sodium hypochlorite solution and then washed in running tap water. *Mimosa tenuiflora* seeds were not disinfected. Subsequently, *C. quercifolius* seeds were scarified and *M. tenuiflora* seeds were immersed in hot water to break dormancy as practised by Bakke et al. (2006a), Sales et al. (2001) as well as Teixeira et al. (2007), and placed in moist sterilised sand.

Following radicle emergence (2 to 3 mm), plantules were transplanted to 0.3 L plastic containers filled with a mixture of soil and goat manure (3:1, v:v) and kept protected from direct sunlight by plastic screen (50% reduction factor) for 75 days. Then, they were transplanted to 4 L plastic bags, filled with the same substrate mixture plus 1.35 g of P and 4.81 g of K/bag. Fifteen days later, 40 mL of solution containing 2.12 g of N/L were added to each bag.

Seedlings were automatically sprinkled with water for 5 min four times a day until the end of November 2008. They were watered twice a day in December 2008 and once every two days in January 2009 for seedling hardening before planting in the field in late January 2009.

Preparation of planting holes and initial care of seedlings

Seedlings were planted into 40 cm × 40 cm × 40 cm holes, dug mechanically in August 2008 by means of a 30 cm diameter steel probe. Squared dimensions of each hole were attained manually. Depth of hole was 40 cm when soil conditions permitted.

Goat manure (20 L = 5.8 kg sun-dried basis) was mixed with soil in each hole in December 2008 together with P and K (4.37 and 2.24 g/hole respectively). Additions in bags and planting holes, on a per hectare basis, were equivalent to 15.2 ton of goat manure, 14.3 kg of P, 17.6 kg of K and 0.2 kg of N.

Herbage was removed from 50 cm radius area around each planted seedling in March and May 2009. Dead seedlings were replaced in March and April 2009 after data collection.

Variables

Seedling survival, height and basal diameter were estimated from the 16 inner seedlings. Plant soil cover was measured from subplots located in the area.

Seedling survival was based on data collected in February 2011, 25 months after planting. Seedling height and basal diameter were collected in late January 2009 at the time of planting in the field. All values for each variable were summed up, divided by 16 and analysed. The same procedure was repeated in October 2009 and February 2011, 9 and 25 months respectively after planting. Seedling height, the length of the longest branch, was measured using graduated rod. Basal diameter was measured 5 cm above the soil surface using digital callipers. Seedling height and diameter increments were differences between January (planting) and October 2009 (nine months after planting) or February 2011 (25 months after planting) data sets.

Herb and tree soil covers (%) in each plot were estimated during the dry season before planting (September 2008, four months before planting), in March, July and October 2009 (two, six and nine months after planting), in March 2010 (14 months after planting) and in March 2011 (26 months after planting) from three randomly chosen 3.1416 m^2 circular subplots by means of three visual estimates made by three persons in each subplot. Similarly, plant soil cover data were collected from six subplots exposed to grazing, adjacent to the experimental blocks.

Treatments, experimental design and statistical analyses

Five treatments (control (T_0), and planting of *P. pyramidalis* (T_1), *M. tenuiflora* (T_2) and *C. quercifolius* (T_3) in pure and mixed (T_4) stands) were assigned to the plots according to a randomised complete block design with five replications (blocks) (Figure 1). Plot size was 12 m × 12 m and each block covered 720 m^2. Each plot contained 36 planting holes in 2 m × 2 m spacing grid. In plots receiving mixed stand treatment (T_4), 12 seedlings of each tree species were planted.

Data were analysed using analysis of variance (ANOVA) (Sampaio 1998). Data were log transformed prior to analysis when homogeneous treatment variance or error normality was lacking. When necessary, treatment means were compared using Tukey's test ($p < 0.01$).

