VEGETATION COVER AND REGENERATION AS PREDICTORS OF DESERTIFICATION PROCESS IN DRY FOREST IN BRAZIL

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Abstract

The Brazilian Caatinga is one of the most diverse dry forests on the planet. Half of its original coverage is degraded, and it is currently identified as one of the main areas undergoing desertification. Natural regeneration depends on climatic and edaphic conditions, as well as the adult stratum present in an area. Despite its importance, this process is little known in the Caatinga. Thus, we aimed to analyze how the anthropic disturbance, vegetation cover, and soil properties influence regenerating stratum under different Caatinga vegetation cover levels. Our study was executed in the driest region of Brazil. We classified our studied areas as Area I (less vegetation cover) and Area II (greater coverage). Six plots of 50 x 20 m were delimited for sampling the adult and regenerating stratum, and the soil in each area. Our results show interactions between soil characteristics and adult and regenerating stratum. Area II showed greater diversity and a greater number of exclusive species; in contrast, a dominance of species more resistant to limiting conditions was observed in Area I, such as *Aspidosperma pyrifolium* Mart. & Zucc. The C and N contents in the soil indicated a positive and significant correlation with the diversity of the regenerating stratum. The data revealed that the area with less vegetation cover, richness, and diversity presented indications of desertification.

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This study investigates the regeneration rates of plant communities and indicators of desertification in areas with different levels of vegetation cover in the Caatinga, located in the driest region of Brazil.

Short title: Regeneration in Dry Forest in Brazil

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Abstract

The Brazilian Caatinga is one of the most diverse dry forests on the planet. Half of its original coverage is degraded, and it is currently identified as one of the main areas undergoing desertification. Natural regeneration depends on climatic and edaphic conditions, as well as the adult stratum present in an area. Despite its importance, this process is little known in the Caatinga. Thus, we aimed to analyze how the anthropic disturbance, vegetation cover, and soil properties influence regenerating stratum under different Caatinga vegetation cover levels. Our study was executed in the driest region of Brazil. We classified our studied areas as Area I (less vegetation cover) and Area II (greater coverage). Six plots of 50 x 20 m were delimited for sampling the adult and regenerating stratum, and the soil in each area. Our results show interactions between soil characteristics and adult and regenerating stratum. Area II showed greater diversity and a greater number of exclusive species; in contrast, a dominance of species more resistant to limiting conditions was observed in Area I, such as *Aspidosperma pyrifolium* Mart. & Zucc. The C and N contents in the soil indicated a positive and significant correlation with the diversity of the regenerating stratum. The data revealed that the area with less vegetation cover, richness, and diversity presented indications of desertification.

Keywords : Semi-arid climate – Plant Communities – Vegetation cover – Chronic Anthropic Disturbance – Desertification – Regenerating Stratum.

Introduction

The increase in the human population and the demand for natural resources are the main causes of global biodiversity loss and changes in the structure of forests around the world (McKee, 2009). Habitat fragmentation (Ribeiro et al., 2015) and changes in soil quality (Ferreira et al., 2018) derived from anthropic pressure reduce tree species richness and alter structural parameters such as stem diameter and basal area (Sobrinho et al., 2016). Such changes over time can shape the desertification process in less resilient areas (Alves et al., 2009). Desertification is defined as a reduction or loss of the biological productivity of drylands, their ecological complexity, and/or their human values, manifested through a reduced provision of the sum of dryland ecosystem services (Verstraete et al., 2009; Reid et al., 2005; Scholes, 2009).

The natural regeneration process of disturbed forests varies according to the abiotic and biotic characteristics of the environment. Seedling establishment is related to climatic conditions of the environment, such as precipitation, temperature and seasonality, richness and composition of the adult plant community, and the history of land use (Ribeiro et al. 2015; Sobrinho et al., 2016). Thus, arid and semi-arid ecosystems are less tolerant to human disturbances, becoming more vulnerable to desertification than humid tropical systems. These ecosystems consequently have lower regeneration rates since seedling establishment, which is the most vulnerable stage of life, can be compromised by prolonged drought periods (Alves et al., 2010; Ferreira et al., 2018; Marinho et al., 2016; Sobrinho et al., 2016). On the other hand, a milder microclimate induced by adult stratum could favor ecosystem regeneration (Derroire et al., 2016a; Lebrija-Trejos et al., 2011).

Seasonally Dry Tropical Forests (SDTF) are currently one of the most threatened ecosystems in the world, with 97% of their territory at risk (Miles et al., 2006). These forests are characterized by high seasonality, long periods of drought, and rainfall ranging from 240 mm to 1,500 mm per year (Pennington et al., 2009). These environments are home to high biodiversity and are main endemism centers, with species marked by their morphophysiological adaptation mechanisms developed to tolerate local climatic conditions (Murphy and Lugo, 1986).

