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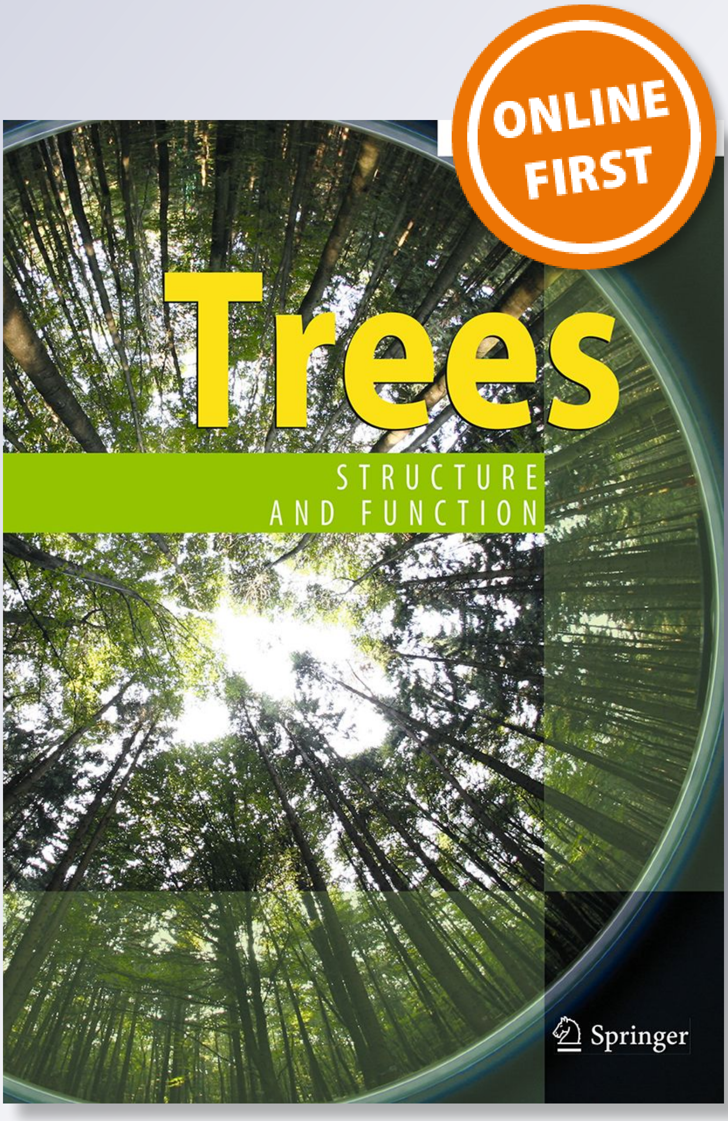

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ORIGINAL ARTICLE

Responses of tree-ring growth in *Schinopsis brasiliensis* to climate factors in the dry forests of northeastern Brazil

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Abstract

Key message **This paper aims to provide evidences of the influence of physical atmospheric parameters on the growth of the endemic tree *Schinopsis brasiliensis*, and their consequent teleconnection with large-scale modes of climate variability affecting rainfall in semi-arid region of the Brazilian Northeast.**

Abstract The Brazilian Northeast is a region of low rainfall and high temperatures and evaporation. The surface temperature of the Atlantic Ocean (STA) modulates the rains in the Northeast in association with El Niño and La Niña (ENSO) events. Tree species that grow in this region, forming the tropical Caatinga dry forests, are subjected to long periods of drought. This study investigated the influence of climatic events on the secondary growth of a typical Caatinga tree species. The analysis was based on 39 samples of *Schinopsis brasiliensis*, from which we derived a chronology of tree-ring growth between 1963 and 2015, with an inter-correlation of 0.56, mean sensitivity of 0.53, and mean growth rate of 3.33 mm per year. Our results indicate that growth ring chronology is related directly to the rainy season, in addition to peaks in humidity associated with isolated downpours occurring during the dry season. On the other hand, air temperature, insolation, and evaporation revealed an inverse relationship with the chronology. Inter-correlations with ENSO events, STA, and precipitation were negative, while those between ENSO events and temperature were positive. Growth in *S. brasiliensis* is associated with the climatic anomalies of the region. Leaf-fall and cambial shutdown occur during the dry season, while the plant is predisposed for potential growth spurts during the intermittent rains that may occur from December onwards.

Keywords Tropical dendro-ecology · *Schinopsis brasiliensis* · ENSO and STA · Dry forest · Caatinga

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Introduction

Northeastern Brazil (herein, the Northeast) is a semi-arid region characterized by low rainfall levels, high temperatures, and high evaporation rates, subject to extreme events, such as severe droughts and torrential downpours (Cavalcanti et al. 2006). The principal mechanism that determines rainfall patterns in the Northeast is the Intertropical Convergence Zone (ITCZ), which is modulated by the sea surface temperature (SST) of the equatorial Atlantic Ocean (Roucou et al. 1996). In this context, when the North Atlantic is cooler than the South Atlantic (negative dipole), the ITCZ shifts to its southern position, favoring the occurrence of seasonal rains in the Northeast. When there is a positive dipole, i.e., the waters of the South Atlantic are cooler than those of the North Atlantic, the ITCZ shifts northward, inhibiting the formation of clouds over the Northeast and reducing rainfall rates (Nobrega and Santiago 2014). Hastenrath and Heller (1977), Moura and Shukla (1981) and Silva (2004) conducted the first studies that described the relationship between precipitation in the Northeast and SST anomalies in the tropical Atlantic.

One other climatic phenomenon associated with SST anomalies—in this case, in the equatorial Pacific—is the El Niño-Southern Oscillation (ENSO), which also influences precipitation patterns in the Northeast. In years with a weak to moderate ENSO, associated with a negative Atlantic dipole, the rainy season tends to be normal. However, when an ENSO is associated with a positive Atlantic dipole or when ENSO is very intense, the rains of the Northeast tend to be below average. During the cool ENSO phase, known as La Niña, conditions in the equatorial Pacific favor an increase in precipitation in the Northeast (Nobrega and Santiago 2014).