The control treatment (T_0) was not included in the ANOVA for tree seedling survival, height and basal diameter. Treatment, block and error terms had 3, 4 and 12° of freedom respectively. For herb or tree soil cover, a date factor (September 2008, March, July and October 2009, March 2010 and March 2011) was included in the design. For herb soil cover, treatment, date (October 2009 data set was removed from the formal analyses because it showed null variance: 100% soil cover for all treatments), treatment × date interaction, block and error terms had 4, 4, 16, 4 and 96° freedom respectively. In the ANOVA of tree soil cover, treatment, date (September 2008 data were not considered because no plot had tree soil cover), treatment × date interaction, block and error had 3, 4, 12, 4 and 88° of freedom respectively. Three 2 m diameter circles, exposed to animal browsing, were randomly sampled outside the fences of sites 1 and 2 to enable further comparisons.

RESULTS

The number of surviving tree seedlings in February 2011, two years after planting, was not significantly affected by treatments (result not shown). An average of 11.6, 15.2 and 12.8 out of 16 *P. pyramidalis*, *M. tenuiflora* and *C. quercifolius* seedlings respectively survived in each plot. Equivalently, 58 (72.5%), 76 (95%) and 64 (80%) of the 80 seedlings (five replications of 16 seedlings) in pure stands survived two dry seasons after planting. Tree seedling survival in T_4 plots (mixed stand) was 80%. Considering each species separately, the values were 85.0, 96.7 and 55.5% for *P. pyramidalis*, *M. tenuiflora* and *C. quercifolius* respectively.

Naturally-regenerating tree seedlings were not observed in 2009 at the inner area of each plot but were observed at the border area of a few plots and outside the plots in both fenced sites. Data on naturally-regenerating tree seedlings were collected in February 2011 considering simultaneously the inner and border areas of each plot. Only *M. tenuiflora* seedlings regenerated naturally, and 106 of them could be observed in the total area (3600 m^2) of the experiment. Thirty-nine of them were observed in five 144 m^2 plots in which no tree seedlings were planted (control treatment), and 17, 5, 27 and 18 in plots where *P. pyramidalis*, *M. tenuiflora* and *C. quercifolius* seedlings were planted in pure or mixed stands respectively. No height nor diameter measurements were taken from these plants, but, in general, their height and basal diameter showed much lower values than the planted *M. tenuiflora*. Some of them were thriving in the planting holes just beside the planted seedlings while others grew quite well even outside the ameliorated environment of the planting holes.

Average heights of tree seedling in January 2009, 4.5 months after sowing, at the time they were planted in the field were greater ($p < 0.01$

by Tukey's test) for *M. tenuiflora* (71.9 cm) compared with *P. pyramidalis* (20.2 cm) and *C. quercifolius* (20.7 cm) (Figure 3). Seedlings of each tree species planted in mixed stand (T4) showed the same trend. In February 2011, total height ranked similarly. The mean seedling height for *M. tenuiflora* (250.5 cm) was greater ($p < 0.01$ by Tukey's test) than those of *P. pyramidalis* (86.5 cm) and *C. quercifolius* (117.5 cm). The heights of planted trees in mixed stand were 156.3, 256.0, 85.6 and 106.3 cm, considering each respective species separately (results not shown).

Average height increase (Figure 3) from January 2009 till February 2011 was significantly ($p < 0.01$ by Tukey's test) higher for *M. tenuiflora* (178.6 cm) than for *C. quercifolius* (96.8 cm) and *P. pyramidalis* (66.3 cm). Most of this increase was observed during the first nine months after planting (147.3 cm for *M. tenuiflora*, 34.3 cm for *P. pyramidalis* and 51.3 for *C. quercifolius*), when seedling height averaged 219.2 cm for *M. tenuiflora*, 54.5 cm for *P. pyramidalis* and 72.0 for *C. quercifolius* (Figure 3).

