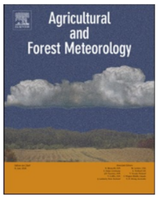
Agricultural and Forest Meteorology 279 (2019) 107712

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Seasonal patterns of deposition litterfall in a seasonal dry tropical forest

Maria Gabriela de Queiroz[a], Thieres George Freire da Silva[b,c,*], Sérgio Zolnier[a], Carlos André Alves de Souza[c], Luciana Sandra Bastos de Souza[b], Steidle Neto[d], Gherman Garcia Leal de Araújo[e], Williams Pinto Marques Ferreira[f]

[a] *Department of Agricultural Engineering, Universidade Federal de Viçosa, Viçosa, Minas Gerais, Brasil*
[b] *Agrometeorology Laboratory, Unidade Acadêmica de Serra Talhada, Universidade Federal Rural de Pernambuco, Serra Talhada, Pernambuco, Brasil*
[c] *Department of Agricultural Engineering, Universidade Federal Rural de Pernambuco, Recife, Pernambuco, Brasil*
[d] *Department of Agrarian Sciences, Universidade Federal de São João Del-Rei, Sete Lagoas, Minas Gerais, Brasil*
[e] *Semiarid Research Centre, Empresa Brasileira de Pesquisa Agropecuária, Petrolina, Pernambuco, Brasil*
[f] *National Coffee Research Centre, Empresa Brasileira de Pesquisa Agropecuária, Viçosa, Minas Gerais, Brasil*

A R T I C L E I N F O

Keywords:
Semi-arid region
Caatinga
Environmental variables
Process of decomposition
Seasonal pattern

A B S T R A C T

The Caatinga Domain is exclusively Brazilian, covered by vegetation exhibiting a great diversity of species, which have morphological and physiological characteristics determined by environmental conditions. These attributes define quantity and quality litterfall deposition on the soil. The litterfall deposition seasonality was monitored a fragment of Caatinga vegetation, located in the semiarid region of Brazil, from 2016 to 2017. The decomposition rate, mean residence time for litterfall (50 and 95%), and the exportation of mineral nutrients via deciduous material were determined. Data from meteorological variables and litterfall were used in the elaboration of Pearson's correlation matrix, and multicollinearity, canonical and path analyzes. The Caatinga deposited on average 637 kg DM (dry mass) ha^{-1} $year^{-1}$ litterfall, including 53% leaves, 26% twigs, 15% reproductive structures and 6% miscellanea, with deposition peaks between the months of March and July, with values above 57 kg MS ha^{-1}. Global solar radiation, vapor pressure deficit, soil heat flux, rainfall and normalized difference vegetation index are controlling factors the litterfall deposition. The decomposition rate of the litterfall was 0.33 kg DM ha^{-1} $year^{-1}$, while the time required for the disappearance of 50% and 95% of the litterfall was respectively 2.1 and 9.1 years, and the exportation of nutrients was 13.59 kg ha^{-1} $year^{-1}$. Litterfall deposition was determined by the environmental conditions and physiological responses of the vegetation, which are fundamental to maintaining the Caatinga Domain.

1. Introduction

Seasonally dry tropical forests are recognized as one of the world's major biomes, being located in a wide area extending from the Amazon basin in South America towards northern Mexico and the Caribbean. In South America, the Caatinga domain located in the Brazilian Northeast is characterized by being the only continuous large area of this type of forest (Santos et al., 2012). The Caatinga is characterized by a mosaic of xerophytic species, composed of woody vegetation with discontinuous tops, formed mainly by succulent species (cacti) and bushes and non-succulent trees (Barbosa et al., 2019; Santos et al., 2012).

For natural ecosystems, the deposition and decomposition of litterfall is therefore the main source of organic matter and energy for heterotrophic organisms, this process contributes to the recovery and conservation of degraded areas by maintaining soil fertility (Campos et al., 2017; Correia et al., 2016; Freitas et al., 2015; Huang and Li, 2017; Rai et al., 2016). Plant species are able to deposit significant amounts of nutrients, which enter naturally into the soil-plant system through the accumulation of litterfall and its subsequent decomposition, promoting reactivation of mineral cycling (Ludvichak et al., 2016; Rai et al., 2016; Sánchez-Andrés et al., 2010).

In the Caatinga, the processes of deposition and decomposition of deciduous material are highlighted, due to the occurrence of soils with low nutrient levels (Santana and Souto, 2011), reduced carbon stocks (Schulz et al., 2016), and frequent abiotic stress (Vieira et al., 2013). Litterfall is composed of the fractions of leaves, twigs, stems, bark,

---

* Corresponding author at: Unidade Acadêmica de Serra Talhada, Universidade Federal Rural de Pernambuco, Recife, Pernambuco, Brasil.
E-mail addresses: thieres.silva@ufrpe.br (T.G.F. da Silva), zolnier@ufv.br (S. Zolnier), carlosandre08_@msn.com (C.A.A. de Souza), sanddrabastos@yahoo.com.br (L.S.B. de Souza), antonio@ufsj.edu.br (S. Neto), gherman.araujo@embrapa.br (G.G.L. de Araújo), williams.ferreira@embrapa.br (W.P.M. Ferreira).

https://doi.org/10.1016/j.agrformet.2019.107712
Received 26 September 2018; Received in revised form 4 August 2019; Accepted 16 August 2019
0168-1923/

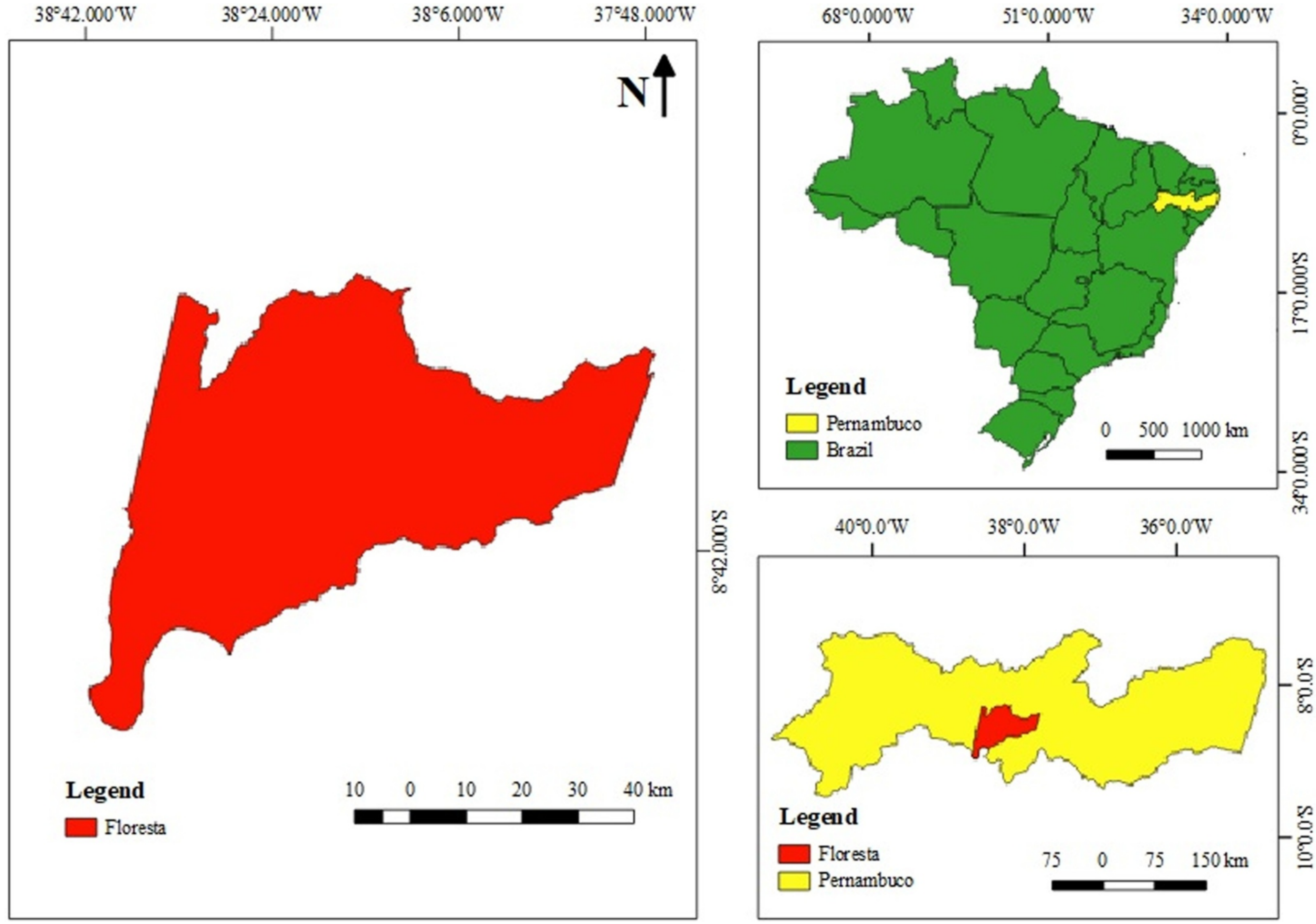


Fig. 1. Location map of the study site.

seeds, fruits, flowers, inflorescences and animal waste (Andrade et al., 2008). These fractions may present expressive and variable depositions over time, and their monitoring allows understanding the phenological of the species found in different ecosystems, indicating the heterogeneity of vegetation and environmental conditions (Andrade et al., 2008; Arato et al., 2003). The foliar fraction, for example, identified in several studies with the highest deposition (Correia et al., 2016; Freitas et al., 2015; Ludvichak et al., 2016; Zhang et al., 2014) reflects the mechanisms adaptive to water stress and/or the physical characteristics of the environment in which the plants are submitted (Costa et al., 2010).

On a local scale, the microclimate environment, local water regime, soil organisms and the quality of the litterfall affect regulation of the decomposition rates of deciduous material (Bernaschini et al., 2016; Cizungu et al., 2014; Holanda et al., 2015; Huang and Li, 2017; Ludvichak et al., 2016; Rai et al., 2016). Studies carried out in a region of arid continental climate in China have shown that ultraviolet radiation, frequency and amount of rainfall and their interactions affected litterfall decomposition in native species, witch photodegradation accelerates the decomposition process of the litterfall (Huang and Li, 2017).

Litterfall deposition fluctuates in response to biotic and abiotic stimuli, such as the successional stage of the vegetation, plant density, age of the plant population, herbivory, nutrient stock, water availability and local weather conditions, among others (Correia et al., 2016; Silva et al., 2009). The interactions between litterfall deposition and climate parameters in the Caatinga environment have hardly been studied, although they are extremely relevant to understand how climate changes, promoted by anthropic action, could affect the deposition of litter by this domain. In seasonally dry forests, such as the Caatinga, vegetation cover is strongly related to spatial and temporal seasonality, and to annual rainfall averages, since in periods of drought vegetation expresses extremely low levels of photosynthetic activity (Cunha et al., 2019). However, there is evidence that the seasonality of litterfall deposition would be determined by other environmental variables in addition to rainfall, as exposed by Zhang et al. (2014), which show that in tropical forests rainfall and solar radiation limit the fall of deciduous material. Silva et al. (2009) suggest the association between meteorological variables and litterfall production can explain how forests respond to water stress conditions. These authors found correlations between the litterfall and wind speed, global solar radiation and photosynthetic active radiation, soil temperature and moisture content, and rainfall.

Determining the litterfall deposition in the actual climatic conditions can help improve the performance of climate models and subsidize projections of nutrient cycling in dry forests. The fifth report of the Intergovernmental Panel on Climate Change (IPCC AR5) alludes to temperature increases and, rises or reductions in rainfall for South America by 2100, with projected warming ranging from 1.7 °C to 6.7 °C (IPCC, 2014). The investigates mentioned in IPCC AR5 explain that the northeastern region of Brazil, although already highly vulnerable to climate conditions, will be affected by rainfall deficit and increased aridity predicted for the next century, with negative consequences for the Caatinga domain (IPCC, 2014). In semi-arid tropical areas understanding the response of vegetation to drought conditions is essential in establishing the relations between climate change and land degradation

(Barbosa et al., 2019).

It is estimated that 80% of the territory occupied by Caatinga vegetation has been modified (Vieira et al., 2013), as intensive exploitation of the northeastern semi-arid region, especially by agriculture and livestock, promotes a loss of biodiversity, a decrease in soil fertility and an increase in the processes of erosion (Coelho et al., 2014; Souza et al., 2015). Land degradation is one of the most serious regional and global environmental problems, so that all forest ecosystems have considerable changes to their original areas, mainly due to anthropogenic action (Coelho et al., 2014; Correia et al., 2016; Rai et al., 2016). In this sense, the litterfall is indicated as a good indicator of recovery of degraded areas, in order to promote succession and restoration of vegetation in an accelerated manner (Arato et al., 2003).

The rich biodiversity of species of the Caatinga, annually deposits organic waste on the soil, which will be decomposed and will provide nutrients to plants. In this study, we sought to determine the quantity and seasonality of the litterfall accumulation, its nutrient content and its speed of decomposition in the Caatinga vegetation, as well as identify the mechanisms that cause the pattern of deposition, in order to verify the role of this component in the functional maintenance of this vegetation.