The Brazilian Caatinga consists of one of the largest and most diversified dry forests in the world (Costa et al., 2016; Prado et al., 2015), with an extension of 912,529 km^2 (Silva et al., 2017). Approximately 46% of the native Caatinga vegetation has been cleared due to agriculture and pastures developed since the 16^{th} century and currently due to industrial and timber extraction (Lapola et al., 2014; Ribeiro et al., 2015; Sfair et al., 2018). In addition, it is expected that the climatic changes which have occurred will affect the maintenance of endemic species in the Caatinga, reducing the vegetation cover and areas of climatic conditions suitable for establishing communities (Silva et al., 2019).

Reduced vegetation cover makes the soils more susceptible to erosion and compaction processes, reducing the water infiltration rates and the Organic Carbon and Organic Nitrogen levels, in addition to making the microclimate of the environment more stressful due to greater sun exposure, compromising regeneration from the community (Derroire et al., 2016a; Sousa et al., 2012). These factors induce the biotic homogenization of degraded lands (Leal et al., 2005) by limiting the occurrence of sensitive species and favoring the occurrence of stress resistance (Lôbo et al. 2011; Ribeiro-Neto et al., 2016).

In this study, we hypothesized that regenerating stratum in areas with less vegetation cover would show lower: i) richness, ii) diversity indices and iii) individuals with lower height and average diameter than in areas with denser vegetation cover. This hypothesis is due to higher environmental stress caused by increased sun exposure (Derroire et al., 2016b), limited soil nutrients (Sousa et al., 2012), and higher pressure from herbivores on the vegetation as animal access is facilitated in more open areas (Marinho et al., 2016; Skarpe et al., 2007).

Material and Methods

The study area encompasses the region known as Cariri Paraibano, in Northeastern Brazil. The region is located in the Borborema Plateau, between 400 and 1,100 m of altitude. This region extends over 11,192 km^2. According to IBGE (2010), the region has a population of 185,235 inhabitants.

Cariri Paraibano is one of the driest regions in Brazil. The climate is hot semi-arid (BSh) according to the Koppen classification (Alvares et al., 2013), with precipitation between 300 and 600 mm $year^{-1}$, constituting the lowest rainfall levels in the country. The rains are usually concentrated in consecutive months, generally from January to July, resulting in long drought periods for the rest of the year, with September being the driest month (Silva et al., 2018). The average annual temperature is 27 °C, with a minimum of 23 °C and a maximum of 41 °C. Potential evapotranspiration is up to four times greater than precipitation, and a marked water deficit predominates in the region (Souza et al., 2015b).

The regional economy has been based on extensive agriculture and livestock since the beginning of its occupation (Alves, 2009; Souza et al., 2015b). Climatic conditions together with this anthropogenic exploration regime have lead the region to become sensitie to the desertification process (Souza et al., 2015a). The study by Oyama and Nobre (2004) shows that this process generates changes in the hydrological cycle, affecting precipitation, evapotranspiration, atmospheric humidity, and decreased runoff, leading to the possibility of significant local and large-scale climate change if the degradation regime continues unchecked.

Mineral weathering is incipient due to the semi-arid climate. Luvisols (40.9 % of the total area), Leptosols (35.6 %) and Regosols (3.9 %) dominates the Cariri (Araújo Filho et al., 2017). These soils are dominantly loamy, shallow (<1 m deep), eutrophic, and have low water retention capacity (Ferreira et al., 2018; Giongo et al., 2011; Menezes et al., 2012; Rückamp et al., 2010).

2.1 Site selection

The sites were selected based on the normalized difference vegetation index (NDVI), which estimates the biomass and productivity of the vegetation by calculating: NDVI = (Infrared - Red) / (Infrared + Red), using the ArcGIS 10.2. desktop software program. We used three images captured by the Landsat-8 satellite between September to October 2017 (earthexplorer.usgs.gov) so that the entire length of the Cariri Paraíbano was covered. This period was chosen because it is the drought season, and the vegetation cover images may change in the rainy season due to the herbaceous stratum established at this time. The calculations were performed using composite images combining bands 4 (Red, wave-length 0.64-0.67) and 5 (Near Infrared, wave-length 0.85-0.88) of the satellite, which is satisfactory for describing vegetation cover. NDVI values can range from -1 to +1, with values close to 0 corresponding to regions with little vegetation and higher values corresponding to areas with denser vegetation cover. A total of 12 plots were established, divided into two areas: a) six plots in sites of NDVI values between 0.15 and 0.37, hereafter referred to as Area I, which corresponds to the lowest vegetation cover, and; b) six plots in sites of NDVI values between 0.44 to 0.66, hereafter referred to as Area II, which comprises environments with higher vegetation cover levels (Figure 1). We first identified all of the sampling sites through the satellite images, and we later visited the areas to confirm. All collections were carried out from November 2018 to July 2019.

Note : Here figure 1 will be inserted

2.2 Sampling of vegetation data

First, 12 plots (50 x 20 m) were delimited for sampling the adult tree stratum, totaling a sampling area of 1.2 ha. The adult stratum represented the vegetation cover of our study and was composed of 2,519 individuals. A total of 1,053 individuals were sampled in Area I, distributed in 24 species and ten families, while Area II presented 1,466 individuals distributed in 36 species and 16 families.