Mean basal diameter of tree seedlings in January 2009 (planting) followed the order: *C. quercifolius* > *M. tenuiflora* > *P. pyramidalis* (7.4 > 5.6 > 3.3 mm) ($p < 0.01$ by Tukey's test) (Figure 3). By February 2011, two years later, averages were ($p < 0.01$ by Tukey's test) in a different order: *M. tenuiflora* (41.4 mm) > *C. quercifolius* (26.0 mm) > *P. pyramidalis* (12.6 mm). At this date, diameter of planted trees growing in mixed stand showed an overall three species average of 27.7 mm, and 45.7, 21.4 and 11.9 mm considering each respective species separately (results not shown).

Average diameter increase from January 2009 till February 2011 was significantly ($p < 0.01$ by Tukey's test) higher for *M. tenuiflora* (35.8 mm) than for *C. quercifolius* (18.6 mm) and *P. pyramidalis* (9.3 mm). Most of this increase was observed during the first nine months (20.4 mm for *M. tenuiflora*, 9.3 mm for *C. quercifolius* and 4.9 mm for *P. pyramidalis*), when basal diameter averaged 26.0 mm for *M. tenuiflora*, 16.7 mm for *C. quercifolius* and 8.2 mm for *P. pyramidalis* (Figure 3).

Herb soil cover increased ($p < 0.01$) higher than 70% and tended to be unaffected ($p > 0.01$) by the level of tree introduction, except for the negative effect observed in March 2011 in *M. tenuiflora* plots (53%) (Table 2). In September 2008 (the dry season prior to the experiment), herb soil cover averaged 14% and was composed of physiologically inactive stems with no leaves. By March and July 2009, during the first growing season and after grazing was no longer allowed in the experimental area, herbs covered respectively an average of 61 and 87% of the soil surface with physiological active plant structures. Herb soil cover increased to 100% in October 2009 and consisted mainly of senesced biomass, while herb soil cover in the adjacent grazed plots averaged 10%. Herb soil cover was higher in the ungrazed plots than in the adjacent grazed plots from October 2009 till March 2011.

Tree soil cover was affected by the level of tree introduction and date (Table 2). No significant tree soil cover was observed from natural regeneration in the control plots, and literally no naturally regenerating tree could be seen in the six adjacent grazed plots. *Poincianela pyramidalis*

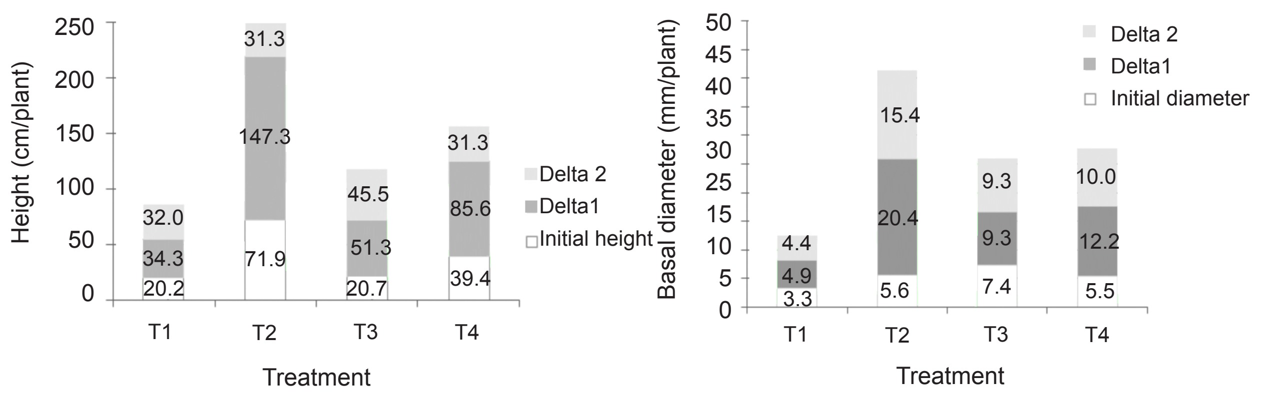

Figure 3 Mean height and basal diameter of three tree species after 25 months in the field, planted in anthropised Caatinga sites and protected from browsing, showing the initial value at the time of planting in January 2009, increases from January till October 2009 (Delta 1) and from October 2009 to February 2011 (Delta 2); T_1 = *Poincianella pyramidalis*, T_2 = *Mimosa tenuiflora*, T_3 = *Cnidoscolus quercifolius* in pure stands, T_4 = mixed stand of the tree species