While precipitation levels fluctuate considerably, air temperatures in the Northeast vary only discreetly. The region is dominated by coastal plains, plateaus, and depressions, with altitudes of up to 600 m, and is characterized by a high incidence of sunlight throughout the year (Lucena and Steinke 2015), which results in high and almost constant temperatures. The minimum temperatures (approximately 27 °C) are recorded at the end of the rainy season (June–July) while the maximum temperatures (approximately 35 °C) occur during the dry season (November–February).

As the SST anomalies of the equatorial Pacific and Atlantic oceans influence rainfall patterns in the Northeast, and the temperature affects the metabolic and physiological processes of the region's living organisms, it is important to understand how the region's plants react to these phenomena. Tree species found in semi-arid tropical forests typically present a range of responses to the variation in climatic conditions (Aroca 2012). The formation of growth rings in the secondary xylem of these plants is just one of these responses (Schweingruber 1996), and a significant increase in the radial width of the tree may occur in the context of extreme rainfall events (López et al. 2006).

The Brazilian Caatinga is a tropical dry forest endemic to the Northeast, where the availability of groundwater and rainfall are both scarce and heterogeneously distributed (Prado and Gibbs 1993; Prado 2005; Silva et al. 2012). Many of the tree species found in these forests form growth rings, whose width is closely related to climatic conditions on both regional and global scales (Nogueira 2011; Anholeto 2013; Pagotto 2015; Pagotto et al. 2015). One species of interest to dendroecological research is *Schinopsis brasiliensis* Engl. (Anacardiaceae), known locally as the braúna. This deciduous tree species is endemic to the Caatinga and Cerrado biomes of Brazil (Silva-Luz and Pirani 2015). This tree is one of the largest in the Caatinga, where it may reach a height of 15 m and trunk diameter of 60 cm. The timber of this species is extremely resistant, and is widely used for the construction of external structures, such as fences. In the Caatinga, *S. brasiliensis* is a highly-valued hardwood, although the excessive exploitation of the species has led to almost complete exhaustion of stocks in the Northeast, where it is now considered to be under imminent risk of extinction (Maia 2012).

Recent studies have shown that growth rings of *S. brasiliensis* can be used for dendroecological research and climatic reconstruction. Cardoso (2014) analyzed growth rings in *S. brasiliensis* from the Caatinga of the Brazilian state of Sergipe, and obtained an expanded chronology, based on the examination of lumber used in constructions in rural areas, which correlated with regional precipitation levels and the surface temperature of the South Atlantic (STA). Lopez and Villalba (2016) have emphasized the value of *S. brasiliensis* for the understanding of the climate dynamics of South America.

The present study investigated the influence of local climate parameters (temperature, precipitation, wind speed, insolation, evaporation, and humidity) associated with global phenomena (ENSO and STA) on the growth of *S. brasiliensis* in the Brazilian semi-arid zone. The study tested the hypothesis that the secondary growth of *S. brasiliensis* responds to the climatic variation in the Caatinga. Precipitation is predicted to affect tree-ring growth positively, and high temperatures to affect growth negatively.

Materials and methods

Study area

The present study focused on remnants of Caatinga habitat in the municipality of Paulo Afonso, (09°30′50.37″S, 38°09′22.15″W) in the state of Bahia, Brazil (Fig. 1). The climate of this region is semi-arid, dry and hot, typical of the *Bsh* category in the Koppen (1948) classification. During the study period (1962–2015) the mean temperature was 30 °C and the mean of accumulated annual precipitation was 460 mm. In this range (1962–2015), the minimum temperature (17 °C) was recorded in July 1974 and a maximum (36 °C) in February 1998. The lowest accumulated monthly precipitation (178 mm) occurred in 1982, while the highest (852 mm) in 1966.

Rainfall is highly seasonal, with a rainy season between March and July, corresponding to the austral winter, and a dry season in the austral summer, between August and February (Fig. 2). Torrential downpours may occur sporadically from December to February (Barros et al. 2012).

The region's soils are predominantly chromic luvisols, quartzic neosols, and haplic planosols, which all have a reduced capacity for the retention of water (EMBRAPA 2016). The local vegetation in the study area is hyperxerophilous, typical of the Caatinga biome, characterized by a hot and semi-arid climate, with plant species adapted for an arid climate, including deciduous and annual herbaceous species, succulents, aculeate and spiny plants, and a predominance of shrubs and small trees with a discontinuous canopy (http://ainfo.cnptia.embrapa.br/digital/bitstream/item/18267/1/Biodiversidade_Caatinga_parte2.pdf).

Tree sampling and tree-ring width measurements

A total of 52 radii (at breast height, i.e., 1.30 m) were sampled randomly from 40 live *S. brasiliensis* trees with no major twists or other imperfections in their trunks, using a hollow drill bit (hole saw) attached to a Stihl BT45 drill. The samples were dried at ambient temperature, and then sanded with paper of increasingly finer grit sizes (ISO86: P80–P600; Orvis and Grissino-Mayer 2002). Growth rings were demarcated under a stereomicroscope and digitalized in the TIF format using a scanner (HP Deskjet F4100) with a resolution of 1200 dpi. Xylem tree-ring widths were measured from medulla to bark in each sample, using Image Pro-plus (version 4.5.0.29), with a precision of 0.01 mm.