Each plot was subdivided into 10 subplots (10 x 10 m), with four subplots being randomly chosen for sampling the regenerative stratum. The height and diameter of all individuals were measured. The species of all individuals were identified in the field. The main descriptive characteristics (height, diameter, habit, floral attributes) for unidentified individuals were recorded, and samples were collected for later taxonomic determination in the laboratoryusing specialized bibliography and consulting digitalized and herbal databases, and classified according to the Angiosperm Phylogeny Group IV (APG IV, 2016). All living individuals with height [?]1 m and diameter at ground level (DGL) [?]3 cm were identified as adult individuals (Rodal et al., 2013). Living specimens with a height <1 m and a DGL between 0.5 and 2.9 were identified as seedlings (Farias et al., 2016).

Hill numbers of order 0, 1, and 2 were used to quantify diversity (Jost, 2006). The diversity of order 0 (D0) refers to species richness, which is not sensitive to abundance; the diversity of order 1 (D1) considers the abundance of each species and its weight in the community is given accordingly. Thus, it is interpreted as the number of common species in the community; diversity of order 2 (D2) is also sensitive to abundance and favors the highest number of species, being interpreted as the number of dominant species in the community (Jost, 2006). Since the focus of our work is the data from the regenerating stratum, we will use RegD0, RegD1, and RegD2 to refer to the diversity data of orders 0, 1, and 2, respectively, of that stratum. The calculations were performed through the website https://chao.shinyapps.io/iNEXTOnline/. The*iNext* is a species diversity interpolation and extrapolation software program.

2.3 Anthropogenic disturbances

Next, three subplots were chosen in each vegetation plot by drawing lots to measure pressure metrics by domestic herbivores. We used the fecal pellets of these animals (goats, sheep, cows, and horses) as evidence of their presence in the plot in question. All pellets in the selected subplots were counted, and three of these were collected and weighed to calculate average biomass of each pellet. Finally, the total fecal biomass of each of these animals in the plot was calculated (Martorel and Peters 2005).

The fecal biomass from goats, sheep, cattle, and horses were entered as individual metrics in a Principal Component Analysis (PCA). The metrics were correlated with the first two axes of the PCA, and then we determined a single measure through the sum of their coordinates, which we called the Herbivory Pressure Index (Martorel and Peters 2005).

2.4 Soil sampling and analysis

A soil profile was opened, described, and classified in each vegetation plot according to the World Reference Base for soil resources (FAO, 2015). We collected deformed composed samples in the superficial horizons (A Horizon) in each profile, which varied from two to 10 cm in depth. We only considered this horizon because it exerts a more significant influence on the regenerating stratum since the roots of the seedlings do not yet reach the deepest horizons (Taiz et al., 2017). The collection method was based on the Field Soil Description and Collection Manual (Santos et al., 2005). We used a properly sanitized garden shovel, avoiding contamination risk of the samples, and collecting approximately 2 kg of soil in plastic bags.

These samples were air-dried, ground, and sieved in a 2 mm sieve prior to analysis. The coarse sand, fine sand, silt, and clay contents were determined after slow agitation with 0.1 M NaOH by the sieve-pipette method (Donagema et al., 2011). The soil pH was determined in deionized water (1: 2.5). The Al^{3+}, $Ca^{2+,}$ and Mg^{2+} contents were determined by 1 M KCl extraction. K^{+}, Na^{+} and P were determined after Mehlich^{-1} extraction. Potential acidity (H+Al) was determined by calcium acetate at pH 7.0. The soil organic carbon content was determined by acid digestion, according to the Walkey-Black method (Silva and Mendonca, 2007). The total nitrogen content was determined by the Kjeldahl method. the sum of bases (SB), cation exchange capacity (CEC), base saturation (V), and C/N ratio were subsequently calculated from these procedures.

Undisturbed samples were collected using volumetric rings (Donagema et al., 2011). The bulk density, particle density and the soil water retention curve (0, -6, -10, -30, -100, -1500 kPa) were determined. Total porosity, field capacity (FC), wilting point (WP), water subject to drainage, available water, and unavailable water were calculated from these data.

2.5 Statistical procedures

Biomass of individuals was calculated based on the DGL using the equation: Biomass = 0.173 DGLcm$^{2.295}$ (Amorim et al., 2005). We tested the normality of the data using the Shapiro Wilk test and homogeneity using the Bartlett's test (Crawley, 2013). Plot values for richness, abundance, height, diameter, biomass and each physical and chemical soil property were averaged for each area. The areas were compared using Student's T-tests and Pearson's chi-squared test for parametric data and non-parametric data, respectively.

We performed Pearson's correlation analyses to elucidate the relationships between vegetation and soil properties. Simple linear regressions were performed between the variables with the highest correlation, establishing the model which best described the results. The adult and regenerative strata were also correlated, as the adult vegetation acts as a vegetation cover and influences the regenerating stratum. We subsequently generated graphs only for the significantly correlated variables, using the plot function of the R statistical software program (R Core Team, 2018). Only the soil properties in the surface horizons were used in correlation analyses for the regenerating stratum. As a result, all horizons below the surface horizon were disregarded in the following analyses.