Table 2 Mean herb and tree soil cover (%) of anthropised Caatinga sites, protected from grazing and planted with three tree species, according to treatments (tree planting level) or in adjacent subplots exposed to grazing with no tree planting, from September 2008 till March 2011

Date	Treatment					
	T0	T1	T2	T3	T4	AEG
	Herb soil cover (%)					
Sept/08 (drought)	14	16	14	13	14	5
March/09 (rain)	67	54	62	56	65	40
Jul/09 (rain)	84	86	89	86	91	30
Oct/09 (drought)	100	100	100	100	100	10
March/10 (rain)	84	72	57	70	66	37
March/11 (rain)	93 a	88 a	53 b	87 a	74 ab	47
	Tree soil cover (%)					
Sept/08 (drought)	0	0	0	0	0	0
March/09 (rain)	0	12	28	12	25	0
Jul/09 (rain)	0	17	49	15	33	0
Oct/09 (drought)	0	12	42	14	20	0
March/10 (rain)	0	13	47	20	29	0
March/11 (rain)	0	24 c	77 a	22 c	44 b	0

T_0 = Control (no tree planting), T_1 = planting of *Poincianella pyramidalis*, T_2 = planting of *Mimosa tenuiflora*, T_3 = planting of *Cnidoscolus quercifolius*, T_4 = planting of the three tree species in mixed stand; AEG = area exposed to grazing; values followed by the same letter do not differ ($p < 0.01$) by Tukey's test; AEG means were not included formally in statistical analyses

and *C. quercifolius* showed lower potential (< 24%) to cover the soil than *M. tenuiflora* (up to 77%). In plots where trees were planted, tree soil cover showed a peak in July 2009, six months after planting, decreased a little in October 2009, three months later due to leaf senescence in the dry season but resumed growth until March 2011, especially in plots of *M. tenuiflora*.

DISCUSSION

Total rainfall in 2009 was above the annual regional mean. This stimulated seedling survival and growth of herbs and trees. However, total rainfall was not the most important impacting factor, as survival remained high in 2010 although experiencing below average precipitation.

The observed high survival rates for tree seedlings planted in degraded Caatinga sites were greater than those reported by Bhatt et al. (2010) for 10-year-old native trees planted in wider spacing and fertilised planting holes in degraded areas in Himalaya and by Holl et al. (2011) for three-year-old trees planted in abandoned pastures in Costa Rica. This shows the difficulty of re-establishing trees in degraded sites even in moist areas and that survival of planted seedlings can be high in dry regions.

Survival of planted *M. tenuiflora* contrasted the 7.5% survival of naturally regenerating *M. tenuiflora* seedlings at grazed Caatinga sites as reported by Bakke et al. (2006b). Their data were equivalent to 53 seedlings/144 m^2, higher than the maximum value of 7.8 naturally regenerating *M. tenuiflora* plants/control plot in the present study. This suggested the high level of degradation observed in experimental sites 1 and 2.

No survival was observed when sowing the equivalence of 1.4×10^7 seeds/ha of four native trees after soil amelioration and 1.5 to 59% seed germination (Sales 2008). Less than 24% seed germination was reported for five tree species in an abandoned pasture in moist tropical Brazil (Engel & Parotta 2001). These data show that natural tree regeneration comes after the death of many seedlings and that tree planting greatly increases the rate of tree establishment.

A total of 2.8 and 40.2% of *P. pyramidalis* and *M. tenuiflora* seedlings respectively survived to the third growing season (Sales 2008). These low survival rates were due to the smaller seedling bags and planting holes, less goat manure and chemical fertiliser and not due to the amount of rainfall. This was because survival rate of seedlings in the present study remained higher in the subsequent year of 364 mm total rainfall than the survival rates reported by Sales (2008) in years with double amounts of rain.