Radial measurements of ring-width were cross-dated (Stokes and Smiley 1996; Fritts 1976) with COFECHA (Holmes 1983). After, the final tree-ring width index chronology was computed using ARSTAN (ARS41d_xp version) software package (Cook 1985). ARSTAN removes the biological age trend of individual tree series and any other stand dynamic trends (Cook 1985). We used a cubic smoothed spline with a 50% frequency response cutoff equal to 67%

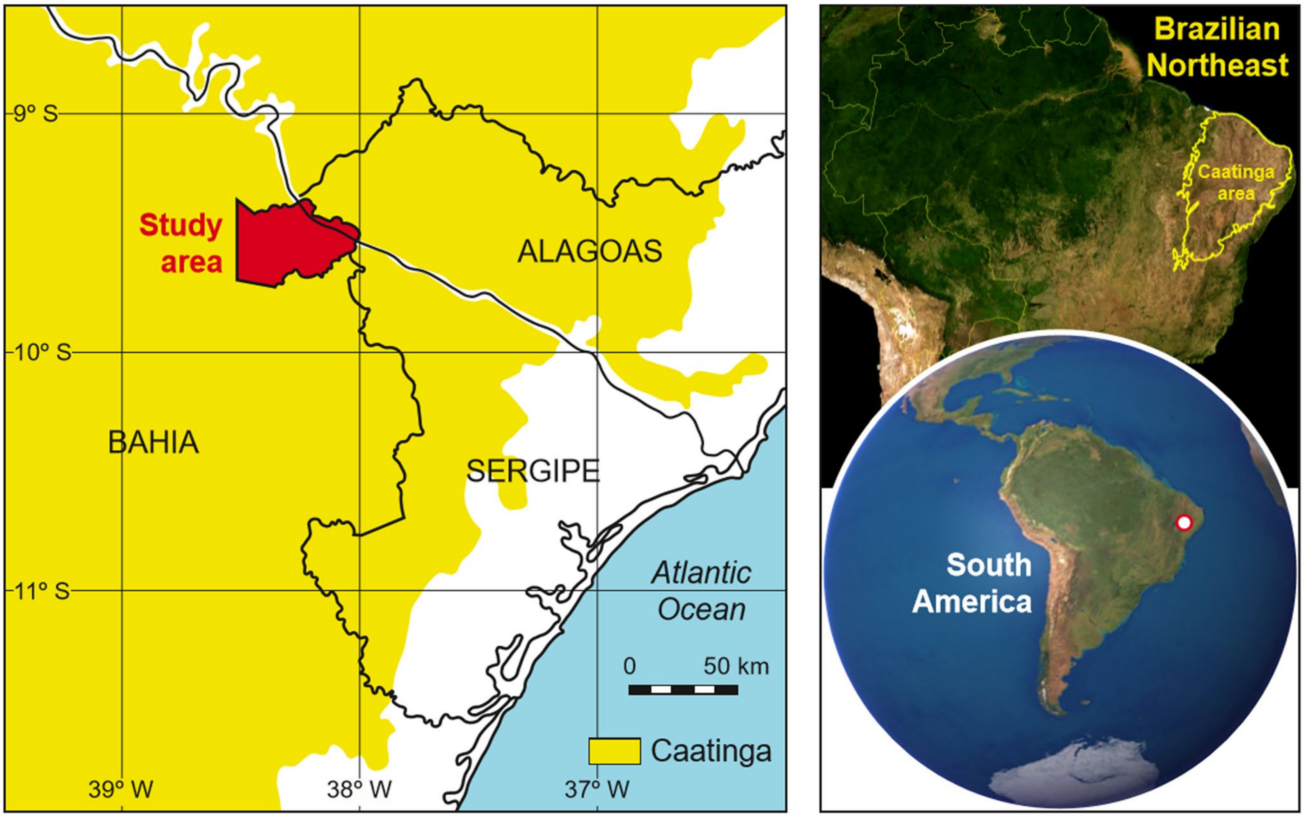

Fig. 1 A set of maps showing the location of the Caatinga biome in the Brazilian Northeast (yellow area). The red area in the more detailed map is the municipality of Paulo Afonso in Bahia, Brazil

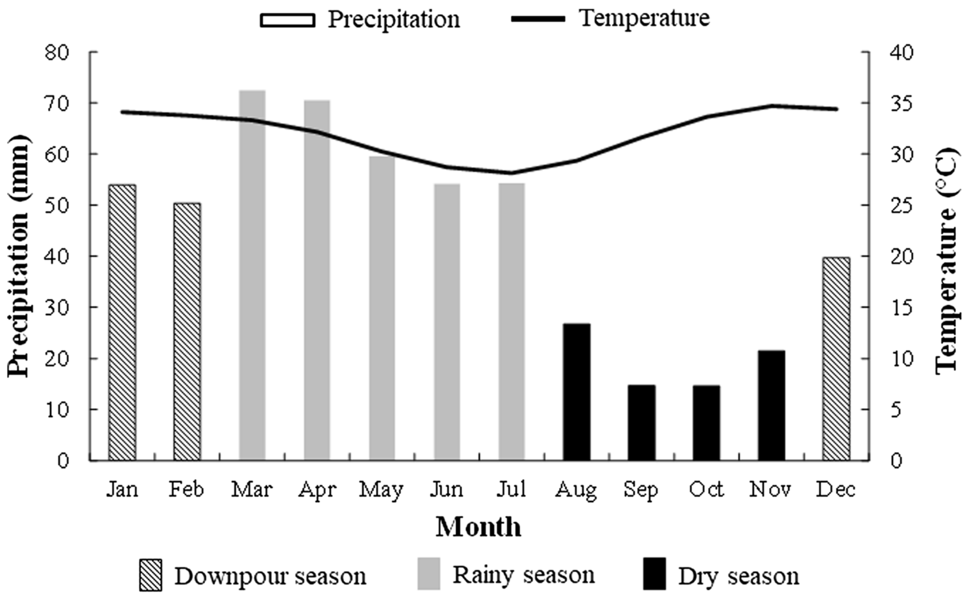

Fig. 2 The climate diagram (period 1962–2015) of the study area. The bar and line represent precipitation and temperature, respectively. Source: INMET

of the series length to minimize the differences inherent to each individual (Cook and Peters 1981; Stahle et al. 1999).