2. Material and methods

2.1. Description of the study area

The study site is located in a rural area of the district of Floresta, in the State of Pernambuco (PE), in the Northeast of Brazil (08°18′31″S, 38°31′37″W, 378 m) (Fig. 1). The climate in the region is semi-arid, type BSh (Alvares et al., 2014). The local climate and the physical and chemical characteristics of the soil area are presented in Tables 1 and 2 respectively. To this end, data from weather stations located in the municipality of Serra Talhada-PE and Floresta-PE were used to climatically characterize the region of the study area. To define the chemical-physical attributes of the soil in the area, samples were collected to a depth of 0.60 m, resulting in six layers from 0.00–0.10 m to 0.50–0.60 m.

The research was carried out in a private property, which has a vegetation area of Caatinga of 81,000 m^2. It has a support density of 930 trees ha^{-1}, with a mean diameter at breast height (DBH, measured 1.3 m from the ground) of 26 cm and 5 cm, mean diameter at the base (DAB, measured 0.3 m from the ground) of 33 cm and 7 cm, and mean height of 8 m and 3 m, for tree and shrub plants respectively. These data were obtained by forest inventory and from biomass equations specific to trees and shrubs of the Caatinga, as described by Albuquerque et al. (2015) and Sampaio and Silva (2005).

2.2. Litterfall deposition and decomposition

Litterfall refers to material of organic origin that is deposited and accumulated on the ground, and is a primary source of nutrients for ecosystems (Correia et al., 2016; Rai et al., 2016). To quantify accumulated deposition in the Caatinga, the trap method was used, where the aim was to collect the plant debris, using a systematic sampling (Fig. 2). To do this, 26 collectors were used, 0.50 m × 0.50 m (0.25 m^2) in size, made from plastic sheeting and 1 mm meshes, with collectors installed below the plant canopy at a height of 1 m above the ground (Fig. 3A and B).

Litterfall deposition was monitored in predominant species in the area: Anacardiaceae: *Spondias tuberosa* Arruda; Burseraceae: *Commiphora leptophloeos* (Mart.) Gillett; Euphorbiaceae: *Cnidoscolus quercifolius* Pohl. and *Croton blanchetianus* Baill.; Apocynaceae: *Aspidosperma pyrifolium* Mart. and Fabaceae: *Cenostigma pyramidale* (Tul.) Gagnon & Lewis. Table 3 shows the mean characteristics of the monitored plants.

The litterfall was collected monthly (last days of each month) and the material separated into the following fractions: leaves (covering petioles and leaflets), twigs (of all sizes, with the bark), reproductive structures (flowers, inflorescences, fruit and seeds) and miscellanea (components of animal origin and unidentifiable parts) (Fig. 3C). Litterfall deposition was monitored from March 2016 to October 2017 (20 samples). All the samples were dried in a forced circulation oven at 65 °C, for a period of 48 h to constant weight and then weighed on an analytical balance. Litterfall contribution per hectare (kg ha^{-1}) was estimated based on the area and average monthly amount of dry matter per sample (0.25 g m^{-2}).

At the same time, plant debris deposited on the ground was collected by means of a wooden 0.50 m × 0.50 m frame. The frame was placed randomly in areas near the litterfall collectors (Fig. 3D), with five samples being collected in each measurement campaign. From the litterfall data, the rate of decomposition and mean decomposition time were determined, as well as the average residence time of the litterfall.

The rate of decomposition was obtained by calculating the constant *k*, where this parameter indicates the speed of the decomposition process, using the values for annual litterfall production taken from the suspended collectors, and the annual mean value for litterfall on the ground (Eq. (1)).

$$k = \frac{L}{Xss} \tag{1}$$

k = litterfall decomposition rate (year^{-1});
L = litterfall produced annually (Kg ha^{-1} year^{-1});

Table 1
Climate normals (1961–1990) for meteorological elements in the district of Floresta, PE, in the central hinterlands of Brazil.

Month	Rainfall	T_N	T_M	T_X	RH	u	ETo	R_G
	(mm)		°C		(%)	(m s^{-1})	(mm)	(MJ m^2 day^{-1})
January	66.1	21.7	27.4	34.7	59.9	2.0	5.9	23.4
February	79.4	21.5	26.7	33.9	63.8	1.9	5.7	23.6
March	104.3	21.4	26.5	33.6	68.5	1.9	5.5	23.2
April	66.7	21.0	26.0	32.8	70.4	1.9	5.0	21.5
May	37.2	20.2	25.0	31.8	70.4	2.0	4.4	18.7
June	19.9	18.9	23.8	30.7	70.1	2.4	4.2	16.9
July	16.6	18.1	23.3	30.4	69.0	2.5	4.3	17.9
August	7.0	18.1	24.1	31.7	61.1	2.7	5.4	21.8
September	7.6	19.3	25.9	33.7	54.1	2.9	6.3	23.8
October	12.1	20.8	27.6	35.3	50.3	2.7	6.8	25.5
November	22.6	21.8	28.3	36.0	50.8	2.4	6.8	25.7
December	49.8	22.0	28.0	35.2	54.2	2.1	6.3	24.1
Annual	489.3	20.4	26.1	33.3	61.9	2.3	5.5	22.2

T_N, T_M e T_X – minimum, mean and maximum temperature; RH – relative humidity; u – wind speed; ETo – reference evapotranspiration; R_G – global solar radiation.

Table 2

Physical and chemical characterization of the soil at the site in the Caatinga Domain, in the district of Floresta, PE, in the central hinterlands of Brazil.

Depth	Ds	Dp	Total P	pH	P	K	Na	Ca	Mg	H + Al	SB	CTC	V
cm	--kg dm^{-3}--		%		mg dm^{-3}		cmolc dm^{-3}						%
0–10	1.44	2.58	44.07	6.3	9.64	5.37	0.68	5.32	1.98	1.03	13.37	14.38	90.6
10–20	1.45	2.52	43.46	6.1	4.24	2.51	1.07	5.37	2.20	1.88	11.12	13.02	85.6
20–30	1.44	2.53	42.76	6.1	3.63	1.29	2.39	5.75	2.23	1.40	11.67	13.07	88.3
30–40	1.46	2.54	42.74	6.2	2.00	1.31	4.84	6.73	2.70	1.32	14.17	15.48	84.7
40–50	1.46	2.56	42.52	6.7	3.69	1.29	8.28	6.73	2.92	0.73	19.23	19.98	94.5
50–60	1.47	2.54	42.38	6.9	20.96	1.62	8.97	6.83	3.05	0.62	20.48	21.10	95.6

Ds – bulk density; Dp – particle density; Total P – total porosity; pH – potential of hydrogen; P – phosphorus; K – potassium; Na – sodium; Ca – calcium; Mg – magnesium; H + Al – acid potential; SB – sum of bases; CTC – cation exchange capacity; V – base saturation.

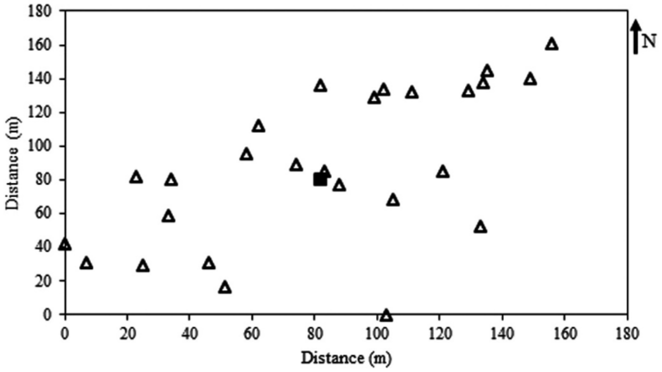


Fig. 2. Mapa da parcela experimental mostrando a localização das árvores com os coletores de serapilheira (Δ). ■, torre micrometeorológica.

Xss = mean annual litterfall accumulated on the ground (Kg ha^{-1})

The mean residence time (return) of the litterfall on the ground is the inverse of k (1/k), expressed in years. Finally, the mean disappearance time of the material was calculated for 50% (t0.5) and 95% (t0.05) (Eq. (2) and (3)) (Arato et al., 2003; Olson, 1963; Vital et al., 2004).

$$t_{0.5} = \frac{\ln 2}{k} \tag{2}$$

$$t_{0.05} = \frac{3}{k} \tag{3}$$

Due to the sparse arrangement of the Caatinga areas, vegetation and soil covers were obtained through orbital images between the years 2016 and 2017, for an area of 81,000 m^2, corresponds to the limits of the monitored property. Seven images of the Landsat 8 satellite were obtained (https://earthexplorer.usgs.gov/), using as a criterion of choice have at least 80% area no clouds. Based on these images the NDVI (Normalized Difference Vegetation Index) was calculated for each date. The identification of the areas covered by vegetation and exposed soil was made based on a supervised classification using software Qgis version 4.3.3., considering as vegetation NDVI values higher than 0.2% (herbaceous and/or tree). Vegetation and soil covers were equal to 57% (± 5%) and 43% (± 5%) respectively. Thus, the percentage values of litterfall were adjusted to the percentage of vegetation coverage (57%).

2.3. Chemical composition of the litterfall

The litterfall dry samples were crushed in a Wiley mill with 30 mesh, and a composite sample (mean of 100 g) was obtained for each collection date. The samples were sent to the Brazilian Agricultural Research Corporation for further chemical analysis, in which the nutrient content per fraction were obtained according to Embrapa (2009). Nutrient export was evaluated based on the levels of potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn) and sodium (Na). For determinate the potassium content was used flame photometry method; sulfur was obtained by turbidimetry and, calcium, magnesium, copper, iron, manganese, zinc and sodium by atomic absorption spectrophotometry (after perchloric digestion of nitrate). The nutrients total in each fraction was calculated by multiplying the nutrient content by the dry matter amount.

2.4. Micrometeorological and soil moisture measurements

Acquisition of the weather data was by electronic sensors arranged in a micrometeorological tower installed of 8 m of height at experimental site, comprising a net radiometer (NR-Lite Inc., Logan, Utah,

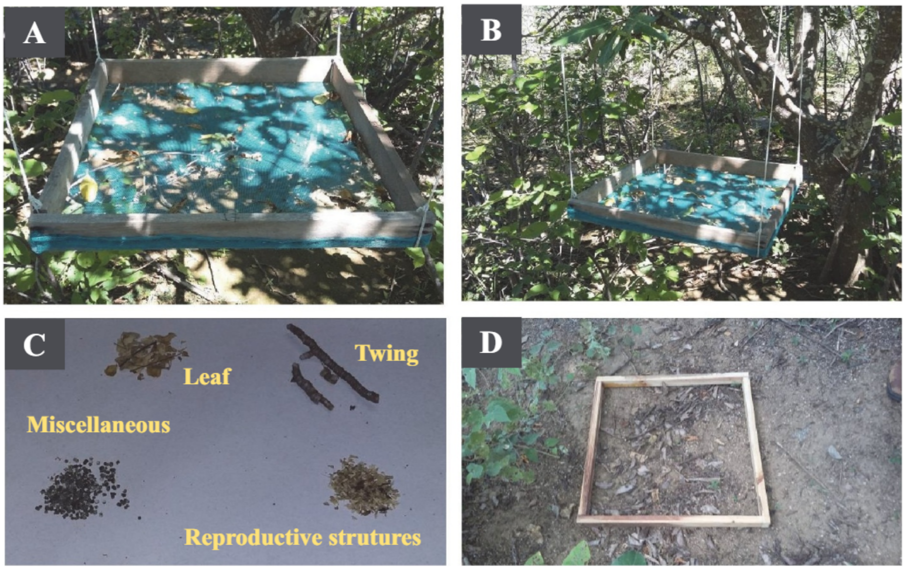


Fig. 3. Suspended litter collectors (A and B); separation of the leaf, twig, reproductive-structure and miscellaneous fractions (C), wooden frame for collecting litter accumulated on the ground (D), in the district of Floresta, PE, in the central hinterlands of Brazil.

Table 3
Characterization of six predominant species of the Caatinga vegetation (mean values for the plants of each species) used to monitor litterfall deposition, in the district of Floresta, PE, in the central hinterlands of Brazil.

Scientific name	Stems	$RD_{(i)}$	DBH	Height	Biomass
			(cm)	(m)	(kg $plant^{-1}$)
Spondias tuberosa	4	0.02	19	5	180
Commiphora leptophloeos	3	0.03	15	5	317
Cnidoscolus quercifolius	6	0.04	6	6	33
Aspidosperma pyrifolium	3	0.29	7	4	15
Cenostigma pyramidale	4	0.45	7	4	6
Croton blanchetianus	2	0.07	7	4	4

$Dor_{(i)}$ – relative dominance; DBH – diameter at breast height (1.30 m from the ground); Biomass estimated with the equation: $0.173.DBH^{2.295}$; as per Sampaio and Silva (2005).

USA) to measure the net radiation (R_N); a pyranometer (SQ300, Apogee/Campbell Scientific Inc., Logan, Utah, USA) for global solar radiation (R_G); a quantum sensor (LI-190SB, Li-color, Nebraska, USA) for measuring the photosynthetically active radiation above the canopy (PAR(ac)); all installed on top of the tower; two flux plates (HFT3-REB5S, Campbell Scientific, Inc., Logan, Utah, USA), installed at a depth of 0.05 m, to measure the soil heat flux (G); and two linear quantum sensors (Q321, Apogee/Campbell Scientific Inc., Logan, Utah, USA), installed at two different positions on the ground below the plant canopy to measure the photosynthetically active radiation below the canopy (PAR(bc)). An automatic rain gage (CS700-L, Hydrological Services, Liverpool, Australia) was also used to record the rainfall (RF); an anemometer (03002 R.M.Young Wind Sentry Set, Campbell Scientific Inc., Logan, Utah, USA) to measure the wind speed (u) and direction (WD); and aspirated psychrometers with T-type thermocouples (copper-constantan) to measure the dry-bulb and wet-bulb temperatures. The psychrometers were used to obtain values for air temperature (T) and relative humidity (RH). Data acquisition was by a CR10X datalogger (Campbell Scientific Inc., Logan, Utah, USA). The intercepted fraction of the PAR (f_{PAR}) was obtained from the difference between the values for the incident PAR above and below the plant canopy. To monitor the soil volumetric moisture (θv), a capacitive sensor (Diviner 2000®, Sentek Pty Ltda., Australia) was used, which was inserted into access pipes installed to a depth of 0.60 m, with readings taken every 0.10 m, with weekly frequency (every 7 days). On-site calibration of the sensor was carried out as suggested by the manufacturer (Araújo Primo et al., 2015; Silva et al., 2007).