We performed a non-metric multidimensional scaling (NMDS) ranking to observe possible ordering in the species composition of regenerating stratum between the different areas using the metaMDS function of the vegan software package. In addition, the similarity between environments was analyzed using the ANOSIM test (Oksanen et al., 2018). All analyzes were performed using the R Studio 3.5.0. statistical software program (R Core Team, 2018).

Results

A total of 3,436 individuals were sampled, 2,519 of them in the adult stratum, distributed in 41 species and 17 families (Appendix 1), which represent the vegetation cover of our study. A total of 917 individuals were sampled in the regenerating stratum, with 29 species identified distributed in 15 families. The species *Aspidosperma pyrifolium*Mart (Apocynaceae) was the most frequent. The most frequent family was Euphorbiaceae (six species). Area I presented 526 individuals from the regenerating stratum, which were distributed in 11 species and six families. Area II presented 391 individuals, 27 species and 15 families. Two species were exclusive to Area I, while 18 species and nine families were exclusive to Area II.

The species were ecologically classified based on their distribution among the areas, with four categories being established: Aridity indicators, being dominant or exclusive species from the driest area (Area I); Sensitive species, being those found only in the most humid environments (Area II); Tolerant species, mainly distributed in the most humid environments, however, some individuals were also found in the drier area, confirming that the species tolerates such conditions; and finally, Common species, being those that are uniformly distributed between both areas (Appendix 1).

The NMDS ranking showed a low-stress value (stress = 0.06), and the similarity analysis showed significant differences between the areas regarding the composition and abundance of species present in the regenerating stratum (ANOSIM, r = 0.20; P=0.03) (Figure 2).

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The mean comparison tests between Area I and II showed significant differences in the seedling diameter and diversity. Area I presented the largest average diameter of seedlings , and Area II had the highest average diversity of orders 1 (RegD1) and 2 (RegD2). The Herbivory Pressure Index in the plots ranged from 0.08 to 13.37, however there was no significant difference between the areas (Table 1).

Note : Here Table 1 will be inserted

Cambisol was the dominant soil group identified in the study area with six soil profiles. We also found three Luvisols, one Gleysol, one Planosol, and one Regosol. All soil properties have high standard deviation values in Area I and Area II, indicating high soil variability (Table 2). All A horizons were classified as ochric horizons. They varied between 2 and 10 cm in thickness. The A horizon in Area I and Area II is dominantly sandy clay loam and has base saturation above 80%. The Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}, and P contents were not significantly different between Areas I and II. Only the average C and N levels showed significant differences, with a higher average in Area II (Table 2).

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The herbivory pressure index showed a weakly positive relationship with the diameter at ground level of saplings (DGL) (Figure 3b) and a negative relationship with the diversity of order 0 of the regenerating stratum (RegD0) (Figure 3c). RegD0 is also showed a positive relationship with biomass (Figure 3d), diversity (D0) (Figure 3e) and abundance of the adult stratum (Figure 3f). The DGL of the regenerating stratum showed a negative relationship with the abundance (Figure 3a) and biomass of the adult stratum. The abundance of seedlings also showed a negative relationship with the height of the adult stratum.

The diversity (RegD0) and biomass of the regenerating stratum also showed positive relationships with soil carbon and nitrogen levels (Figure 3g and Figure 3h). Despite showing relatively weak relationships, these linear regressions are all significant (Figure 3).

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Discussion

Our results indicate significant differences in the floristic composition of regenerating stratum, diversity, DGL, and C and N levels in the soil between different vegetation cover areas. Species more resistant to water and anthropic stress and common in degraded areas, such as *A. pyrifolium, C. pyramidales,* and *T. palmadora*(Meiado, 2012; Souza et al., 2015a, 2015b), are dominant in Area I. On the other hand, Area II presents more than twice the number of species in the first area, and also shows 18 exclusive species. The Hill numbers D1 and D2 also showed higher mean richness in the area of denser vegetable coverage (Area II), indicating a higher number of common and dominant species in it, and consequently a more uniform distribution in the abundances of each species.

The abundance of species and individuals of Euphorbiaceae family can be attributed to their adaptive capacity, palatability, and potential for use by humans (Ribeiro et al., 2015, Rito et al., 2017). The dominance of *A. pyrifolium* , especially in Area I, is attributed to its high resistance to drought and because it is unpalatable to some herbivores, mainly goats and sheep. Such properties are conferred by its epicuticular wax, which in addition to ensuring greater efficiency in the use of water, has a composition rich in toxic compounds, thus presenting a competitive advantage over species more sensitive to semi-arid climates (Medeiros et al., 2017).

Moreover, the anthropic pressure on this species is low since its wood has little utility value. *T. palmadora* , the second most abundant species in our study, is morphophysiologically adapted and resistant to water stress, unpalatable to animals due to its large amount of spines, and has a high reproductive rate. It can spread asexually through its branches and fruits even under limiting conditions (Meiado, 2012). *C. pyramidale* , the third most abundant specie in the study, is resistant to water deficits, high salt concentrations, and high temperatures, being widely found in degraded areas (Matias et al., 2018). Finally, species of genus *Jatropha* also have low wood density, making it of little use for human use. It is considered unpalatable to animals, and it has a high water reserve capacity, guaranteeing its survival and reproductive success (Ribeiro et al., 2015; Silva et al., 2004).