Climate data

Climate variables were extracted from the daily meteorological data for the period between 1962 and 2015 available on the site of the Brazilian National Meteorological Institute (http://www.inmet.gov.br/portal/index.php?r=bdmep/bdmep). Most (80%) of the data were obtained from meteorological station 82986-Paulo Afonso-BA, which is 20 km from the study area. The missing 20% of records were obtained from adjacent meteorological stations following an analysis of the correlation among sites, which should be significant, given their proximity and only occasional climatic dissimilarities were verified (Silva et al. 2012).

The climatic parameters used were (1962–2015): accumulated precipitation (AP), mean temperature (MT), mean maximum temperature (MMaT), mean minimum temperature (MMiT), mean relative humidity (MRH), mean evaporation (ME), mean insolation (MI), and mean wind speed (MWS). Global climatic variables were also incorporated into the analyses through the index of the surface temperature of the Atlantic Ocean (STA) obtained for the area between the coordinates Equator-20S and 10E–30W (http://www.esrl.noaa.gov/psd/data/correlation/tsa.data), as well as the extreme El Niño and La Niña events, obtained from the historical series available on the site http://ggweather.com/enso/oni.htm.

Data analysis

All climate data were evaluated for normality using the Shapiro–Wilk test. The data were standardized for the statistical analyses to minimize the differences in the numerical values among the different parameters. The climatic data were run through a principal components analysis (PCA) for the identification of the variables that most influenced plant growth. Climate parameters and standard chronology were then analyzed using generalized linear models (GLMs) to identify the significant correlations. In addition, the influence of climatic parameters (AP, MT and STA) on standard chronology was analyzed using a Pearson's correlation coefficient (*r*) with a 99% significance level in RESPO software (Holmes et al. 1986). Finally, the El Niño and La Niña indices were correlated with precipitation (AP) and temperature (MTq) to assess the influence of these events on local climatic parameters. The letter "q" (to for APq, MTq and STAq) refers to quarterly indices corresponding to the inter-annual intervals provided by NOAA and calculated for local environmental data. Descriptive terminology for ENSO, i.e., weak, moderate and strong events, was based on NOAA, which shows when El Niño and La Niña events begin in 1 year (June, July, August—JJA) and end in the following year (March, June, July—MJJ). All the statistical tests were run in STATISTICA$^{®}$ 7 (Statsoft 2004) and PAST (Hammer et al. 2001).

Results

Schinopsis brasiliensis has xylem growth rings that are visible to the naked eye, delimited by a fine and continuous marginal axial parenchyma associated with the thickening of the fiber walls, which, as a whole, is identified in the latewood zone of the ring (Fig. 3). The marginal parenchyma is most visible in the sapwood, which is lighter in color than the heartwood. No false or missing growth rings were observed.

The standard tree-ring chronology of *S. brasiliensis* is shown in Table 1 and Fig. 4a, b. The trees analyzed were between 16- and 53-years-old (mean age = 28 years), with a predominance of younger individuals, i.e., 23 out of the 40 trees (57.5%) were less than 28-years-old. Mean tree-ring width was 3.33 mm, ranging from 0.44 to 13.74 mm.

The results of the PCA indicated a significant positive correlation between the standard tree-ring chronology and the AP and MRH values. These results are consistent with the GLM for the relationships between the chronology and the climatic parameters (Table 2).

The results show a positive correlation ($p < 0.05$) between standard chronology and the precipitation of January–June, August and December of the current year (Fig. 5a). Standard chronology is negatively correlated ($p < 0.05$) with mean temperature of March–August and December of the current year and in March of the preceding year (Fig. 5b). However, the STA of April–September of the preceding year was positively correlated ($p < 0.05$) with standard chronology (Fig. 5c).

The influence of extreme climatic events (surface temperature of the Atlantic Ocean, STA, and the El Niño–Southern Oscillation, ENSO) on the dynamics of the local precipitation (AP) and temperature (MT) was evaluated using a Pearson's correlation (see Table 3).

Table 1 Diagnostic data of the tree-ring series of *Schinopsis brasiliensis*

Number of trees (radii)	Time period	Total years	Number of rings analyzed	Series intercorrelation	Mean sensitivity
39 (50)	1963–2015	53	1328	0.560*	0.530

*Significant correlation after COFECHA

Overall, ENSO events (El Niño or La Niña) occurred in 61.5% of the years of the study period (1963–2015), considering weak, moderate and strong events, while downpours were recorded in 73.1% of the years (Table 4). Comparing ENSO events and downpours with the *S. brasiliensis* standard chronology, we observed the formation of both wider and narrower growth rings than average occurs during these events. This indicates that these climatic phenomena influence the secondary growth of *S. brasiliensis* (Fig. 6). Table 4 shows the association between climatic anomalies and the radial measurements above/below the 3 mm threshold. The multiple correlations between the chronology and the rainy season (March–July) and the downpours (recorded during December of the preceding year and January–February of the current year) indicated that the downpours also played a significant role in the formation of annual growth rings in *S. brasiliensis* (Table 5).