2.5. Statistical analysis

The litterfall data which followed a normal distribution according to the Anderson-Darling, Lilliefors and Jarque-Bera tests, were submitted to analysis of variance (*F*-test); Fisher's LSD test (least significant difference) was applied to compare the monthly values ($P < 0.05$). The statistical analysis was carried out using the XLSTAT (Statistical Software and Data Analysis in Excel) tool, v.2017 (Addinsoft, Paris, France, www.xlstat.com).

In order to investigate the dominant environmental conditions on the seasonal variation of litterfall accumulation, the Pearson linear correlation matrix and the multicollinearity test were applied, as well as canonical and path analysis. Initially, the Pearson correlation coefficients were estimated between the data for litterfall deposition, both total and by fraction, together with the fifteen variables that represent the environmental conditions: mean air temperature (T), mean soil temperature (T_S), canopy temperature (T_C), relative humidity (RH), net radiation (R_N), soil heat flux (G), global solar radiation (R_G), water-vapor pressure deficit (VPD), photosynthetically active radiation above and below the canopy (PAR(ac) and PAR(bc)), intercepted fraction of the photosynthetically active radiation (f_{PAR}), wind speed (u), rainfall (RF) and soil volumetric moisture (θv). As the litterfall collections were always performed at the end of each month, it was considered the mean values (T, T_S, T_C, RH, R_N, G, R_G, VPD, PAR(ac), PAR(bc), f_{PAR}, u and θv) and, or, sum (RF) of the meteorological variables of the last 30 days, which means, the delay of approximately 1 month for the vegetation response. The significance of the correlations was evaluated using Student's *t*-test at 1 and 5% probability, and interpreted as: very weak (0 to 0.19), weak (0.20 to 0.39), moderate (0.40 to 0.69), strong (0.70 to 0.89), and very strong (0.90 to 1.00).

Multicollinearity diagnostics were then applied, but only to those response and explanatory variables that showed significant correlations. The condition number (CN), which represents the ratio between the highest and lowest values of the correlation matrix, was used to evaluate the existence of strong ($CN > 1000$), moderate ($100 < CN < 1000$) and weak ($CN < 100$) multicollinearity between the groups of variables (Salla et al., 2015).

The remaining explanatory variables (weak multicollinearity) were then used in the canonical correlation analysis to verify any associations between the groups; for this, the chi-square test was used to verify the significance of the correlations ($P < 0.01$). Finally, path analysis was applied to a breakdown of the Pearson correlation coefficients to evaluate the direct and indirect effect of the explanatory variable on the response variable.

The multivariate analysis was carried out using the Quantitative Genetics and Experimental Statistics - GENES statistical software (Cruz, 2006). The graphs were prepared in the SigmaPlot® v.14.0 software.

3. Results

3.1. Weather conditions

The amount of rainfall in 2016 and 2017 was 337.7 mm and 381.6 mm respectively, with values below the climate normal, which was equal to 489 mm (Table 1). Although the annual rainfall totals in the two years evaluated were close, there was a clear variation in rainfall distribution between the years. In 2016, greater volumes were seen between January and May, which correspond to the rainy period in the region. This was followed by the 2017 water year, during which rainfall events occurred from December 2016 to July 2017 (Table 4).

Higher values for incidence and net radiation were seen during the months of September to February, for both years. This was a result of lower solar declination and the greater intensity of radiation in the region. For the same period, the mean air temperature was high, while values for relative humidity were only lower during months when the incident radiation was high and few rainfall events were seen (September to February) (Table 4). The wind speed had a mean value of 1.7 m s^{-1}, with higher mean values from September to November, corresponding to the months of high solar incidence.

Higher values for the intercepted fraction of photosynthetically active radiation were seen from January to June, clearly caused by the presence of a more-robust plant canopy in response to the water stimuli.

3.2. Litterfall deposition

The monthly values of litterfall during the years 2016 and 2017 varying between 7.07 and 114.78 kg DM(dry mass) ha^{-1} (Fig. 4). The yearly value for the first year of measurements was 516.64 kg DM ha^{-1}, while from January to October 2017 it was 607.19 kg DM ha^{-1}, with a total value for the experimental period (20 months) of 1126 kg DM ha^{-1}. In average values, we found that annual production was 637 kg DM ha^{-1}, equivalent to a total of 0.64 tons DM ha^{-1} $year^{-1}$.

Greater litterfall production was verified in May 2016 (114.78 kg DM ha^{-1}), statistically superior ($P < 0.0001$) (Fig 4), followed by June 2016 and July 2017 (98.59 and 96.99 kg DM ha^{-1}). The months of September to November of 2016 and October 2017 showed the smallest litterfall deposits ($P < 0.0001$) (Fig. 4). For 2016, the largest litterfall deposits occurred between March and June, while in 2017 high values were seen between July and September. In general, the highest rates of litterfall accumulation are seen from March to July, with monthly values greater than 57 kg DM ha^{-1} (Fig. 4). However, it is noticeable that litterfall deposition does not show uniform seasonal patterns between the different years.

Among the fractions, leaf litterfall notably has the greatest contribution, representing 53% of the total amount deposited, with a deposition pattern similar to the curve for total litterfall. Next, the twig fraction makes up around 26%, reproductive structures around 15% and miscellanea only 6% (Fig 4). Leaf deposition was superior to the other fractions in most months, with peaks of production during May, June and July of 2016, and from June to September of 2017.

The contribution of the twig fraction was greater during May and June of 2016, and from January to July of 2017, even surpassing the deposition of the leaf fraction at times. The greatest accumulations of reproductive structures were during March to May of both years. The miscellaneous fraction was low throughout the experimental period, with slightly higher values during December 2016, and February and June of 2017. Seasonal variability was seen in the deposition of each fraction (Fig. 4).

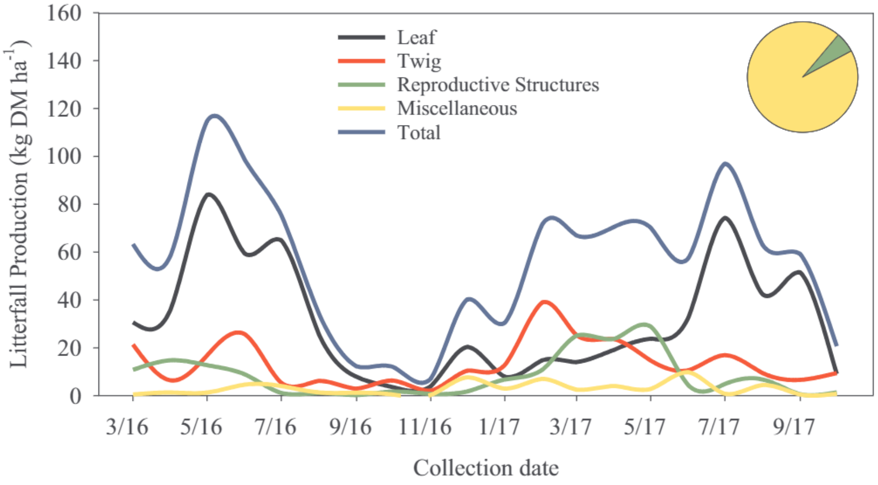
3.3. Effect of environmental conditions on the seasonality of litterfall deposition

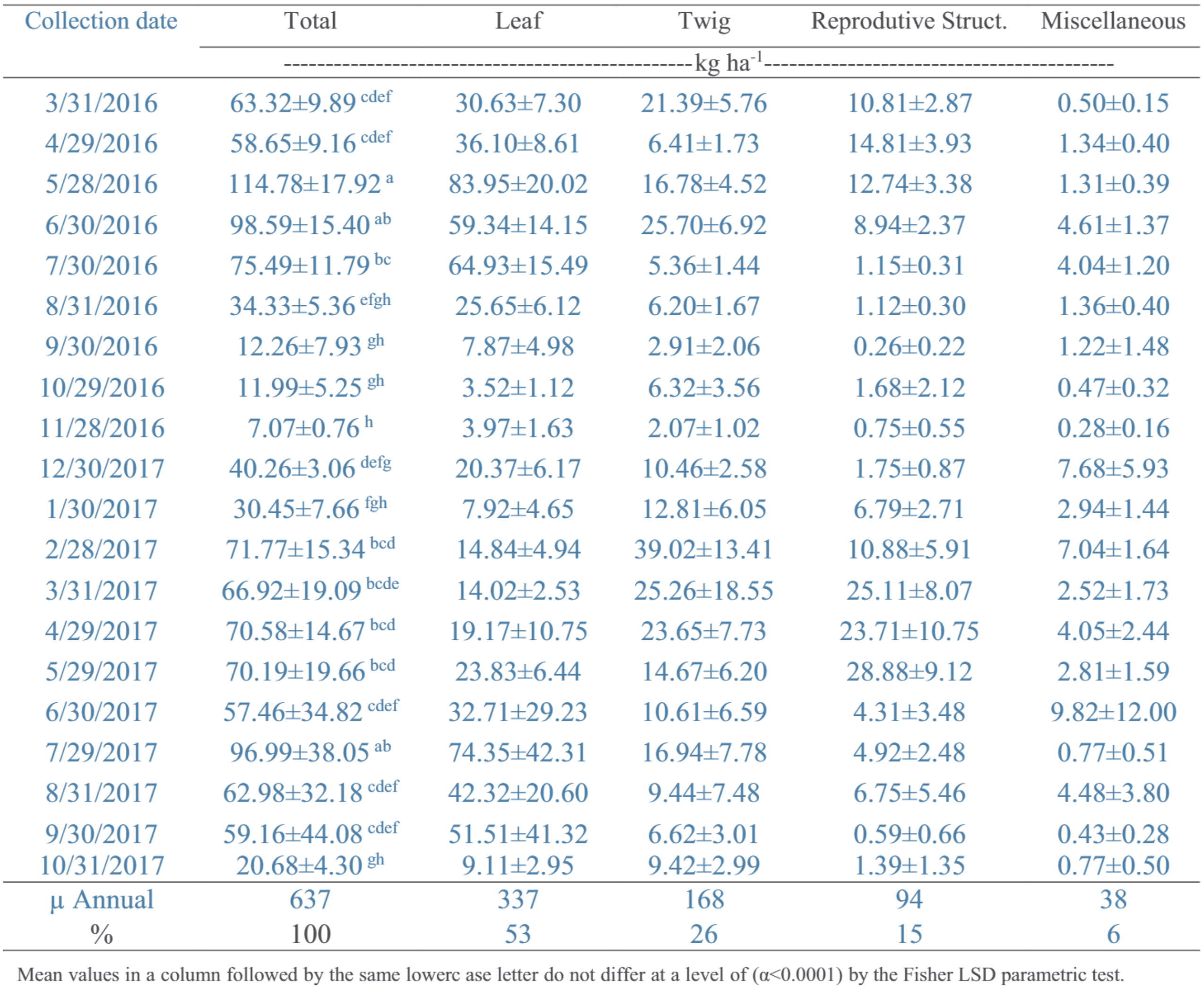
Based on the Pearson correlation, it could be seen that the variations in litterfall deposition of the miscellaneous fraction ($P > 0.05$) could not be explained by the environmental conditions. For the other

Table 4

Monthly values for rainfall (RF), net radiation (R_N), global solar radiation (R_G), soil heat flux (G), mean air temperature (T), relative humidity (UR), water-vapor pressure deficit (VPD), wind direction (WD), wind speed (u), intercepted fraction of the photosynthetically active radiation (f_{RFA}), mean soil volumetric moisture (0.00–0.60 m) (θ_v), and normalized difference vegetation index (NDVI) during the experimental period, in the district of Floresta, PE, in the central hinterlands of Brazil.