The absence of statistical differences in the content of exchangeable bases and texture between soils of Areas I and II can be attributed to: a) affinity of the soils with the parent material, and; b) relative homogeneity of sampled lithologies. The semi-arid climate in Northeast Brazil favors low chemical weathering of minerals and incipient pedogenesis (Araujo et al., 2017). These soils consequently express characteristics associated with their parent material, especially Cambisols and Neossols (FAO, 2015). Since gneiss is the main lithology of Cariri Paraibano (Lages et al., 2018), it is expected that the soils have similar characteristics. On the other hand, the statistical difference in the C and N levels between Areas I and II indicate environments with different inputs of plant residues to the soil and/or different preservation levels.

The environmental conditions provided by the greater abundance, biomass and diversity of adults observed in Area II favor the establishment of a more diverse regenerating stratum by: a) guaranteeing a larger seed bank in the community (Chazdon, 2014); b) attracting dispersing and pollinating agents (Guevara et al., 1986); c) facilitating seedling germination and establishment; and d) and providing greater protection to seedlings. Adult stratum areas with higher biomass protect the regenerating stratum against predation and trampling by herbivores (Derroire et al., 2016b; Marinho et al., 2016). Large herbivores prefer to forage in more open environments due to greater accessibility and to the palatability of the established herbaceous layer (Skarpe et al., 2007). Herbivore pressure negatively influenced species diversity, which was lower in more open areas (Area I). We suggest that the pressure of herbivores in Area I is favored by the ease of access and greater abundance of herbaceous plants present in the area, where their pressure can reduce species diversity.

In addition, microclimate conditions are milder under higher vegetation levels. The shade provided in environments with a higher number of trees reduces the transpiration rates of seedlings by decreasing their exposure to high light and temperature levels, as well as retaining greater moisture in the soil and providing a higher amount of organic waste to the soil (Derroire et al., 2016a; Lebrija-Trejos et al., 2011).

The positive correlations between the diversity of regenerative stratum (RegD0) with C and N levels in the soil indicate the importance of soil organic matter content in the ecological succession of areas. The supply of plant residues and their incorporation into the soil ensures nutrient cycling (Menezes et al., 2012; Sousa et al., 2012). As semi-arid soils are mostly eutrophic, the availability of nutrients derived from mineral weathering, such as Ca, Mg, and K, is not limiting for plant growth. On the other hand, C and N are primary macronutrients derived from the decomposition of soil organic matter (Six et al., 2004), therefore they are highly associated with soil organic matter content and quality (Ostrowska and Porębska, 2015). In addition, higher soil organic matter levels favor aggregate formation, reducing soil density and increasing porosity and water infiltration (Ferreira et al., 2018; Silva e Mendonça, 2007).

The negative correlation between the abundance of seedlings and the adult stratum height can be attributed to establishing a denser canopy in forest conditions than open areas. Areas with taller trees guarantee more favorable environmental conditions for plant growth (Lebrija-Trejos et al., 2011), providing greater balance in the community than the proliferation of more resistant species observed in more disturbed environments such as Area I (Rito et al., 2017). The higher number of exclusive species sensitive to degradation in Area II reinforces this hypothesis (Barbosa et al., 2007, Souza et al., 2015a).

The higher mean DGL of the regenerating stratum in the area of lower plant density (Area I) can be attributed to the decrease in competition for light (Mclaren and Mcdonald, 2003). However, despite the greater shading faced by seedlings in Area II, it is known that light is not one of the most limiting resources in the Caatinga (Sampaio, 2003). Thus, this factor alone does not fully explain our results. The DGL also showed a positive correlation with pressure by herbivory, and we speculate that these effects are indirect, and the greater secondary growth in Area I is related to the plant's physiological adaptations to water stress to which it is subjected.

The growth of some plant species in arid and semi-arid environments is limited to the season of water availability, passing through growth pulses during the rainy season and dormancy during the driest months (García-Cervigón et al., 2017). Therefore, plants respond quickly to precipitation events because of this limitation, investing in wood and leaf production while water is available in soil. The irregular distribution of rainfall observed in the Brazilian semi-arid region with sporadic precipitation events in the dry months can stimulate several growth pulses during the year (Aragão et al., 2019). Furthermore, the distribution of photoassimilates by the plant varies according to the availability of resources, and root growth and secondary growth become the priority over primary growth when under limiting conditions (Mattos, 1999). Thus, the largest mean diameter observed in Area I can be attributed to such factors. However, complementary physiological studies are necessary to confirm this idea since these responses vary between different species (Aragão et al., 2019).

As expected, RegD0 was negatively related to pressure by herbivory. Herbivores generally cause adverse effects on plant communities, causing habitat degradation, limiting the growth of individuals, and affecting the taxonomic composition (Sfair et al., 2018; Souza et al., 2015a). The effects on the regenerative stratum are even more robust, since the animals have a preference for younger individuals due to their palatability, and they are even more susceptible to trampling mortality, compromising the diversity, structure, and maintenance of the plant community in the future (Marinho et al., 2016).