Discussion

The *S. brasiliensis* growth rings recorded in the Brazilian Northeast are annual, and can be identified by the fine continuous line of the marginal axial parenchyma, as described

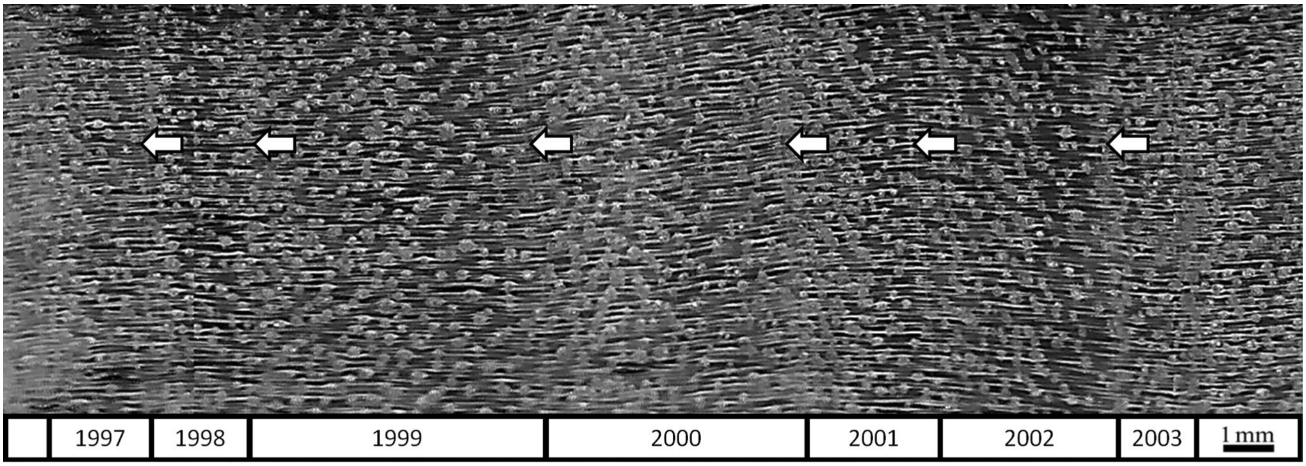

Fig. 3 Transversal surface of the *Schinopsis brasiliensis* wood, showing distinct annual growth rings outlined by a fine marginal parenchymal band (arrows)

Fig. 4 **A** Standard chronology of *Schinopsis brasiliensis*. The shaded area indicates the proportion of samples that contributed to the construction of the chronology. **B** Raw individual tree ring series (gray lines) and the resulting average series (black line). $N = 40$

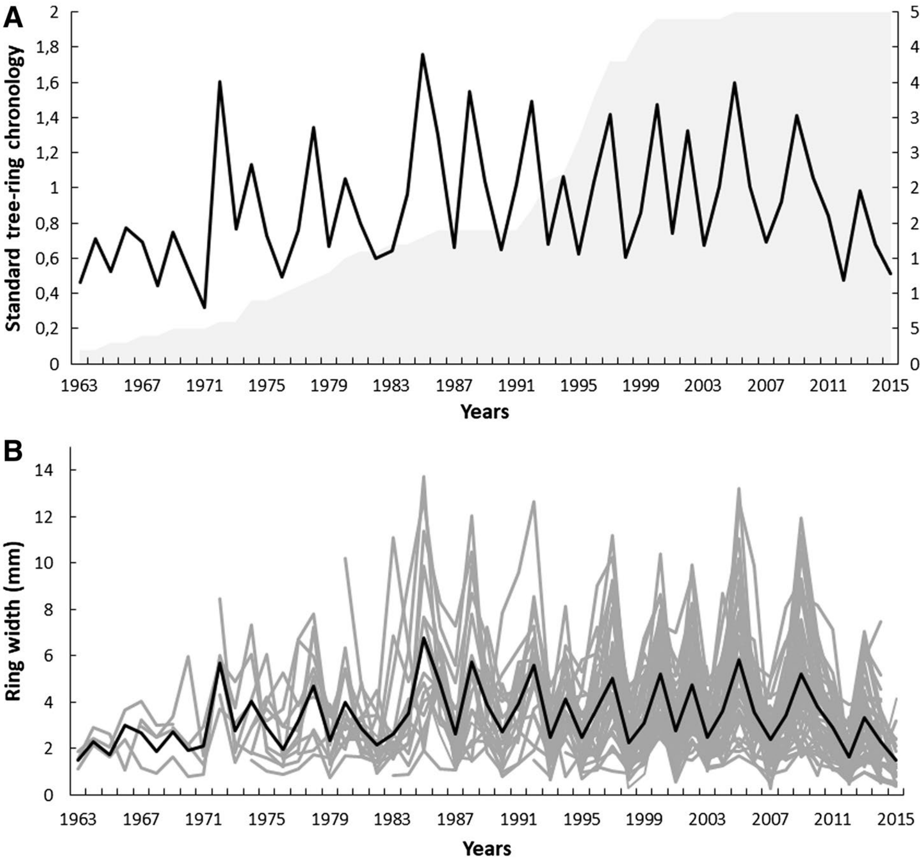

Table 2 Correlations obtained by the GLM between the standard chronology of *Schinopsis brasiliensis* and local climatic variables

Variables	AP	MT	MI	MMaT	MRH	ME	MMiT	MWS
r	0.71*	− 0.59*	− 0.51*	− 0.41*	0.39*	− 0.35*	0.19	− 0.14

AP accumulated precipitation, *MT* mean temperature, *MI* mean insolation, *MMaT* mean maximum temperature, *MRH* mean relative humidity, *ME* mean evaporation, *MMiT* mean minimum temperature; *MWS* mean wind speed

*Significant ($p < 0.05$)

by Lopez and Villalba (2016). The line of the marginal parenchyma is best visualized in the sapwood, due to the greater contrast in coloration, and varied considerably in width within the wood, a pattern also observed in *S. lorentzii* in the Argentinian Chaco, a second region with a strongly seasonal climate (Giménez and Lopez 2002; Ferrero and Villalba 2009; Cardoso 2014). The lack of false growth rings in *S. brasiliensis* emphasizes the influence of climate seasonality on the activity of the cambium in the semi-arid zone of northeastern Brazil.