Month	RF	R_N	R_G	G	T	RH	VPD	WD	u	f_{PAR}	θ_v	NDVI
	mm	MJ m^2 dia^{-1}			ºC	%	kPa	º	m s^{-1}		m^3 m^{-3}	
March 2016	72.0	11.5	18.6	−0.6	28.8	60.0	1.6	163	1.4	0.62	0.08	0.34
April 2016	0.2	10.2	16.8	−0.8	28.0	60.4	1.5	165	1.4	0.63	0.09	0.37
May 2016	34.8	8.8	16.1	−0.7	26.6	63.5	1.3	170	1.4	0.52	0.08	0.30
June 2016	11.7	7.7	15.1	−0.6	24.9	67.0	1.1	170	1.4	0.42	0.08	0.33
July 2016	4.0	8.1	16.7	−0.2	24.3	62.3	1.2	171	1.8	0.28	0.08	0.27
August 2016	0.0	9.3	19.4	0.0	25.4	55.9	1.4	172	1.8	0.29	0.08	0.25
September 2016	0.4	10.1	20.6	0.1	27.4	51.1	1.8	174	2.0	0.32	0.08	0.23
October 2016	0.0	10.6	22.1	0.2	28.9	51.2	2.0	155	2.1	0.31	0.07	0.23
November 2016	0.0	9.9	20.6	0.0	29.5	52.5	2.0	150	2.0	0.30	0.07	0.25
December 2016	33.0	9.6	18.3	−0.1	28.0	55.8	1.8	151	1.8	0.29	0.08	0.26
January 2017	9.0	10.9	20.8	−0.1	29.1	52.0	1.9	167	1.9	0.42	0.08	0.29
February 2017	54.8	11.1	19.7	0.3	28.6	55.1	1.8	171	1.7	0.44	0.09	0.32
March 2017	120.0	12.1	19.0	0.5	28.1	60.9	1.5	172	1.3	0.47	0.09	0.34
April 2017	76.8	11.7	16.9	0.1	26.5	70.3	1.0	170	1.1	0.52	0.12	0.37
May 2017	45.6	7.8	13.3	0.1	25.6	72.6	0.9	172	1.3	0.50	0.08	0.39
June 2017	47.8	7.5	14.6	0.1	23.8	77.1	0.7	176	1.5	0.50	0.08	0.35
July 2017	22.9	6.5	12.9	0.0	21.9	76.3	0.6	178	1.9	0.47	0.06	0.33
August 2017	3.2	8.9	18.3	0.1	24.2	66.6	1.0	172	1.9	0.36	0.06	0.32
September 2017	1.6	9.1	19.3	0.2	24.8	62.4	1.2	171	2.6	0.32	0.06	0.27
October 2017	0.0	10.8	23.3	0.4	27.4	54.8	1.7	163	2.3	0.31	0.06	0.22
Sum(1)/Mean	719.3(1)	9.8	18.1	−0.1	26.6	62.3	1.4	166	1.7	0.43	0.08	0.30





Collection date	Total	Leaf	Twig	Reprodutive Struct.	Miscellaneous
	---	------------------kg ha^{-1}	------------------	--------------------------------------	
3/31/2016	63.32±9.89 ^{cdef}	30.63±7.30	21.39±5.76	10.81±2.87	0.50±0.15
4/29/2016	58.65±9.16 ^{cdef}	36.10±8.61	6.41±1.73	14.81±3.93	1.34±0.40
5/28/2016	114.78±17.92 ^{a}	83.95±20.02	16.78±4.52	12.74±3.38	1.31±0.39
6/30/2016	98.59±15.40 ^{ab}	59.34±14.15	25.70±6.92	8.94±2.37	4.61±1.37
7/30/2016	75.49±11.79 ^{bc}	64.93±15.49	5.36±1.44	1.15±0.31	4.04±1.20
8/31/2016	34.33±5.36 ^{efgh}	25.65±6.12	6.20±1.67	1.12±0.30	1.36±0.40
9/30/2016	12.26±7.93 ^{gh}	7.87±4.98	2.91±2.06	0.26±0.22	1.22±1.48
10/29/2016	11.99±5.25 ^{gh}	3.52±1.12	6.32±3.56	1.68±2.12	0.47±0.32
11/28/2016	7.07±0.76 ^{h}	3.97±1.63	2.07±1.02	0.75±0.55	0.28±0.16
12/30/2017	40.26±3.06 ^{defg}	20.37±6.17	10.46±2.58	1.75±0.87	7.68±5.93
1/30/2017	30.45±7.66 ^{fgh}	7.92±4.65	12.81±6.05	6.79±2.71	2.94±1.44
2/28/2017	71.77±15.34 ^{bcd}	14.84±4.94	39.02±13.41	10.88±5.91	7.04±1.64
3/31/2017	66.92±19.09 ^{bcde}	14.02±2.53	25.26±18.55	25.11±8.07	2.52±1.73
4/29/2017	70.58±14.67 ^{bcd}	19.17±10.75	23.65±7.73	23.71±10.75	4.05±2.44
5/29/2017	70.19±19.66 ^{bcd}	23.83±6.44	14.67±6.20	28.88±9.12	2.81±1.59
6/30/2017	57.46±34.82 ^{cdef}	32.71±29.23	10.61±6.59	4.31±3.48	9.82±12.00
7/29/2017	96.99±38.05 ^{ab}	74.35±42.31	16.94±7.78	4.92±2.48	0.77±0.51
8/31/2017	62.98±32.18 ^{cdef}	42.32±20.60	9.44±7.48	6.75±5.46	4.48±3.80
9/30/2017	59.16±44.08 ^{cdef}	51.51±41.32	6.62±3.01	0.59±0.66	0.43±0.28
10/31/2017	20.68±4.30 ^{gh}	9.11±2.95	9.42±2.99	1.39±1.35	0.77±0.50
µ Annual	637	337	168	94	38
%	100	53	26	15	6

Mean values in a column followed by the same lowerc ase letter do not differ at a level of (α<0.0001) by the Fisher LSD parametric test.

Fig. 4. Monthly litterfall deposition and the leaf, twig, reproductive-structure and miscellaneous fractions of plant species of the Caatinga Domain, from March 2016 to October 2017, in the district of Floresta, PE, in the central hinterlands of Brazil.

response variables, significant correlations were seen between one or more explanatory variables. For these groups of variables, there was severe multicollinearity; therefore, one or more independent variables that were highly correlated were removed. Of the 15 explanatory variables used initially, only 8 obtained an CN of less than 100, leaving: NDVI, R_G, u, RF, θv, G, f_{PA} and VPD.

Based on the results of the canonical analysis between the groups of response variables (total litterfall and by fraction) and explanatory variables (environmental conditions), only one axes could be identified as significant, suggesting that two or more environmental variables

Table 5
Canonical correlations and canonical pairs between the group of response variables (total litterfall and by fraction) and explanatory variables (environmental conditions), at the site in the Caatinga Domain, in the district of Floresta, PE, in the central hinterlands of Brazil.

		Canonical factors			
		1st	2nd	3rd	4th
Response variables	LTF-Total	2.432	3.669	8.134	−7.500
	LTF-Reproductive Struct.	−0.001	−0.581	−1.883	2.902
	LTF-Leaf	−2.455	−2.091	−6.647	6.145
	LTF-Twig	−0.601	−1.298	−3.728	1.830
Explanatory variables	NDVI	0.836	0.275	0.111	−0.934
	R_G	0.155	−0.312	−0.177	0.472
	u	−0.612	0.156	−1.048	−0.708
	RF	−0.123	0.464	−1.309	−1.148
	WD	−0.044	0.184	−0.739	−0.465
	θv	0.054	−0.051	0.158	−0.112
	G	0.635	−0.641	0.902	0.636
	VPD	0.479	−0.369	−0.551	−0.701
	f_{PAR}	−0.085	−0.465	−0.226	1.982
Canonical corr.		0.97*	0.92	0.59	0.37
Chi-square		65	30	7	2
Degree of freedom		36	24	14	6

LTF-Total – total litterfall, LTF-Reproductive Struct. – litterfall in the reproductive-structure fraction, LTF-Leaf – litterfall in the leaf fraction, LTF-Twig – litterfall in the twig fraction, NDVI – normalized difference vegetation index, R_G – global solar radiation, u – wind speed, RF – rainfall, WD – wind direction, θ_v – volumetric soil moisture, G – soil heat flux, VPD – water vapor pressure deficit, f_{PAR} – intercepted fraction of the photosynthetically active radiation.

* highly significant ($P < 0.01$) by the chi-square test.

acted together in the variation of a response variable (Table 5). In the first canonical axis, leaf litter deposition decreases when NDVI, G and VPD are larger, while a reduction in wind speed explains the decrease of this fraction (Table 5). Thus, variations in the deposition of LTF-Leaf occur among associated variables of the explanatory group, whereas for LTF-Total, LTF-Reproductive Structures and LTF-Twig, the effects are isolated, i.e. only one variable is able to explain the variations in the deposition of these fractions via direct and indirect effects, which was confirmed by the path analysis.

For the LTF-Total, the main effect (direct and indirect) was via global solar radiation. In the direct effect, Pearson's correlation coefficient showed a negative effect (−0.55), and indirect effects from NDVI, VPD, f_{PAR}, *u* and WD, achieving coefficients that were superior to the direct effects of the variables themselves (Table 6). Thus, the largest depositions of total litterfall occur during months when the radiation intensity is lower.

The vapor pressure déficit (VPD) and soil heat flux (G) are the main environmental variables that influence the deposition on LTF-Leaf. The VPD contributes negatively through direct (−0.63) and indirect effects (−0.57) on the deposition of LTF-Leaf, with positive indirect effects only via WD (0.45) (Table 6). However, when the G is negative, LTF-Leaf deposition increases (−0.52). Therefore, months with lower values for vapor pressure déficit and lower soil heat flux increase the contribution of this fraction.

Rainfall (RF) was considered the main direct and positive effect (0.58) on the deposition of the LTF-Twig fraction, in addition to its indirect effects on other variables (NDVI, f_{PAR}, u, θv) (Table 6). However, the high effect of the residual variable (0.70) shows that this set of four variables cannot fully explain the variations seen in the deposition of the twig fraction. These changes are probably due to other variables that are not explored in this study, such as plant phenology and morphological characteristics, among others.

It was found that NDVI had a positive direct effect on LTF-Reproductive Struct, in which months of lower NDVI favor deposition of the reproductive structures (0.55). In addition, there were indirect effects from f_{PAR}, u, RF and θ_v. In addition, the correlations between LTF-Reproductive Struct and NDVI showed the lowest residual error values (Table 6). As there were no significant correlations between LTF-Miscellaneous and the environmental conditions (Pearson test and multicollinearity analysis), path analysis was not carried out for this response variable.

3.4. Litterfall deposition by species of the Caatinga domain

Fig. 5 presents the results as boxplots for the litterfall total deposition of the six species monitored, obtained in 20 samples. High values with higher dispersion were observed for *A. pyrifolium* (Fig 5A), while for the other species the dispersion was lower. In 2017, there was greater litterfall deposition for the species, with the exception of *C. blanchetianus* (Fig 5F). The deposition of the species *S. tuberosa* and *C. leptophloeos* was more symmetrical, since the mean values were closer to the median line during the two years of monitoring (Fig. 5C and D), so, for the other species, there was asymmetry in at least one of the years.

The seasonal patterns of the leaf, twig, reproductive-structure and miscellaneous fractions showed an obvious variation between the six plant species under evaluation, as outlined in Fig. 6. Among the species, *A. pyrifolium* had the highest leaf contribution (183.04 kg DM ha^{-1}), while the lowest values were obtained with *C. pyramidale* (46 kg DM ha^{-1}), demonstrating the same behavior seen for total deposition among the species. During May, June and July of 2016, and July 2017 there were cumulative increases in almost all the plant species, and to a lesser extent, in *C. pyramidale* (Fig. 6A).

In relation to the deposition of the twig fraction, the largest contributions came from the species *C. leptophloeos* and *A. pyrifolium*, with February 2017 showing the greatest deposition for all species (Fig. 6B). The contribution of the reproductive structures of *S. tuberosa, C. leptophloeos* and *C. blanchetianus* hardly varied during the period of analysis (March 2016 to October 2017), with totals of 10.13, 13.01 and 12.44 kg DM ha^{-1} respectively. On the other hand, *C. pyramidale* had the lowest deposition (3.11 kg DM ha^{-1}). *C. quercifolius* and *A. pyrifolium* contributed most to the fall of reproductive structures, achieving a total accumulation of 76.27 and 52.37 kg DM ha^{-1} respectively, especially during March, April and May of 2017 (Fig 6C).

For the miscellaneous fraction, the collectors located below the species *C. quercifolius* and *C. pyramidale* had the largest deposited amounts of this material, especially during December 2016 for *C. quercifolius*, and June 2017 for *C. pyramidale* (Fig. 6D). The species *A. pyrifolium* and contributed most to the total litterfall deposition, followed by *C. quercifolius, C. leptophloeos, C. blanchetianus, S. tuberosa* and *C. pyramidale* with depositions equal to 317.97, 228.59, 212.50, 130.01, 129.61 and 107.75 kg DM ha^{-1} respectively during the evaluation period.

3.5. Decomposition of the litterfall

The annual mean for litterfall accumulated on the ground was 2046 kg ha^{-1}. The mean decomposition constant for litterfall mass loss was 0.33 kg DM ha^{-1} $year^{-1}$; the time required for 50% and 95% of the litterfall to disappear shows that the rate of decomposition is quite high, with slow reuse of the nutrients (Table 7).

3.6. Nutrient export from the vegetation to the litterfall

The analysis of the chemical composition of litter indicated that the average concentrations of the macronutrients K, Ca, Mg and S were respectively 3.6, 12.6, 1.4 and 1.3 g kg^{-1}, whereas for the micronutrients Cu, Fe, Mn, Zn and Na, it was 13.5, 296.1, 44.5, 25.3 and 449.2 mg kg^{-1}. In Fig. 7 shows the average amount of nutrients

Table 6
Path analysis between the group of response variables (Total litterfall and fractions) and explanatory variables (environmental conditions), at the site in the Caatinga Domain in the district of Floresta, PE, in the central hinterlands of Brazil.