Other researchers reported above 85% survival of planted trees in moist tropical regions in Brazil by improving soil conditions with sewage residue (Maas et al. 2008) or gypsum (Ferreira et al. 2002) or after direct sowing (Engel & Parrotta 2001), although Engel and Parrotta (2001) reported less than 10% survival of germinated seeds for some tree species. These results reinforced earlier comments on how much seedling planting could accelerate tree seedling establishment in degraded sites.

However, knowledge of the conditions that allowed the establishment of the 106 naturally regenerating *M. tenuiflora* plants observed in the present study would make the expensive practice of tree planting unnecessary. Regeneration of only a few *M. tenuiflora* resulted in sparse and monospecies stands. Thus, dense and multispecies stand is expected to occur after such a long time, during which grazing has been minimised. The inherent low cost of natural tree establishment may be overshadowed by the fast establishment and rapid growth of more than one species resulting from tree planting. Even if limited to small areas due to cost, tree planting can be used to establish small stands scattered in the degraded area to help the recovery of adjacent sites by attracting birds and rodents that can enrich the seed bank.

The mean *M. tenuiflora* height in October 2009 was greater than the maximum 20 cm height of naturally regenerating 2-year-old seedlings exposed to grazing and harsh microsite conditions as observed by Bakke et al. (2006b). Mean heights for *P. pyramidalis* and *M. tenuiflora* in October 2009 (first growing season) exceeded those reported by Sales (2008) for planted seedlings. This could be a result of the stronger seedlings and superior field conditions present in this study.

The decrease in the growth rate of *M. tenuiflora* seedlings and the two other tree species in the second growing season probably resulted from the low rainfall in 2010 and soil nutrient deficiencies after the first year of growth.

Mimosa sp. and *P. pyramidalis* were reported to sprout as high as 3.8 m, six years after clear cutting (Sampaio et al. 1998). These high values are certainly due to lower level of site degradation, nutrient flush resulting from slash burning and sprouting vigour generally shown in stumps with well-developed root systems. However, average heights reported in the present study (Figure 3) make it possible that planted trees, especially *M. tenuiflora* and *C. quercifolius*, reach or surpass values observed for sprouts if conditions are favourable.

Mean height for *C. quercifolius*, 25 months after planting, was intermediate compared with that reported for this species by Candeia (2005) at the end of the second growing season in non-degraded sites. The intermediate value was unexpected. This could be due to the bigger bags, longer period for seedling development in nursery, larger planting holes, and higher levels of fertiliser and goat manure.

The height values reported by Ferreira et al. (2002) and Bruel et al. (2010) for 1- to 2-year-old planted trees in degraded sites and those by Engel and Parrotta (2001) for two successful directly sown tree species in moist tropical regions in Brazil are very similar to the current values for *M. tenuiflora*, *P. pyramidalis* and *C. quercifolius,* two years after planting. This indicated the high growth potential of these trees in dry tropical degraded Caatinga sites.

Mimosa tenuiflora showed dichotomised inclined branches and wider circular canopy when compared with the vertical canopies of *P. pyramidalis* and *C. quercifolius.* This may yield more forage (leaves and fine branches) and protection to the soil. This also implies that *M. tenuiflora* can be planted in wider spacing and still provide enough soil protection. This can reduce planting costs and result in thicker wood and more herb forage production. However, the slow initial growth of *P. pyramidalis* may be an ecological adaptation of this species to withstand the initial adverse environmental conditions (Sampaio et al. 1998).

Average diameter values in October 2009 for *P. pyramidalis* and *M. tenuiflora* were higher than the respective values reported by Sales (2008) while average diameter for *C. quercifolius* surpassed those reported by Candeia (2005). The diameters of two native species after direct sowing in tropical moist region in Brazil (Engel

& Parrotta 2001) were similar to that of *M. tenuiflora*, and superior to those of *P. pyramidalis* and *C. quercifolius*. However, they reported much lower values for the other two trees, making them thinner than any of the species in the present study.