Our results indicate a more advanced secondary succession stage in Area II. In addition to the low diversity, Area I has many individuals identified as *A. pyrilifolium* , which suggests biotic homogenization due to anthropic disturbance. Diversity in degraded environments is reduced due to a decrease in species which are more sensitive to environmental changes and an increase in the abundance of the most resistant species (Ribeiro-Neto et al., 2016). The lower C and N levels in the soils of Area I also seem to be directly related to the anthropic disturbance. This scenario is the first step towards establishing the desertification process. These results are a consequence of the degradation regime imposed on the Caatinga since its colonization, including agricultural activities (Travassos and Souza, 2014). Nowadays, deforestation and inappropriate land use in agricultural areas compromise productivity, hampering natural regeneration in these areas (Leal et al., 2005; Marinho et al., 2016; Sousa et al., 2012; Sfair et al., 2018).

Considering the colonization and occupation processes of Cariri Paraibano, the impacts could mainly be related to livestock activities, especially goat farming, since it is a prevalent practice in the area, in which animals are raised freely to feed on native vegetation (Leal et al., 2005). This was evidenced in our study through the high biomass of fecal pellets found. This fact is pointed out as one of the main reasons for the vegetation cover loss in drylands and a strong driver of the desertification process (Marinho et al., 2016).

These results highlight the importance of adjusting the grazing practice of these areas to guarantee maintenance of plant communities and biological diversity. One of the most efficient land management practices is fallow, which isolates the land and allows it to recover through its resilience, promoting recovery of soil fertility, water storage capacity, and plant communities (Ferreira, et al., 2018). In the case of the Brazilian semi-arid region, this practice is not yet realistic for social and economic reasons. However, the development of public policies to raise awareness and incentives for more sustainable development is indicated. For example, better livestock management along with the creation of trapped herders avoids continuous removal of native vegetation andallows its restoration through natural regeneration (Leal et al., 2005). Another measure of fundamental importance would be creating Conservation Units of Integral Protection, which are still scarce in the Caatinga (Antongiovanni et al., 2020; MMA, 2011).

Conclusions

Our results confirm the effects of vegetation cover on the natural regeneration of plant communities in the Brazilian semi-arid region. The higher biomass and diversity of the adult stratum added to a higher C and N content in Area II soil led to the establishment of a higher number of species, with even greater equity.

The results indicate overgrazing as one of the main threats and drivers of the desertification process in the region, highlighting the importance of implementing management techniques in the use of these lands. Creating Conservation Units of Integral Protection and encouraging more sustainable development through environmental education are essential measures to be implemented.

Conflict of Interest Statement

The authors declare no conflicts of interest.

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Titles and Legends

Table 1. Mean (standard deviation) of regenerating community variables in two areas with different vegetation cover levels in the Brazilian semi-arid region. (Area I: Less coverage; Area II: Increased coverage) */= Bold values are statistically different.

Table 2. Mean (standard deviation) of soil properties in two areas with different vegetation cover levels in the Brazilian semi-arid region. (Area I: Less coverage; Area II: Increased coverage) */= Bold values are statistically different.

Fig. 1 – Dry forest biome in Brazil (a), study area location (b), and sample distribution in the study area according to NDVI (c).

Fig. 2 – Floristic groups of the regenerating stratum of the study area. The vegetation plots are ordered for each of the two dimensions produced by NMDS ranking performed using a Bray-Curtis similarity and altitude matrix based on abundance and vegetation cover. The vegetation plots of Area I and Area II are represented as black dots and gray dots, respectively.

Fig. 3 – Statistically significant linear regressions at $p < 0.05$ for relationships between regenerating stratum data with adult vegetation data, herbivore pressure and soil properties e. Reg. = Regenerating. 3.a) Reg DGL x Abundance of Adults; 3.b) Reg DGL x herbivory pressure relationships; 3.c) Reg D0 x Herbivory pressure relationships; 3.d) Reg D0 x Adult Biomass relationships; 3.e) Reg D0 x D0 Adults relationships; 3.f) Reg D0 x Abundance of Adults; 3.g) Reg D0 x Organic Carbon relationships; 3.h) Reg D0 x Total Nitrogen relationships.

Table 1

Community variables	Area I	Area II	p value*	t / w
Families	6	15	-	-
Observed richness	11	27	-	-
Absolute abundance	526	391	-	-
Abundance (Ind.)	87.66 (45.72)	65.16 (37.45)	0.37	0.9324
Diameter (cm)	1.6 (0.65)	1.0 (0.61)	**0.00**	139770
Height (m)	0.49 (21.20)	0.50 (26.24)	0.91	103260
Biomass (mg / m^2)	50.08 (42.03)	16.87 (19.60)	0.17	27
Order Div. 0 (RegD0)	6.50 (1.72)	11.47 (6.73)	0.33	11.5
Order Div 1 (RegD1)	3.91 (0.96)	5.94 (3.20)	**0.04**	5
Order Div 2 (RegD2)	2.75 (0.84)	4.84 (2.00)	**0.05**	-2.3569
Equability	0.39 (0.10)	0.51 (0.19)	0.22	-1.3175
Herbivory Pressure Index	0.43 (0.11)	0.44 (6.66)	0.44	10