LTF-Total			LTF-Leaf			LTF-Twig			LTF-Reproductive Struct		
D	NDVI	−0.18	D	G	−0.52	D	NDVI	0.22	D	NDVI	0.55
ID	VPD	0.04	ID	VPD	−0.04	ID	f_{PAR}	0.01	ID	f_{PAR}	−0.08
ID	R_G	0.40	ID	R_G	0.04	ID	u	−0.08	ID	u	0.10
ID	f_{PAR}	0.20	ID	WD	0.01	ID	RF	0.34	ID	RF	0.17
ID	u	0.08		r-total	−0.51	ID	θ_v	0.04	ID	θ_v	0.07
ID	WD	0.09	–	–	–		r-total	0.53		r-total	0.80
	r-total	0.64	–	–	–	–	–	–	–	–	–
D	VPD	−0.07	D	VPD	−0.63	D	f_{PAR}	0.01	D	f_{PAR}	−0.09
ID	NDVI	0.11	ID	G	−0.03	ID	NDVI	0.19	ID	NDVI	0.46
ID	R_G	−0.46	ID	R_G	0.09	ID	u	−0.07	ID	u	0.09
ID	f_{PAR}	−0.08	ID	WD	−0.09	ID	RF	0.32	ID	RF	0.15
ID	u	−0.03		r-total	−0.65	ID	θ_v	0.04	ID	θ_v	0.07
ID	WD	−0.14	–	–	–		r-total	0.48		r-total	−0.63
	r-total	−0.68	–	–	–	–	–	–	–	–	–
D	R_G	−0.55	D	R_G	0.11	D	u	0.10	D	u	−0.13
ID	NDVI	0.13	ID	G	−0.19	ID	NDVI	−0.17	ID	NDVI	−0.43
ID	VPD	−0.06	ID	VPD	−0.53	ID	f_{PAR}	−0.01	ID	f_{PAR}	0.07
ID	f_{PAR}	−0.12	ID	WD	−0.06	ID	RF	−0.39	ID	RF	−0.19
ID	u	−0.06		r-total	−0.67	ID	θ_v	−0.06	ID	θ_v	−0.11
ID	WD	−0.10	–	–	–		r-total	−0.53		r-total	−0.78
	r-total	−0.77	–	–	–	–	–	–	–	–	–
D	f_{PAR}	0.24	D	WD	0.12	D	RF	0.58	D	RF	0.28
ID	NDVI	−0.15	ID	G	−0.05	ID	NDVI	0.13	ID	NDVI	0.32
ID	VPD	0.02	ID	VPD	0.45	ID	f_{PAR}	0.01	ID	f_{PAR}	−0.05
ID	R_G	0.28	ID	R_G	−0.06	ID	u	−0.06	ID	u	0.08
ID	u	0.08		r-total	0.46	ID	θ_v	0.04	ID	θ_v	0.08
ID	WD	0.06	–	–	–		r-total	0.70		r-total	0.72
	r-total	0.53	–	–	–	–	–	–	–	–	–
D	u	−0.11	–	–	–	D	θ_v	0.07	D	θ_v	0.14
ID	NDVI	0.14				ID	NDVI	0.11	ID	NDVI	0.27
ID	VPD	−0.02	–	–	–	ID	f_{PAR}	0.01	ID	f_{PAR}	−0.05
ID	R_G	−0.32	–	–	–	ID	u	−0.07	ID	u	0.10
ID	f_{PAR}	−0.18	–	–	–	ID	RF	0.34	ID	RF	0.17
ID	WD	−0.04	–	–	–		r-total	0.70		r-total	0.62
	r-total	−0.53	–	–	–	–	–	–	–	–	–
D	WD	0.20	–	–	–	–	–	–	–	–	–
ID	NDVI	−0.08	–	–	–	–	–	–	–	–	–
ID	VPD	0.05	–	–	–	–	–	–	–	–	–
ID	R_G	0.28	–	–	–	–	–	–	–	–	–
ID	f_{PAR}	0.07				–	–	–	–	–	–
ID	u	0.02	–	–	–						
	r-total	0.55	–	–	–	–	–	–	–	–	–
r^2		0.65	–	–	0.66	–	–	0.51	–	–	0.77
Residual		0.59	–	–	0.58	–	–	0.70	–	–	0.48

D – direct effect, ID – indirect effect. LTF-Total – total litterfall, LTF-Leaf – leaf litterfall, LTF-Twig – twig litterfall, LTF-Reproductive Struct – reproductive-structure litterfall, NDVI – normalized difference vegetation index, VPD – water-vapor pressure deficit, RG – global solar radiation, f_{PAR} – intercepted fraction of the PAR, u – wind speed, WD – wind direction, RF – rainfall, G – soil heat flux, θv – volumetric soil moisture.

exported by the Caatinga vegetation to the total litterfall produced during the 20 months of the analysis (product of the nutrient concentration by the total litterfall of each month).

Among the macronutrients, the element calcium is exported in the greatest quantity, followed by potassium. Among the micronutrients, higher export values were obtained for sodium and iron, and lower values for copper (Fig. 7). The export of nutrients via the litterfall followed the descending order: Ca > K > Mg > S > Na > F > Mn > Zn > Cu. With the exception of nitrogen, phosphorus and boron (data not obtained), the estimated total return of macronutrients and micronutrients was 13.1 and 0.49 kg ha^{-1} year^{-1} respectively.

Temporal variations in nutrient export by the vegetation were relatively small, and the seasonal variation accompanied fluctuations in the total litterfall deposition. The greatest nutrient fluxes were observed in the months of June and July, and the lowest rates between August and January, irrespective of concentration (Fig. 7).

4. Discussion

4.1. Litterfall deposition

For Caatinga vegetation, information on litterfall production is still insufficient, with only a small number of published works. In this study, the annual litterfall deposition was 0.64 tons ha^{-1} year^{-1}. It is estimated that litterfall production in the Caatinga is in the range of 1.5 to 3.0 tons ha^{-1} year^{-1}, and can reach values higher than 6.0 tons ha^{-1} year^{-1} at the wettest locations. However, these values are still lower than values seen in other forest formations in Brazil (Menezes et al., 2012).

Table 8 shows a review of works related to the litterfall contribution

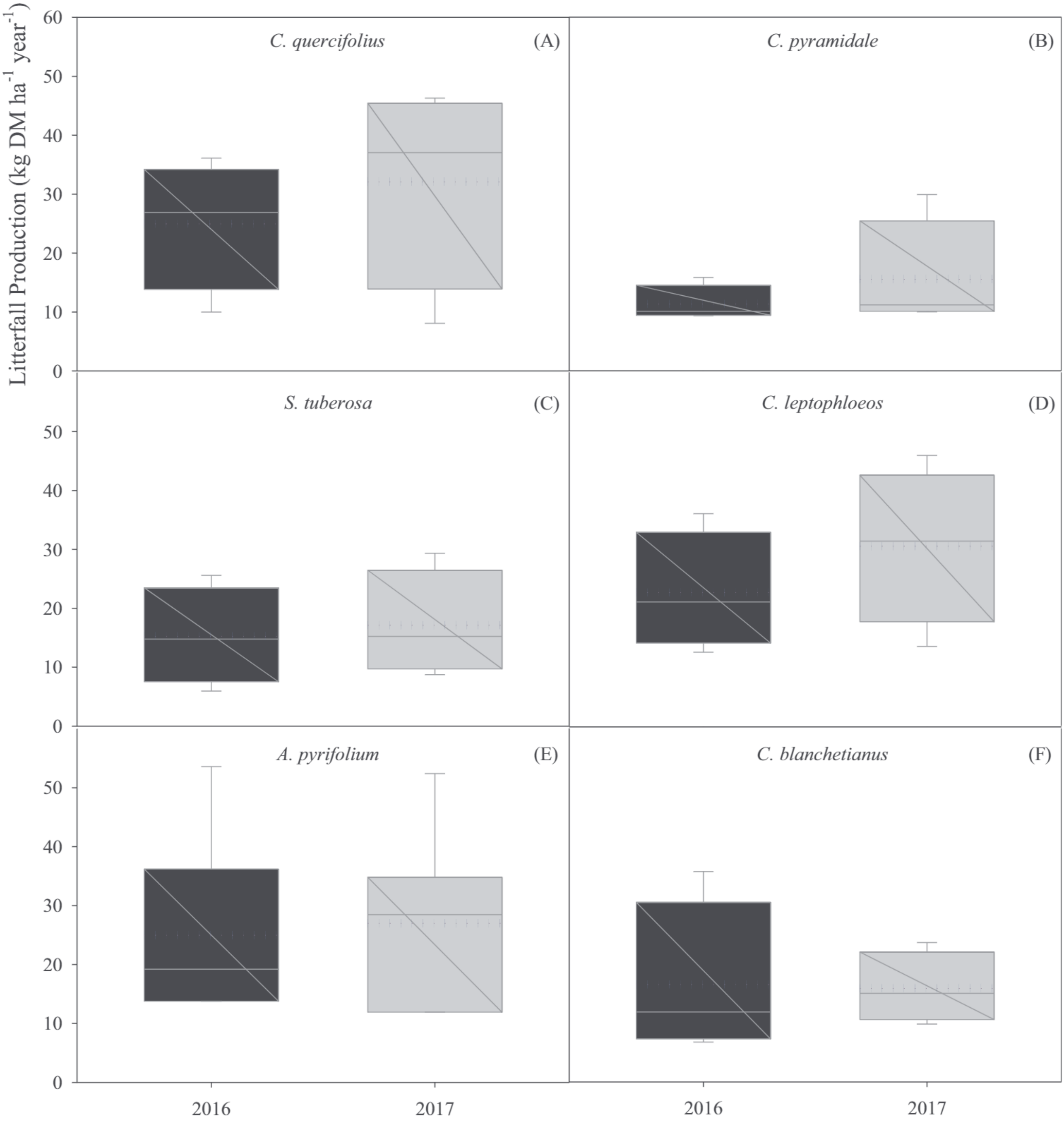


Fig. 5. Blox plot of annual litterfall production in six plant species of the Caatinga Domain: 2016 (March to December) and 2017 (January to October), in the district of Floresta, PE, in the central hinterlands of Brazil. Blue dotted lines indicate the mean.

to environments of Caatinga vegetation and other plant typologies. It is assumed that higher values for litterfall deposition in the other types of plant formation shown in Table 8 reflect the abundance of tree-like individuals, with greater height, greater trunk thickness, larger wood volume and canopies that are more closed (Nunes and Pinto, 2007).

Irrespective of the litterfall production capacity in each plant typology, in all forest ecosystems the presence of this material promotes the recovery of degraded areas, reflecting the productive capacity, conservation, biodiversity and natural maintenance of forest ecosystems (Alves et al., 2006; Arato et al., 2003; Correia et al., 2016; Freitas et al., 2015; Santana and Souto, 2011; Zhang et al., 2014). Therefore, litterfall can act as an indicator for evaluating and monitoring forest restoration through the soil-plant-litterfall system (Correia et al., 2016).

In Central Africa, Cizungu et al. (2014) found that annual litterfall deposition in a preserved tropical forest was almost twice that obtained in an adjacent area planted with Eucalyptus, with values of 4.17 and 2.21 tons ha^{-1} year^{-1} respectively. Correia et al. (2016) compared the litterfall accumulated in a forest under restoration and another primary dense ombrophilous forest in the Vales Nature Reserve, in the State of Espírito Santo; for the forest under restoration, the average deposition was 3.18 tons ha^{-1} year^{-1}, while for the other it was 4.41 tons ha^{-1} year^{-1}. The differences between the two sites show, that even after years of restoration (23), the vegetation was still not able to reach values for litterfall stock similar to those of preserved

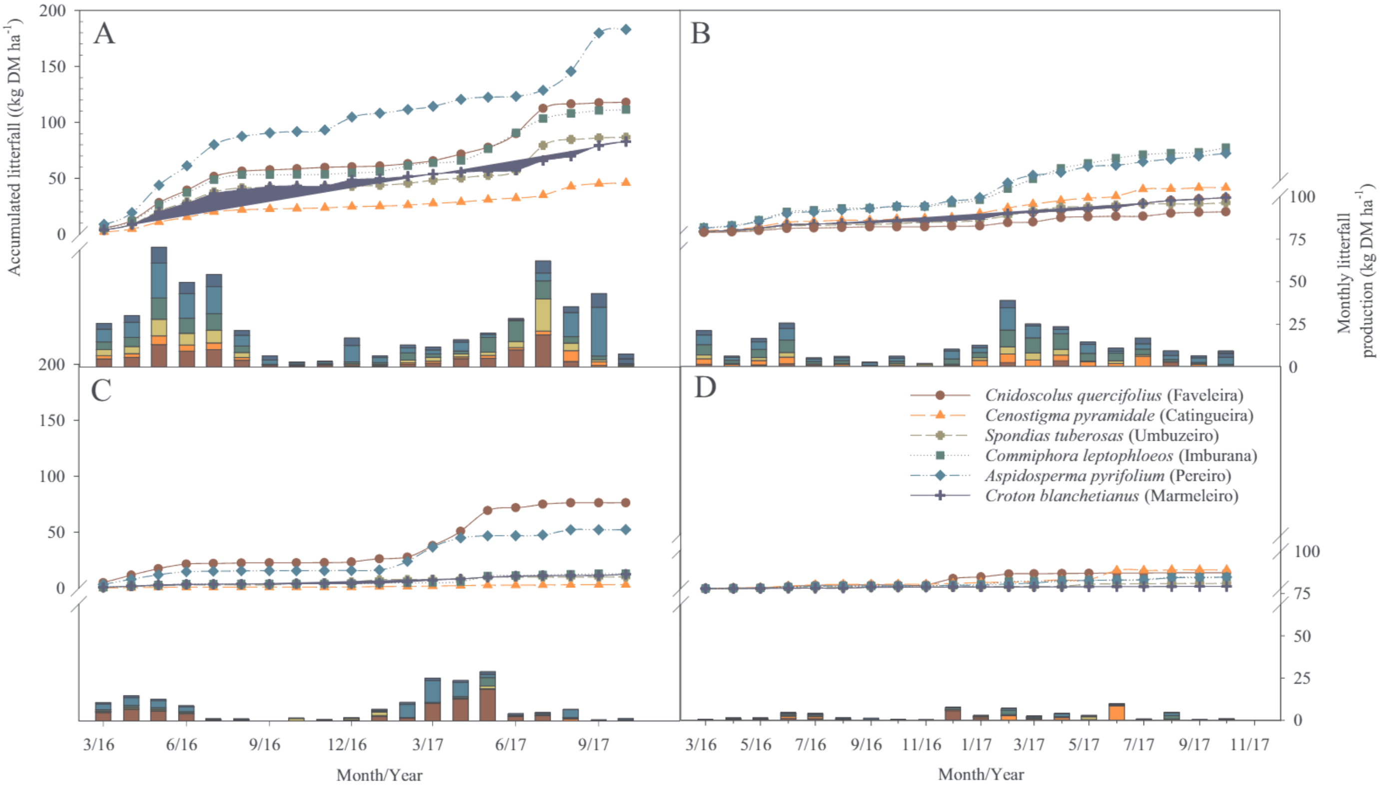


Fig. 6. Monthly accumulated litterfall of the Leaf (A), Twig (B), Reproductive-structure (C) and Miscellaneous (D) fractions, in six plant species of the Caatinga Domain, from March 2016 to October 2017, in the district of Floresta, PE, in the central hinterlands of Brazil.

areas. Nunes and Pinto (2007) obtained values for litterfall production of 15.1 tons ha^{-1} year^{-1} in a native forest and 11.4 tons ha^{-1} year^{-1} in an area of reforestation. This difference in values may be related to the floristic composition and successional stage of the vegetation.