The increases in basal diameter from January 2009 till February 2011 were greater in *M. tenuiflora* than in *P. pyramidalis* and *C. quercifolius*. Most of the increase was observed in the first nine months after planting. The decrease in growth rate during the second year could be due to exploitation of available nutrients in the fertilised soil of the planting holes and difficulty in exploring the soil outside the planting hole (Nussbaum et al. 1995).

The relative growth rates of diameter for the first nine months were 3.6, 1.5 and 1.3 for *M. tenuiflora*, *P. pyramidalis* and *C. quercifolius* respectively (Figure 3). Relative growth rate of 3.6 meant that the diameter increase of *M. tenuiflora* in nine months corresponded to 3.6 times the initial diameter. From January 2009 till February 2011, relative growth rates were 6.4, 2.8 and 2.5 for *M. tenuiflora, P. pyramidal*is and *C. quercifolius* respectively. These values were higher than those reported by Bruel et al. (2010) in all but one of the six pioneer fast- growth native tree species planted in degraded abandoned pasture. This clearly shows that the concept 'fast growth' is relative. The growth potential of tree species indigenous to dry regions is equal or higher than that of trees in hot rainy biomes. This proves that the dry Caatinga biome, and not only the moist biome supporting exuberant vegetation, has ecological importance or is a major carbon sequester.

The long branches and thick stems observed in *M. tenuiflora* favoured the production of calorific biofuel (4482 kcal/kg of wood and 6866 kcal/kg of charcoal; Oliveira 2003, Oliveira et al. 2006), forage, the development of soil cover and decreased the necessity of weeding, compared with the other two tree species.

Both *P. pyramidalis* and *M. tenuiflora* are precocious. Flowering and fruit production occurred in 2009, especially in *M. tenuiflora*. This means that these species are able to attract fauna early in their lifespan and produce food for wild and domestic animals (Cordão 2011). This is an advantage when reclaiming degraded areas and feeding ruminants.

The non-significant effect of trees on herbs indicated no excessive competition for soil nutrients and light, except for *M. tenuiflora,* 25 months after planting. Wider spacing between trees or pruning of fine branches can overcome this negative effect on herbs and provide forage to ruminants (Cordão 2011). This is in accordance with Araújo Filho's (1992) findings that herb and animal production increased when 30 to 40% of the soil surface remained covered by tree canopy.

All three species have a place in the revegetation process because they produce fruits at different times: *M. tenuiflora* in June and October–November, *P. pyramidalis* in March–April and *C. quercifolius* in March–May. This is also true for forage production: fresh *M. tenuiflora* leaves and fine branches are available mainly in the middle of the growing season, fresh and senesced *P. pyramidalis* leaves respectively at the beginning and end of the growing season, and senesced *C. quercifolius* leaves at the end of the growing season.

The increasing anthropic pressure on natural resources of the Caatinga biome, the widespread environmental degradation and poor natural tree regeneration observed in degraded sites are issues that must be addressed. Current forest management practices led to the imminent collapse scenario in firewood demanding ceramic and gypsum industries. Probably, it will be necessary to plant fast-growing native or exotic trees in the near future. *Poincianella pyramidalis*, *C. quercifolius* and, especially, *M. tenuiflora* seemed to be the promising species to be planted in the semiarid region of north-east Brazil.

CONCLUSIONS

Herb and tree soil cover of degraded Caatinga sites could increase to 93 and 77% respectively within two years of planting the native trees *P. pyramidalis*, *M. tenuiflora* and *C. quercifolius*. The management practices used in the present study such as grazing deferment and planting of well developed 4.5-month-old tree seedlings into sizable planting holes enriched with manure and fertilisers were useful in re-establishing plant soil cover in degraded Caatinga sites.

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