Table 2

Soil propertie	**Area I**	**Area II**	**p value***	**t / x**
Surface layer	**Surface layer**	**Surface layer**	**Surface layer**	**Surface layer**
Organic carbon (%)	0.79 (0.50)	1.93 (1.20)	**0.05**	-2.2473
Total nitrogen (%)	0.07 (0.02)	0.16 (0.08)	**0.03**	-2.5265
C/N ratio	10.38 (3.21)	11.54 (1.43)	0.48	-0.7540
Ca^{2+} (cmolc /dm^3)	10.86 (4.33)	10.30 (9.39)	0.89	0.1399
Mg^{2+} (cmolc /dm^3)	1.60 (3.20)	1.93 (1.52)	0.87	19
Na^+ (mg /dm^3)	24.93 (36.43)	16.81 (59.99)	0.51	22
K^+ (mg /dm^3)	153.60 (80.63)	237.71 (113.72)	0.16	-1.4991
P (mg /L)	23.2 (159.74)	25.9 (51.13)	0.75	15
Base saturation (%)	88.44 (8.94)	80.64 (11.94)	0.22	1.2926
Coarse sand (%)	34 (0.04)	33 (0.10)	0.94	0.071049
Fine sand (%)	27 (0.14)	28 (0.12)	0.88	-0.1491
Silt (%)	18 (0.07)	16 (0.05)	0.59	0.55141
Clay content (%)	21 (9)	15 (14)	0.20	26
Available water (m^3 /m^3)	0.11 (0.37)	0.10 (0.38)		
Unavailable water (m^3 /m^3)	0.07 (0.43)	0.07 (0.40)		
Total porosity (m^3 /m^3)	0.42 (1.43)	0.43 (1.69)		
Wilting point (m^3 /m^3)	0.07 (0.43)	0.07 (0.40)		

Figure 1

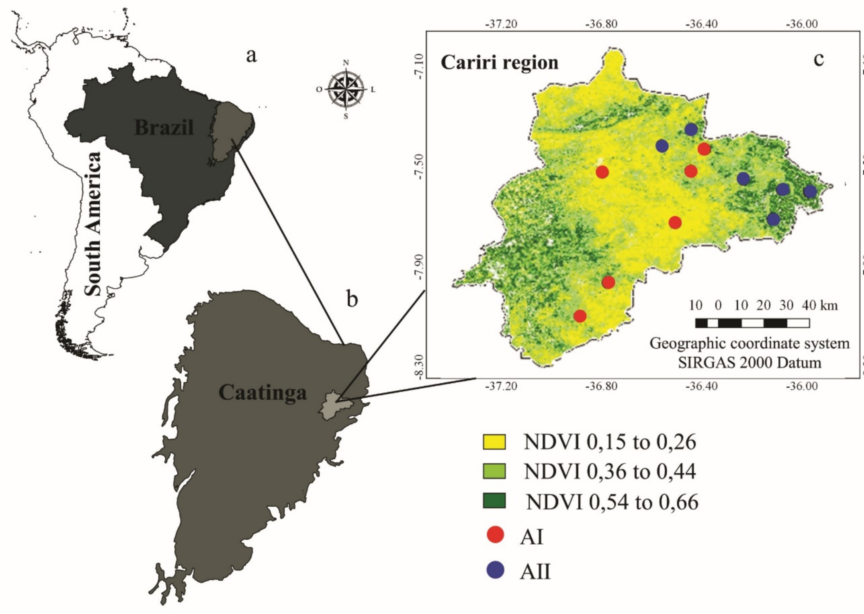
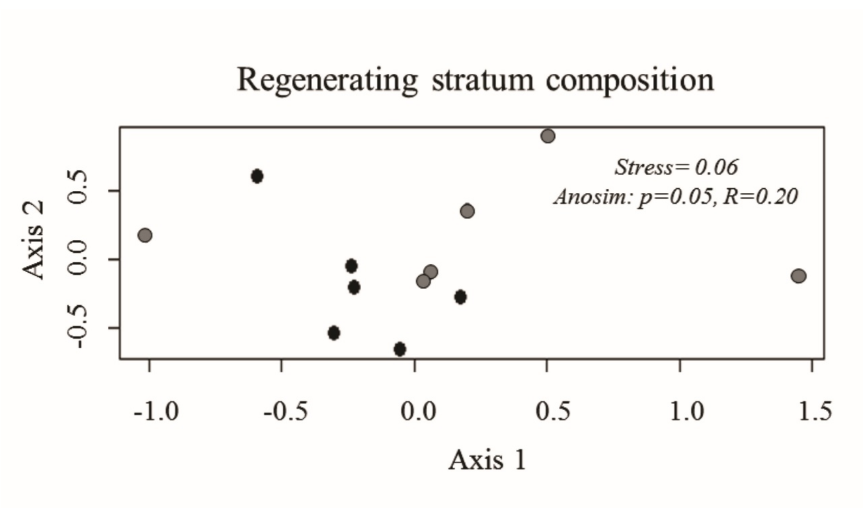

a
b
c
Brazil
South America
Caatinga
Cariri region
10 0 10 20 30 40 km
Geographic coordinate system
SIRGAS 2000 Datum
NDVI 0,15 to 0,26
NDVI 0,36 to 0,44
NDVI 0,54 to 0,66
AI
AII