In view of the above, the removal of Caatinga vegetation to use the area for agricultural or extractive purposes results in the irreparable loss of the complete dynamics and interaction of the soil-plant-litterfall system. Furthermore, abandoned agricultural areas take decades to establish vegetation similar to the original (Pereira et al., 2003); in areas of Caatinga with anthropogenic intervention, the loss of dry matter deposited on the ground can reach 0.64 tons ha^{-1} year^{-1}.

Of the material that makes up the litterfall, the greatest was leaf production (Fig. 4). Studies in areas of Caatinga report that the leaf fraction is the main material to be deposited, with percentages varying between 56% and 80%, while the twig fraction is between 7% and 28%, reproductive structures between 8% and 13%, and that the miscellaneous fraction is 0.8% of the total litterfall (Alves et al., 2006; Andrade et al., 2008; Costa et al., 2010, 2007; Santana and Souto, 2011), confirming the results of the present study.

The greater contribution of the leaf fraction to the formation of litterfall is not exclusive to plants of the Caatinga, but is also found in the scientific literature for other plant formations, whether natural or introduced (Arato et al., 2003; Correia et al., 2016; Freitas et al., 2015; Ludvichak et al., 2016; Terror et al., 2011; Vital et al., 2004; Zhang et al., 2014).

4.2. Effect of environmental conditions on the seasonality of litterfall deposition

Through statistical analysis, we explored relationship between environmental variables and litterfall deposition seasonality for the Caatinga. The absence of significant correlations between environmental conditions and LTF-Miscellaneous is because this component is not a constituent part of the plant, since it mostly refers to material of animal origin, for example of dead parts and waste. Its deposition therefore is little influenced by the environment, being more related to the presence of small herbivorous animals, a fact confirmed by the irregular seasonal pattern of this fraction (Fig. 4). Arato et al. (2003) also found no significant correlation between litterfall deposition and climate variables, which presented low Pearson coefficients.

The seasonality of total litterfall deposition was affected strongly and negatively by the global solar radiation. Therefore, for this area of Caatinga, the greatest contribution of deciduous material occurs during months with a low incidence of radiation (May to July), which in the Southern Hemisphere coincide with the transition between autumn and winter (Vianello and Alves, 2012). In an area of Caatinga, Correia et al. (2016) found that the higher the plant area index and the less compacted the soils, the greater the concentration of litterfall

Table 7
Results for litterfall decomposition rate (k, year^{-1}), mean renovation time ($1/k$) and decomposition times of 50% ($t_{0.5}$) e 95% ($t_{0.05}$), at the site in the Caatinga Domain, in the district of Floresta, PE, in the central hinterlands of Brazil.

Period	$k = L/Xss$	$1/k$	$t_{0.5} = \ln 2/k$	$t_{0.05} = 3/k$
	–	year		
March 2016–October 2017	0.33	3.0	2.1	9.1

L – litterfall produced annually (kg ha^{-1} year^{-1}); Xss – mean annual litterfall accumulated on the ground (kg ha^{-1}).

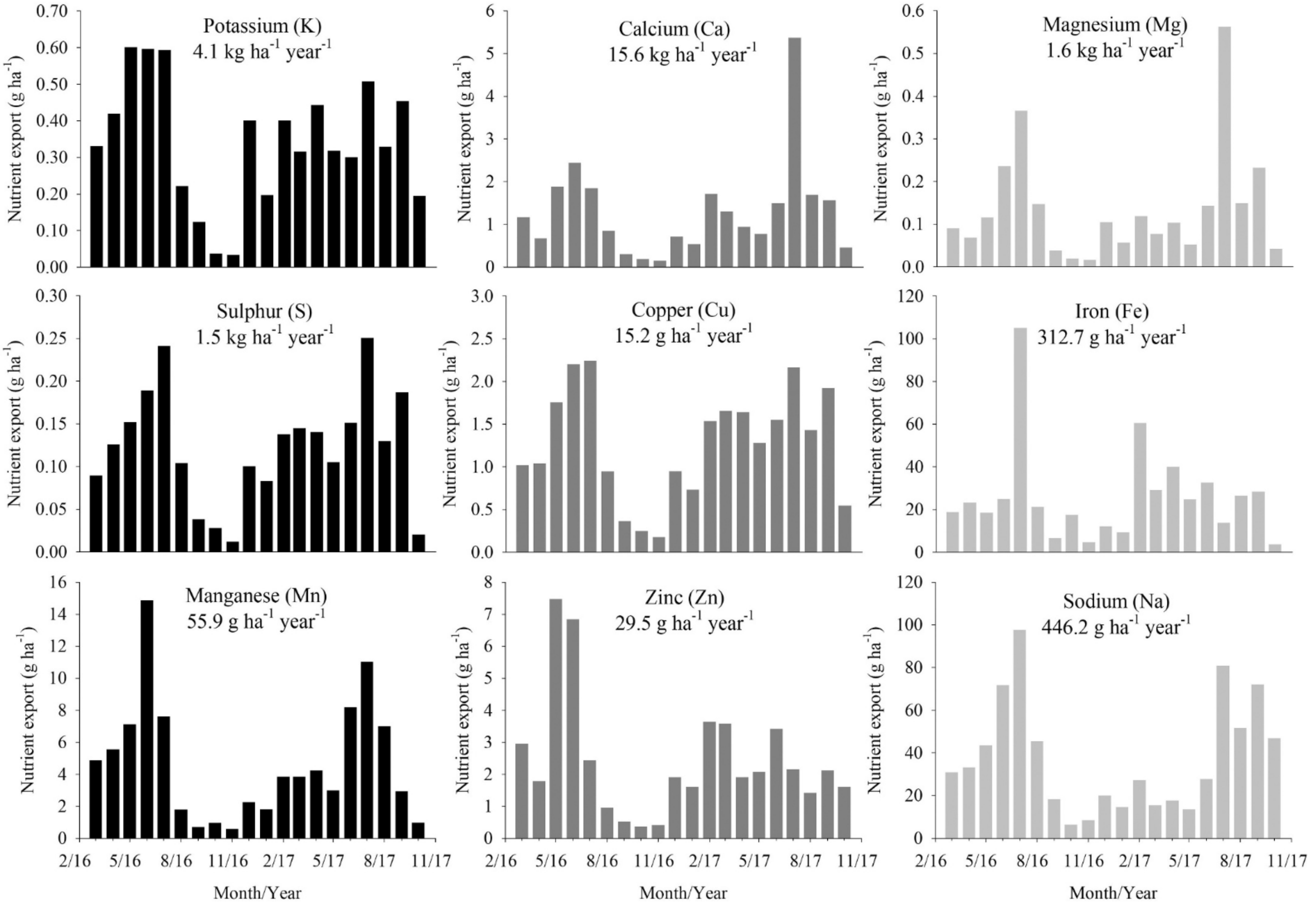


Fig. 7. Seasonal variation in mean nutrient export from the vegetation to the total litterfall at the site in the Caatinga Domain, from March 2016 to October 2017, in the district of Floresta, PE, in the central hinterlands of Brazil.

Table 8
Annual litterfall deposition (kg ha^{-1} year^{-1}) in different Brazilian typologies.

Reference	Deposition	Plant typology – Locality
This study	637	Caatinga - Tree-like shrub, State of Pernambuco, Brazil
Silva et al. (2015)	1631	Caatinga - advanced stage of regeneration, State of Paraíba, Brazil
Santana and Souto (2011)	2069	Caatinga - Hyperxerophilic tree-like shrub, State of the Rio Grande do Norte, Brazil
Costa et al. (2010)	3384	Caatinga - Hyperxerophilic/tree-like, State of the Rio Grande do Norte, Brazil
	2580	Caatinga - Hyperxerophilic/shrub-like, State of the Rio Grande do Norte, Brazil
Lopes et al. (2009)	2855	Caatinga - Hyperxerophilic, State of the Ceará, Brazil
Andrade et al. (2008)	2284	Caatinga - Closed tree-like shrub, State of Paraíba, Brazil
Costa et al. (2007)	2985	Caatinga - Hyperxerophilic, State of the Rio Grande do Norte, Brazil
Alves et al. (2006)	899	Caatinga - Hyperxerophilic, State of Paraíba, Brazil
Correia et al. (2016)	4411	Dense Ombrophilous Forest, State of the Espírito Santo, Brazil
	3177	Forest under regeneration, State of the Espírito Santo, Brazil
Freitas et al. (2015)	8982	Dense Mountain Ombrophilous Forest, State of the Espírito Santo, Brazil
Ludvichak et al. (2016)	6990	Plantation of *Eucalyptus dunnii* – Pampas Biome, State of the Rio Grande do Sul, Brazil
Terror et al. (2011)	5680	Paludal forest, State of Minas Gerais, Brazil
Nunes and Pinto (2007)	15,100	Mesophyllic semi-deciduous forest, State of Minas Gerais, Brazil
	11,400	Reforested ciliary vegetation, State of Minas Gerais, Brazil
Vital et al. (2004)	10,646	Semi-deciduous seasonal forest, State of São Paulo, Brazil
Arato et al. (2003)	10,165	Agroforestry system/tree and fruit species, State of Minas Gerais, Brazil

accumulated on the ground.

Other studies also suggest that solar radiation is the dominant environmental variable in seasonal patterns of litterfall deposition. Silva et al. (2009) showed that litterfall deposition has a negative correlation with rainfall, being positively influenced by the flux density of the photosynthetically active radiation. Zhang et al. (2014) suggest that rainfall and solar radiation are limiting factors in regulating litterfall deposition in tropical forests. In these environments, the deposition of mature leaves, rather than the appearance of new leaves, occurs during periods of abundant radiation, resulting in high accumulated values.

The monthly fluctuation in the litterfall fractions (leaf, twig and reproductive structures) showed a dependent relationship with other environmental variables (Table 6). The soil heat flux and water-vapor pressure deficit were determinant in the variation of LTF-Leaf values, having direct negative effects. Thus, months with a high positive soil heat flux (more-exposed soil), typical of spring and early summer, resulted in low deposition of the leaf fraction. The largest depositions of the foliar fraction observed between the months of May and August coincide with the conditions of lower values for G and VPD. Also, expressive deposition of leaves at the end of the rainy period is defensive action used by the vegetation under water stress (Andrade et al., 2008). The leaves are structures for photosynthesis and transpiration, but have high water demand (Costa et al., 2010).

The plants of the Caatinga use morphological and physiological adaptations to stay alive during periods of water stress, such as leaf and deciduous senescence, which are a preventive plant response to high water loss through transpiration (Andrade et al., 2008; Santana and Souto, 2011). In other plant typologies, leaf abscission due to water stress is another mechanism of plant adaptation (Arato et al., 2003; Zhang et al., 2014). In mangrove forests, high temperatures can accelerate the rate of transpiration, increasing the salt content of the leaves, which results in their abscission. In contrast, rainfall events promote reductions in water salinity and consequently lower litterfall production (Zhang et al., 2014).

For LTF-Twig, the rainfall had a direct positive influence on variations in the deposition of this fraction, probably due to the mechanical action of the raindrops on dried twigs retained in the canopy (Arato et al., 2003; Martins and Rodrigues, 1999). During months of higher rainfall, the deposition of twigs was greater than of the other fractions (Table 4 and Fig. 4). However, due to the high residual value of the path analysis, the direct and indirect effects of the rainfall cannot fully explain the variations in this fraction. Ye et al. (2013) found significant correlations of leaf litterfall with air temperature and rainfall, and of twig deposition with rainfall, which explain the seasonality of litterfall production in mangrove forests. Arato et al. (2003) observed peaks of twig deposition in one month with zero rainfall, and point out that the action of wind speed on the plants without leaves may be decisive to obtain greater contributions of this fraction. For our study, such relationships in dry periods were not identified. The twig fraction, although it contributes significantly to the litterfall, presents amount and seasonality quite variable, making it difficult to understand (Andrade et al., 2008; Arato et al., 2003).