Tree age of the genus *Schinopsis* may reach 250 years as observed in *S. lorentzii* (Giménez and Ríos 1999). However, the chronology recorded in the present study can be considered satisfactory in terms of the inter-correlation and the sensitivity of the growth ring series (Table 1), which indicates that this species is a good model for studies in tropical dendrochronology, with practical applications in both dendroecology and dendroclimatology. Chronologies can also be extended into the past through the analysis of growth rings in dead wood (Fritts 1976), as shown by Cardoso (2014), who analyzed *S. brasiliensis* lumber used in constructions in rural areas. These timbers produced chronologies of up to 127 years in length (unpublished data). In the Caatinga, *S. brasiliensis* is exploited primarily for the production of fence posts (Nascimento 2007), due to both its availability, and the durability of its wood, which is resistant to decay (Pereira et al. 2003). The lumber of *S. brasiliensis* is considered to be of high quality and excellent durability (Matos et al. 2005).

The correlation found between the standard chronology and climatic parameters indicates that the growth of *S. brasiliensis* in the study region is closely related to the water

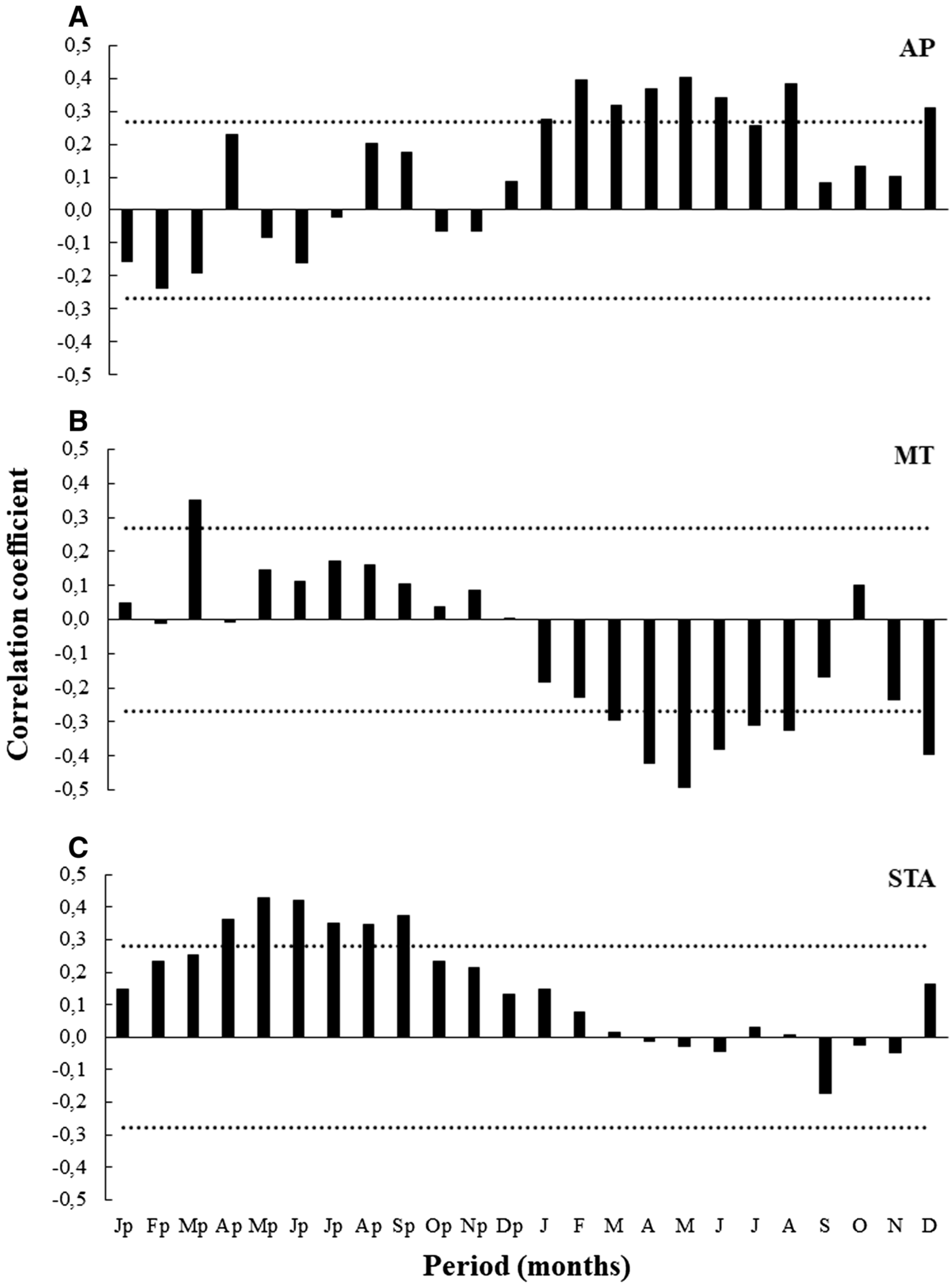

Fig. 5 Correlation between the standard chronology of *Schinopsis brasiliensis* and the climatic variables: **A** accumulated precipitation; **B** mean temperature; **C** temperature of the Surface of the Atlantic Ocean. The significance level ($p < 0.05$) is indicated by the dotted line. The "p" after the months indicates the previous year

availability (Table 2). The relationship between the standard chronology and precipitation (Fig. 5a) highlights the formation of growth rings during both the rainy season and the months during which downpours occur (Table 5). The downpours are often associated with high summer temperatures, and may contribute as much as 267 mm of rainfall, which is often a major contribution to the annual total, during a very short period of time.