Figure 2


Regenerating stratum composition
Stress= 0.06
Anosim: p=0.05, R=0.20
Axis 1
Axis 2

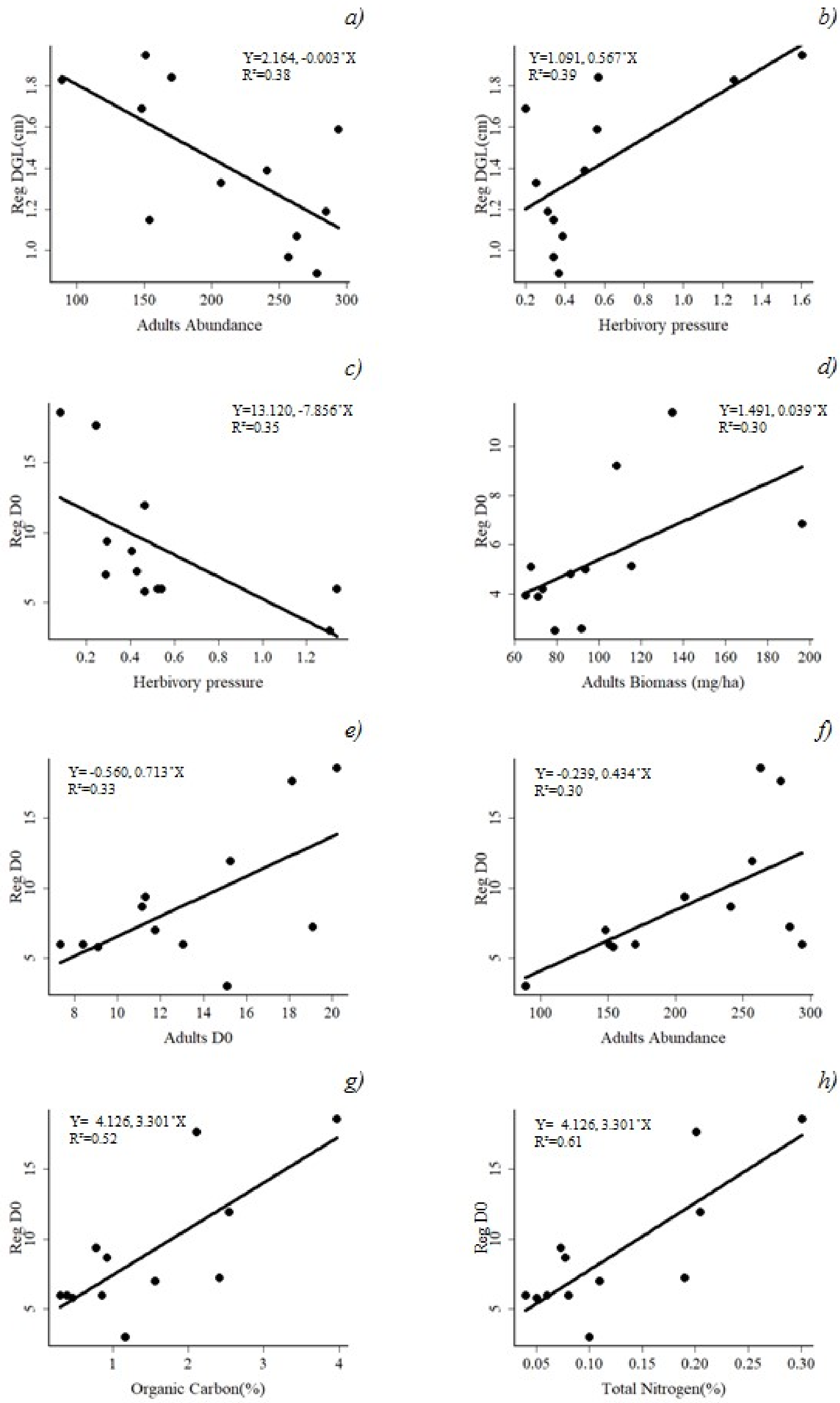

a)
Y=2.164, -0.003*X
R²=0.38
Reg DGL(cm)
Adults Abundance
b)
Y=1.091, 0.567*X
R²=0.39
Reg DGL(cm)
Herbivory pressure
c)
Y=13.120, -7.856*X
R²=0.35
Reg D0
Herbivory pressure
d)
Y=1.491, 0.039*X
R²=0.30
Reg D0
Adults Biomass (mg/ha)
e)
Y= -0.560, 0.713*X
R²=0.33
Reg D0
Adults D0
f)
Y= -0.239, 0.434*X
R²=0.30
Reg D0
Adults Abundance
g)
Y= 4.126, 3.301*X
R²=0.52
Reg D0
Organic Carbon(%)
h)
Y= 4.126, 3.301*X
R²=0.61
Reg D0
Total Nitrogen(%)

Figure 3