On the other hand, the deposition of LTF- Reproductive Structure is jointly influenced by NDVI, which suggests that months with higher NDVI values favor deposition of this fraction (Table 6). It is noted that the largest depositions of reproductive structures occur from 1 to 2 months prior to the maximum foliar intake (Fig. 4), coinciding with maximum values of NDVI (Table 4). However, significant correlations were not obtained between NDVI and LTF-Leaf. The NDVI delay in relation to rainfall ranges from 1 to 3 months, perhaps due to the massive formation of leaves after the first rains of the rainy season, which take from 2 to 3 months to complete their total expansion (Barbosa et al., 2019). This indicates that, in the months when there is presence of leaves (formed vegetal canopy, and higher NDVI), it is those in which there is a greater drop in reproductive structures. This situation may also be conditioned by the entire flowering and fruiting cycle of most Caatinga species occurring after the onset of the rains (Andrade et al., 2008; Parente et al., 2012), as a way of assuring perpetuation of the species in the short term. Silva et al. (2009) found that the fall in reproductive fractions was also influenced by wind speed, but with positive effects.

In this study, the greatest depositions of litterfall occurred during the months of March to July, with smaller depositions during the months September, October and November (Fig. 4). Other studies have verified this pattern in areas of Caatinga (Costa et al., 2010; Menezes et al., 2012). Andrade et al. (2008) found that a massive accumulation of litterfall occurred in June, with high values also in May, July and August. Alves et al. (2006) found greater deposition after the rainy season, which was in June. Santana and Souto (2011) found the maximum production during May.

Numerous works are of a general nature, and associate litterfall deposition with the seasons, considering only the magnitude and pattern of the rainfall. However, it is the combined effects of meteorological variables (e.g. rainfall, air temperature, radiation, etc.) that in fact are responsible for the seasonality of litter accumulation in the various ecosystems of the world (Correia et al., 2016; Sánchez-Andrés et al., 2010; Silva et al., 2009; Vital et al., 2004; Zhang et al., 2014).

4.3. Litterfall deposition by species of the Caatinga domain

The total annual deposition and by litterfall fractions in the six species studied showed discrepant values, inferring that the deposition pattern is especially related to the development and growth of the canopy, which depends on the nature of each species (Rai et al., 2016) (Figs. 5 and 6).

The species *A. pyrifolium* contributed most to both the total accumulation and the leaf fraction, with depositions almost every month. Leaf emission in this species does not respond immediately to water stimuli, and its leaves are known to remain for a longer period, indicating that the species is more tolerant to low water availability (Parente et al., 2012). The vulnerability of the Caatinga vegetation to rainfall pulses is caused by its delayed response to the events of this variable (Barbosa et al., 2019). Thus, some species may present variable leaf deciduity peaks, as seen in *A. pyrifolium*. Santana and Souto (2011) confirm the findings of this study, noting that between the months of August and December (dry period), 46% of the litterfall deposition was supplied by *A. pyrifolium*, and that peak of leaf deposition occurred four months after the beginning of the dry season.

Next, the large depositions of the species *C. quercifolius* are due to its leaves being long and thick, with small aculei on the blade and stinging spines along the veins, resulting in greater amounts of dry matter for this fraction (Drumond et al., 2007). It should also be noted that the increases in deposition seen in all species in July 2017 are consistent with the results of the correlations, since during that month there was a lower incidence of solar radiation and lower temperatures (Table 4).

For the twig fraction, the greatest deposition values seen were for *C. leptophloeos*, and may be associated with the peculiarities of this species, which has a larger diameter stem (DBH 24.9 cm; Table 3) and smooth bark that comes off in thin slivers and is deposited gradually (Maia, 2012). This characteristic explains the high residual effect obtained in the path analysis, since the plant releases these structures even during periods of low rainfall.

For litterfall that originates in the reproductive structures, the species *A. pyrifolium* and *C. quercifolius* again have the greatest contribution, the latter being superior. The flowers of this species appear in small axillary and terminal bunches, where flowering occurs over a long period of the year, with the continuous production of small amounts of seed and dehiscent fruit (Drumond et al., 2007). Similar to the persistence of the leaves seen in *A. pyrifolium*, the fruit also lasts from one year to the next (Parente et al., 2012). In both species, peaks of intensity in the deposition of reproductive structures were seen between the months of March and May of both years of 2016 and 2017, corroborating with the direct effects of NDVI (Table 6) and with the literature (Andrade et al., 2008). Some studies state that peak budding activity begins after the occurrence of rainfall, and is followed by flowering and fruiting in some Caatinga species (Maia, 2012; Parente et al., 2012).

In this study, the miscellaneous fraction was composed predominantly of the body parts and feces of insects. This contribution essentially did not vary between species or over the years, with the highest peaks seen in some months being due to the herbivorous activity of insects, in which heavy defoliation and the large presence of insect feces were seen. Santana and Souto (2011) also demonstrated the participation of herbivorous insects in the process of deposition, which resulted in increases in the miscellaneous fraction.

The species *A. pyrifolium* and *C. quercifolius* showed high rates of deposition, mainly by the larger contribution of the leaf and twig fraction, in this order. However, the contributions of the other species are significant, irrespective of the smaller amount accumulated, since species richness and abundance offers the environment greater diversity, especially with the current exploratory model of the Caatinga. For the Caatinga, the heterogeneity of the litterfall deposition is a reflection of the morphological, physiological and ecological aspects of the plants that give them different responses to the characteristics of the environment (Costa et al., 2010). Therefore, some species may present variable peaks of leaf deciduity (Santana and Souto, 2011). Throughout the year, many forest ecosystems have a continuous production of litterfall, and differences observed monthly in quantity and quality depend on the characteristics of the vegetation monitored (Silva et al., 2009). In the Caatinga, the perennial behavior of the species is a conditioning factor in the litterfall production, causing some deciduous trees to remain with leaves in periods of lower soil moisture, such as *C. sonderianus, C. pyramidalis* and *A. pyrifolium* (Santana and Souto, 2011).

Species such as *A. pyrifolium* and *C. pyramidale* are abundant in degraded areas after cutting or burning the Caatinga, and are considered abundant in environments affected by desertification (Souza et al., 2015). These authors identified plants groups occurring in non-desertified and desertified environments, by means of positive and negative scores, in this order. The species *A. pyrifolium* was related to desertified environments, while *C. pyramidale* occurred in both environments. Also, measures of absolute and relative abundance (values in brackets, respectively) were determined for *A. pyrifolium* (8 and 21.05) and *C. pyramidale* (26 and 32.50) in the desertified environment.

This is attributed to the drought resistance of these species, in addition to characteristics that reduce the impacts of anthropogenic pressure and the grazing activity of domestic animals (cattle, goats and sheep) (Ferraz et al., 2014; Pereira et al., 2003; Souza et al., 2015). Around 70% of Caatinga species are used as food by cattle, for example, the *S. tuberosa* and *C. leptophloeos* (Souza et al., 2015), and grazing activities of goats and sheep inhibit the formation of young shoots (Parente et al., 2012; Souza et al., 2015).

However, for the species *A. pyrifolium* its wood does not have the quality required for the production of charcoal or firewood, which are responsible for supplying 30% of the energy matrix of the Northeast, nor is it used in the manufacture of fences by the farmers (Ferraz et al., 2014; Souza et al., 2015). Still, the consumption of leaves by animals occurs when they begin the process of senescence and fall to the ground losing their toxic characteristics (Parente et al., 2012; Souza et al., 2015). The intoxication by *A. pyrifolium* is evidenced by reproductive disorders in goats (Souza Lima and Soto-Blanco, 2010). These authors report that in *A. pyrifolium* there are several indolent monoterpenic alkaloids, which exhibit cytotoxic activity and may be the toxic compounds of this species. However, further studies are needed to identify component toxicity mechanisms of *A. pyrifolium* (Souza Lima and Soto-Blanco, 2010).

4.4. Decomposition of litterfall

The decomposition of litterfall is the basic way for nutrient cycling to occur, and is an energy source for heterotrophic organisms (Correia et al., 2016; Freitas et al., 2015; Rai et al., 2016). The decomposition rate of the litterfall was low ($k = 0.33$), indicating that in this areas Caatinga the decomposition of the litterfall occurs relatively slowly, when compared to other ecosystems, for example, semi-deciduous seasonal forests that have presented k-values between 1.02 and 1.6, and Neotropical forests, ranging from 1.1 to 1.7 (Arato et al., 2003). This may be related to local water restrictions, since local microbial activity is inhibited under low water availability (Holanda et al., 2015; Huang et al., 2016).

For tropical forests, k values range from 0.3 to 4.0 (Olson, 1963). Lopes et al. (2009), in an area of Caatinga in the State of Ceará, obtained a value of 0.71. k values vary for different plant typologies. Vital et al. (2004) verified that in a semi-deciduous seasonal forest the decomposition rate of the litterfall is high, with values between 1.2 and 1.9. Those authors found values for k of 1.71, and a 50% and 95% disappearance time for the litterfall of 0.4 and 1.75 years, which demonstrates the rapid use of the material. Arato et al. (2003) found a k value of 1.17 and an estimated 50% disappearance time of 215 days. The values obtained by these two authors are close to those found in semi-deciduous seasonal forests.

Although in the present study the k value was low, the accumulation and permanence of deciduous material on the ground has several advantages in a semi-arid environment. The deciduous material protects the soil from the incidence of the sun's rays and from the direct impact of raindrops, avoids daily thermal fluctuations in the soil and increases aeration, in addition to storing seeds and harboring faunal communities that are active in the decomposition process (Andrade et al., 2008; Cizungu et al., 2014; Holanda et al., 2015; Huang and Li, 2017; Sánchez-Andrés et al., 2010; Santana and Souto, 2011).

4.5. Nutrient export from litterfall

The values for litterfall returned by the Caatinga vegetation were lower than values obtained in other Brazilian forest ecosystems, as in the case of Semideciduous forest in riparian zone (Vital et al., 2004), Granite Rock Complex (Freitas et al., 2015) and stand of *Eucalyptus dunnii Maiden* (Ludvichak et al., 2016). This fact may be mainly related to low monthly deposition and low nutrient content obtained for Caatinga. Vital et al. (2004) suggest proposed limits for macronutrient concentrations in dry matter: potassium (0.1–0.3%), calcium (0.02–5%) and magnesium (0.02–2.5%). In the present study, the percentage of these elements was included in the above range, representing 0.30%, 1.07% and 0.12% respectively.

Terror et al. (2011), studying nutrient transfer in litterfall in a swamp forest fragment, obtained values for potassium concentrations of $3.07\ \text{g kg}^{-1}$, similar to the values found in the present study ($3.6\ \text{g kg}^{-1}$). In a semi-deciduous seasonal forest located in the south-central region of the State of São Paulo, Vital et al. (2004) obtained transfer rates of 52.79 kg (K) ha^{-1}, 199.80 kg (Ca) ha^{-1} and 38.70 kg (Mg) ha^{-1}. The greatest export values at these locations are associated with the high annual deposition of litterfall from the studied forests (Table 8).

The deposition of serapillera by the Caatinga vegetation is seasonal and influenced by deciduous characteristics of the species and environmental variables. The species studied present different patterns and quantities of deposition, showing that the floristic composition of the Caatinga Domain is very heterogeneous. This taxonomic diversity is a strong argument to include a larger number of species, principally of tree species. Phenological monitoring of species can contribute substantially to the understanding of the performance of physiological mechanisms on seasonal deposition patterns.

5. Conclusions

Our results provide a conception of the litterfall deposition in the Caatinga vegetation monitored during 20 months, with emphasis on the following main conclusions: the litterfall amount in the Caatinga Domain was lower than in other tropical ecosystems, and its peak deposition occurred at the end of the rainy period, reflecting the xerophytic nature of the species and their delayed response to water pulses; significant relationships of dependence were obtained between the litterfall fractions and environmental conditions, with global solar radiation, heat flow in the soil, vapor pressure deficit, rainfall and normalized difference vegetation index presenting direct and indirect effects; the litterfall deposition between species indicate that leaf deciduity is variable, due to morphological and physiological intrisecal characteristics of species.

Acknowledgments

The authors would like to thank the Research Support Foundation of the State of Pernambuco (FACEPE - APQ-0215-5.01/10 and FACEPE - APQ-1159-1.07/14) and the National Council for Scientific and Technological Development (CNPq - 475279 / 2010-7, 476372 / 2012-7 and 152251/2018-9) for the financial support. The authors would also like to thank the CNPq (305286/2015-3 and 309421/2018-7) and the Coordination for the Improvement of Higher Education Personnel (CAPES - Finance Code 001) for the research and study grants respectively.

References

Albuquerque, E.R.G.M., Sampaio, E.V.S.B., Pareyn, F.G.C., Araújo, E.L., 2015. Root biomass under stem bases and at different distances from trees. J. Arid Environ. 116, 82–88. https://doi.org/10.1016/j.jaridenv.2015.02.003.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2014. Köppen's climate classification map for Brazil. Meteorol. Zeitsch. 22, 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Alves, A.R., Souto, J.S., Souto, P.C., de Holanda, A.C., 2006. Aporte e decomposição de serrapilheira em área de Caatinga, na Paraíba. Rev. Biol. Ciências Terra 6, 194–203.

Andrade, R.L.de, Souto, J.S., Souto, P.C., Bezerra, D.M., 2008. Deposição de serrapilheira em área de Caatinga Na RPPN “Fazenda Tamanduá”, Santa Terezinha-PB. Rev. Caatinga 21, 223–230.