There was a negative response of the chronology to the mean temperatures (Fig. 5b) recorded in March–August and December of the current year, confirming that temperature also interferes in the formation of the growth rings. In addition to the mean temperature, other parameters associated with heat waves, i.e., the MI, MMaT, and ME, further reinforced this pattern in the results of the GLM (Table 2). The increase in relative humidity following rainfall also interferes in local temperature dynamics, with the effects being most apparent during the dry season, when the downpours occur. It seems possible that these events contribute to the resumption of growth in these trees. The negative correlation between growth and maximum temperatures may thus be related, at least in part, to the alleviation of high dry season temperatures by the downpours (Devall et al. 1995). The hydrological deficit during the period of reduced rainfall

Table 3 Pearson's correlations, considering the period between January of the previous year (y – 1) and December of the current year, and the El Niño–Southern Oscillation (ENSO) and STAq (ENSO/STAq); ENSO and precipitation (ENSO/APq); ENSO and air temperature (ENSO/MTq); surface temperature of the Atlantic Ocean (STA) and annual rainfall (STA/AP); STA and air temperature (STA/MT), for the period between 1963 and 2010

Quarter	ENSO/STAq	ENSO/APq	ENSO/MTq	Month	STA/AP	STA/MT
JJA y – 1	0.06	– 0.21	0.13	Jan y – 1	0.17	0.02
JAS y – 1	0.04	– 0.23	0.15	Feb y – 1	0.21	– 0.02
ASO y – 1	0.03	– 0.25	0.20	Mar y – 1	0.25	– 0.07
SON y – 1	0.02	– 0.27	0.22	Apr y – 1	0.33*	– 0.14
OND y – 1	– 0.01	– 0.28*	0.23	May y – 1	0.39*	– 0.17
NDJ y – 1	– 0.02	– 0.31*	0.24	Jun y – 1	0.39*	– 0.18
DJF y – 1	– 0.04	– 0.32*	0.25	Jul y – 1	0.32*	– 0.17
JFM y – 1	– 0.03	– 0.33*	0.27	Aug y – 1	0.38*	– 0.27
FMA y – 1	– 0.00	– 0.35*	0.33*	Sep y – 1	0.38*	– 0.31*
MAM y – 1	– 0.00	– 0.41*	0.40*	Oct y – 1	0.18	– 0.12
AMJ y – 1	0.01	– 0.43*	0.43*	Nov y – 1	0.13	– 0.15
MJJ y – 1	0.01	– 0.33*	0.36*	Dec y – 1	0.02	– 0.04
JJA	0.09	– 0.19	0.26	Jan	0.02	0.05
JAS	0.11	– 0.12	0.23	Feb	0.03	0.11
ASO	0.08	– 0.12	0.22	Mar	– 0.01	0.17
SON	0.04	– 0.14	0.24	Apr	0.02	0.08
OND	– 0.00	– 0.13	0.22	May	– 0.02	0.09
NDJ	– 0.01	– 0.13	0.22	Jun	– 0.00	0.05
DJF	– 0.03	– 0.13	0.24	Jul	0.00	0.08
JFM	– 0.06	– 0.15	0.27	Aug	0.01	0.16
FMA	– 0.15	– 0.19	0.30*	Sep	– 0.19	0.34*
MAM	– 0.29*	– 0.23	0.31*	Oct	– 0.11	0.22
AMJ	– 0.44*	– 0.19	0.19	Nov	– 0.03	0.17
MJJ	– 0.49*	– 0.07	0.04	Dec	0.11	0.07

*Critical correlation ($r = 0.28$) considering a significance level of 1%

Table 4 Relative frequency (%) of climatic anomalies (ENSO and downpours) in comparison with the relative frequency (%) of annual growth rings of different sizes (mm) in *Schinopsis brasiliensis*

Climatic anomaly	1963–2015	Rings < 3 mm	Rings > 3 mm	Downpours
ENSO	61.5	63.3	59.1	68.8
El Niño	34.6	40.0	27.0	43.8
La Niña	26.9	23.3	32.0	25.0
ENSO (absent)	38.5	36.7	40.9	31.2

is the principal seasonal factor limiting cambial activity, and the variation observed among years in the width of the growth rings is related directly to the precipitation falling during the beginning of the growing season (Brienen and Zuidema 2005).

The correlation between the chronology and STAs (Fig. 5c) indicates that ocean temperatures in April–September of the preceding year are associated with the formation of growth rings. This suggests that the occurrence of large-scale meteorological phenomena affects the climate of the Caatinga region, and consequently, the growth of *S. brasiliensis*. Similar patterns have been observed in *Poincianella pyramidalis* and *Aspidosperma pyrifolium* in the semi-arid zone of the Brazilian Northeast (Pagotto et al. 2015).

In tropical regions with prolonged arid conditions, the seasonality of precipitation is the principal factor determining the phenology of deciduous trees (Roig 2000). Seasonal leaf-fall and the subsequent flushing of new leaves, associated with the strong seasonal variation in climate is important for the formation of annual growth rings in trees (Stahle et al. 1999). This ecological response of the trees to climatic limitations is fundamental to dendrochronology (Fritts 1976). *Schinopsis brasiliensis* is deciduous, with leaves flushing at the end of the dry season. This leaf flush continues until the end of the rainy season (Lima 2007). The loss of leaves and the discontinuation of cambial activity during the dry season, together with the predisposition of the plant to grow during downpours, permit the formation of a

Fig. 6 Comparison of the standard chronology of *Schinopsis brasiliensis* (black dotted line) in comparison with annual precipitation (light gray area), downpours (black bars) and the precipitation recorded during the rainy season (gray bars) for the study period (1963–2015). The white circles indicate the years during which ENSO events did not occur