Arato, H.D., Martins, S.V., Ferrari, S.H.D.S., 2003. Produção e decomposição de serapilheira em um sistema agroflorestal implantado para recuperação de área degradada em Viçosa-MG. Rev. Árvore 27, 715–721. https://doi.org/10.1590/S0100-67622003000500014.

de Araújo Primo, J.T., da Silva, T.G.F., Siqueira e Silva, S.M., de Moura, M.S.B., de Souza, L.S.B., 2015. Calibração de sondas capacitivas, funções físico-hídricas e variação do armazenamento de água em um argissolo cultivado com palma forrageira. Rev. Ceres 62, 20–29. https://doi.org/10.1590/0034-737X201562010003.

Barbosa, H.A., Kumar, T.V.L., Paredes, F., Elliott, S., Ayuga, J.G., 2019. Assessment of Caatinga response to drought using meteosat- SEVIRI normalized difference vegetation index (2008–2016). J. Photogramm. Remote Sens. 148, 235–252. https://doi.org/10.1016/j.isprsjprs.2018.12.014.

Bernaschini, M.L., Moreno, M.L., Pérez-Harguindeguy, N., Valladares, G., 2016. Is litter decomposition influenced by forest size and invertebrate detritivores during the dry season in semiarid Chaco Serrano? J. Arid Environ. 127, 154–159. https://doi.org/10.1016/j.jaridenv.2015.11.009.

Campos, C.A., Cruz, H.L., Rocha, O.S., 2017. Mass, nutrient pool, and mineralization of litter and fine roots in a tropical mountain cloud forest. Sci. Total Environ. 575, 876–886. https://doi.org/10.1016/j.scitotenv.2016.09.126.

Cizungu, L., Staelens, J., Huygens, D., Walangululu, J., Muhindo, D., Van Cleemput, O., Boeckx, P., 2014. Forest ecology and management litterfall and leaf litter decomposition in a central African tropical mountain forest and Eucalyptus plantation. For. Ecol. Manage. 326, 109–116. https://doi.org/10.1016/j.foreco.2014.04.015.

Coelho, V.H.R., Montenegro, S.M.G.L., das Almeida, C.N., de Lima, E.R.V., Ribeiro Neto, A., de Moura, G.S.S., 2014. Dinâmica do uso e ocupação do solo em uma bacia hidrográfica do semiárido brasileiro. Rev. Bras. Eng. Agrícola Ambient. 18, 64–72. https://doi.org/10.1590/S1415-43662014000100009.

de Correia, G.G.S., Martins, S.V., Miranda Neto, A., de Silva, K.A., de Correia, G.G.S., Martins, S.V., Miranda Neto, A., de Silva, K.A., 2016. Estoque de serapilheira em floresta em restauração e em floresta atlântica de tabuleiro no sudeste brasileiro. Rev. Árvore 40, 13–20. https://doi.org/10.1590/0100-67622016000100002.

de Costa, C.C.A., Camacho, R.G.V., de Macedo, I.D., da Silva, P.C.M., 2010. Análise comparativa da produção de serapilheira em fragmentos arbóreos e arbustivos em área de caatinga na FLONA de Açu-RN. Rev. Árvore 34, 259–265.

Costa, C.C.A., Souza, A.M., da Silva, N.F., Camacho, R.G.V., Dantas, I.M., 2007. Produção de serapilheira na Caatinga da Floresta Nacional do Açú-RN. Rev. Bras. Biociências 5, 246–248. https://doi.org/10.4067/S0718-34292011000200011.

CRUZ, C.D., 2006. Programa GENES: biometria. Viçosa, UFV, pp. 382.

Cunha, J., Nóbrega, R.L.B., Rufinod, I., Erasmie, S., Galvão, C., Valentef, F., 2019. Surface albedo as a proxy for land-cover clearing in seasonally dry forests: evidence from the Brazilian Caatinga. Remote Sens. Environ. https://doi.org/10.1016/j.rse.2019.111250.

Drumond, M.A., Salviano, L.M.C., de Cavalcanti, N.B., Pereira, L.G.R., 2007. Produção, distribuição da biomassa e composição bromatológica da parte aérea da faveleira. Rev. Bras. Ciências Agrárias 2, 308–310.

Empresa Brasileira de Pesquisa Agropecuária, 2009. Manual de Análises Químicas de Solos, Plantas e Fertilizantes. In: second ed. https://doi.org/10.1590/S0103-90162007000600012. Embrapa, Brasília, DF, Brazil.

Ferraz, J.S.F., Ferreira, R.L.C., da Silva, J.A.A., Meunier, I.M.J., dos Santos, M.V.F., 2014. Estrutura do componente arbustivo-arbóreo da vegetação em duas áreas de caatinga, no município de Floresta. Pernambuco. Rev. Árvore 38, 1055–1064.

de Freitas, C.A.A., Caldeira, M.V.W., Horn, S.K., Castro, K.C., Viera, M., 2015. Serapilheira acumulada em complexo rupestre de granito, Mimoso do Sul, ES. Rev. Árvore 39, 671–681. https://doi.org/10.1590/0100-67622015000400009.

Holanda, A.C., Feliciano, A.L.P., Maragon, L.Ca., Freire, F.J., Holanda, E.M., 2015. Decomposição da serapilheira foliar e respiração edáfica em um remanescente de Caatinga na Paraíba. Rev. Árvore 39, 245–254.

Huang, X., Shi, Z.H., Zhu, H.D., Zhang, H.Y., Ai, L., Yin, W., 2016. Soil moisture dynamics within soil profiles and associated environmental controls. Catena 136, 189–196. https://doi.org/10.1016/j.catena.2015.01.014.

Huang, G., Li, Y., 2017. Photodegradation effects are related to precipitation amount, precipitation frequency and litter traits in a desert ecosystem. Soil Biol. Biochem. 115, 383–392. https://doi.org/10.1016/j.soilbio.2017.08.034.

IPCC, 2014. Climate change. Synthesis report. In: Pachauri, R.K., Meyer, L.A. (Eds.), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change IPCC, 2014. Geneva, Switzerland. pp. 151.

Lopes, J.F.B., de Andrade, E.M., de Lobato, F.A.O., de Palácio, H.A.Q., Arrae, F.D.D., 2009. Deposição e decomposição de serapilheira em área da Caatinga. Rev. Agro@mbiente On-line 3, 72–79.

Ludvichak, A.A., Schumacher, M.V., Dick, G., Momolli, D.R., Pablo De Souza, H., Do, C., Guimarães, C., 2016. Nutrient return through litterfall in a eucalyptus dunnii maiden stand in sandy soil. Rev. Árvore 40, 1041–1048. https://doi.org/10.1590/0100-67622016000600009.

Maia, G.N., 2012. Caatinga: Árvores e Arbustos e Suas Utilidades, second ed. Fortaleza.

Martins, S.V., Rodrigues, R.R., 1999. Produção de serapilheira em clareiras de uma floresta estacional semidecidual no município de Campinas, SP. Rev. Bras. Botânica 22, 405–412. https://doi.org/10.1590/S0100-84041999000300009.

Menezes, R., Sampaio, E., Giongo, V., Pérez-Marin, A., 2012. Biogeochemical cycling in terrestrial ecosystems of the Caatinga Biome. Braz. J. Biol. 72, 643–653. https://doi.org/10.1590/S1519-69842012000400004.

Nunes, F.P., Pinto, M.T.C., 2007. Produção de serapilheira em mata ciliar nativa e reflorestada no alto São Francisco. Minas Gerais. Biota Neotrop. 7, 97–102. https://doi.org/10.1590/S1676-06032007000300011.

Olson, J.S., 1963. Energy storage and the balance of producers and decomposers in ecological systems. Ecology 44, 322–331. https://doi.org/10.2307/1932179.

Parente, H.N., de Andrade, A.P., da Silva, D.S., Santos, E.M., Araujo, K.D., de Parente, M.O.M., 2012. Influência do pastejo e da precipitação sobre a fenologia de quatro espécies em área de caatinga. Rev. Árvore 36, 411–421. https://doi.org/10.1590/S0100-67622012000300003.

Pereira, I.M., Andrade, L.A., Sampaio, E.V.S.B., Barbosa, M.R.V., 2003. Use-history effects on structure and flora of Caatinga. Biotropica 35, 154–165. https://doi.org/10.1111/j.1744-7429.2003.tb00275.x.

Rai, A., Singh, A.K., Ghosal, N., Singh, N., 2016. Understanding the effectiveness of litter from tropical dry forests for the restoration of degraded lands. Ecol. Eng. 93, 76–81. https://doi.org/10.1016/j.ecoleng.2016.05.014.

Salla, V.P., Danner, M.A., Citadin, I., Sasso, S.A.Z., Donazzolo, J., Gil, B.V., 2015. Análise de trilha em caracteres de frutos de jabuticabeira. Pesqui. Agropecuária Bras 50, 218–223. https://doi.org/10.1590/S0100-204X2015000300005.

Sampaio, E.V.S.B., Silva, G.C., 2005. Biomass equations for Brazilian semiarid caatinga plants. Acta Bot. Bras. 19, 935–943. https://doi.org/10.1590/S0102-33062005000400028.

Sánchez-Andrés, R., Sánchez-Carrillo, S., Alatorre, L.C., Cirujano, S., Álvarez-Cobelas, M., 2010. Litterfall dynamics and nutrient decomposition of arid mangroves in the Gulf of California: their role sustaining ecosystem heterotrophy. Estuar. Coast. Shelf Sci. 89, 191–199. https://doi.org/10.1016/j.ecss.2010.07.005.

da Santana, J.A.S., Souto, J.S., 2011. Produção de serapilheira na Caatinga da região semi-árida do Rio Grande do Norte. Brasil. Idesia 29, 87–94. https://doi.org/10.4067/S0718-34292011000200011.

Santos, R.M., Oliveira-filho, A.T., Eisenlohr, P.V, Queiroz, L.P., 2012. Identity and relationships of the arboreal Caatinga among other floristic units of seasonally dry tropical forests (SDTFs) of North-Eastern and Central Brazil. Ecol. Evol. 2, 409–428. https://doi.org/10.1002/ece3.91.

Schulz, K., Voigt, K., Beusch, C., Almeida-Cortez, J.S., Kowarik, I., Walz, A., Cierjacks, A., 2016. Grazing deteriorates the soil carbon stocks of Caatinga forest ecosystems in Brazil. For. Ecol. Manage. 367, 62–70. https://doi.org/10.1016/j.foreco.2016.02.011.

Silva, V.N., Souto, L.S., Dutra Filho, J.A., Souza, T.M.A., Borges, C.H.A., 2015. Deposição de serapilheira em uma área de caatinga preservada no semiárido da Paraíba. Brasil. Rev. Verde 10, 21–25. https://doi.org/10.18378/rvads.v10i2.3409.

da Silva, C.R., de Andrade Júnior, A.S., Alves Júnior, J., de Souza, A.B., Melo, F.D.B., Coelho Filho, M.A., 2007. Calibration of a capacitance probe in a Paleudult. Sci. Agric. 64, 636–640.

da Silva, R.M., da Costa, J.M.N., de Ruivo, M.L.P., da Costa, A.C.L., Almeida, S.S., 2009. Influência de variáveis meteorológicas na produção de liteira na Estação Científica Ferreira Penna, Caxiuanã. Pará. Acta Amaz. 39, 573–582. https://doi.org/10.1590/S0044-59672009000300012.

Souza, B.I., Menezes, R., Cámara Artigas, R., 2015. Efeitos da desertificação na composição de espécies do bioma Caatinga, Paraíba/Brasil. Investig. Geogr. 2015, 45–59. https://doi.org/10.14350/rig.44092.

Souza Lima, M.C.J., Soto-Blanco, B., 2010. Poisoning in goats by *Aspidosperma pyrifolium* Mart.: biological and cytotoxic effects. Toxicon 55, 320–324. https://doi.org/10.1016/j.toxicon.2009.08.004.

Terror, V.L., de Sousa, H.C., Kozovits, A.R., 2011. Produção, decomposição e qualidade nutricional da serapilheira foliar em uma floresta paludosa de altitude. Acta Bot. Brasilica 25, 113–121. https://doi.org/10.1590/S0102-33062011000100014.

Vianello, R.L., Alves, A.R., 2012. Meteorologia Básica e Aplicações, second ed. UFV, Viçosa, MG.

Vieira, I.R., de Araújo, F.S., Zandavalli, R.B., 2013. Shrubs promote nucleation in the Brazilian semi-arid region. J. Arid Environ. 92, 42–45. https://doi.org/10.1016/j.jaridenv.2013.01.009.

Vital, A.R.T., Guerrini, I.A., Franken, W.K., Fonseca, R.C.B., 2004. Produção de serapilheira e ciclagem de nutrientes de uma floresta estacional semidecidual em zona ripária. Rev. Árvore 28, 793–800. https://doi.org/10.1590/S0103-40142000000100005.

Ye, Y., Chen, Y.P., Chen, G.C., 2013. Litter production and litter elemental composition in two rehabilitated Kandelia obovata mangrove forests in Jiulongjiang Estuary, China. Mar. Environ. Res. 83, 63–72. https://doi.org/10.1016/j.marenvres.2012.10.011.

Zhang, H., Yuan, W., Dong, W., Liu, S., 2014. Seasonal patterns of litterfall in forest ecosystem worldwide. Ecol. Complex. 20, 240–247. https://doi.org/10.1016/j.ecocom.2014.01.003.