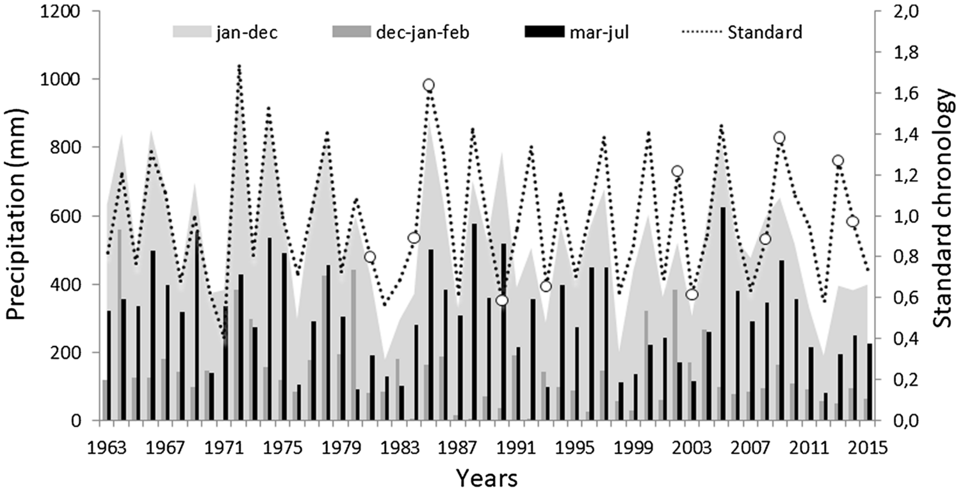

Table 5 Multiple regression analysis between the standard chronology (dependent variable) and the historical mean precipitation (1963–2015) of December (y − 1), January–February and March–July

Variable	*b*	Standard error	*β*
Intercept	0.3327	0.0922	–
Dec (y − 1), Jan–Feb	0.0012	0.0002	0.4641*
March–July	0.0014	0.0002	0.6430*

*$p = 0.0000$; $F = 28.506$; $R^2 = 0.56$; standard error of estimate = 0.2197; $N = 48$. R^2 = coefficient of determination; b = regression coefficient; β = standardized coefficient

new crown of leaves from December onwards, a characteristic of the response of the species to fluctuations in climate.

The atmospheric circulation of the tropical region is modulated primarily by ocean temperatures, with thermodynamic patterns being modified profoundly in years when anomalies occur in the surface temperatures of the Pacific Ocean, provoking changes in the Hadley and Walker cells, and interfering with the rainfall dynamics of the tropics (Ferreira and Mello 2005). The correlation recorded here between the standard chronology of *S. brasiliensis* and the PM and TCM (Table 2) contribute to our understanding of the influence of ENSO events and extreme fluctuations in STAs on plant growth.

The dynamics of the atmospheric circulation of the Brazilian Northeast may be associated directly with the greater influence of the TSA on precipitation patterns during the rainy season in the semi-arid zone. Our results are consistent with the findings of Andreoli and Kayano (2005), who showed that the TSA has a major influence on the variability in precipitation patterns in the region, independently of ENSO events, reinforcing the importance of the influence of the temperatures of the Atlantic and Pacific oceans. The variability in the TSA is the predominant factor determining anomalies in the region's precipitation, with the more remote ENSO events either weakening or reinforcing these anomalies (Uvo et al. 1998; Pezzi and Cavalcanti 2001; Ambrizzi et al. 2004; Souza et al. 2004; Andreoli and Kayano 2005).

The Pearson correlations (Table 3) indicate that ENSO events and TSAq are associated negatively with the March–May and May–July quarters, which would account for the limitations on the rainy season imposed by ENSO events in the Brazilian semi-arid zone. This conclusion is further reinforced by the relationship between ENSO and the MTq, which was positive for the February–April and May–July quarters of the preceding year, as well as the February–April and March–May quarters of the current year, which indicates a direct relationship between the variation in the surface temperature of the Pacific (ENSO) and the MTq. The ENSO events also had a negative effect on the APq in the October–December and May–July quarters of the preceding year. This inverse relationship is similar to that observed between the chronology and both the AP and the MT (Fig. 5a, b).

Together with ENSO events, the dipole of the tropical Atlantic has a direct influence on the position of the Intertropical Convergence Zone (ITCZ), which influences rainfall patterns in northern and eastern South America, in particular, the Brazilian Northeast, where it determines the level of the seasonal rains (Ferreira and Mello 2005). These external climatic factors provoke droughts in the Northeast when warmer waters and low pressure systems form in the Northern Hemisphere (Polzin and Hastenrath 2014), maintaining the ITCZ in its northern extreme (Kucharski et al. 2008). Anomalies in the TSA also have a profound influence on precipitation patterns in the Northeast (Kayano and Capistrano 2014).

The dry forests of the Brazilian Northeast are located within a region of relatively anomalous precipitation patterns, in comparison with other regions at the same latitudes, such as Amazonia (Alves and Repelli 1992). In the Caatinga, precipitation patterns and temperatures are frequently modified during El Niño and La Niña years, affecting not only the total precipitation, but also the frequency and duration of the rains. The impacts of these global events on climatic conditions in Brazil can be observed in the changes in rainfall patterns and air temperatures (Berlato and Fontana 2003).

The growth of *S. brasiliensis* is closely associated with the region's climatic anomalies (Fig. 6), in particular the occurrence of downpours. Downpours occurring during the dry season have a significant influence on the survival of this species in the Caatinga (Table 5). The sensitivity of the chronology of *S. brasiliensis* to the rainy season and downpours is consistent with the adaptation of this native species to the scarcity of water in the semi-arid zone. Seasonal droughts in this region often provoke the full or partial loss of herds of cattle, and the irregularity of the short, intense rains tends to impact water supplies (Silva et al. 1998). Climatic studies on the Northeast and the Caatinga (Nobrega and Santiago 2016) have demonstrated a trend towards an increase in the volume of the rains and a more concentrated distribution of the precipitation during positive anomalies in the eastern Pacific (El Niño) and negative anomalies over the South Atlantic (positive dipole). These processes accentuate the natural climatic extremes of this biome, in which the rainy season is normally concentrated into a 4-month period.

The chronology recorded for *S. brasiliensis* in the semi-arid zone of northeastern Brazil provides important insights into the ecology of the species, its growth dynamics and relationship with climatological variables, and the long-term effects of ENSO and TSA events, which may contribute to the development of effective measures for its conservation. The Caatinga is the Brazilian region most vulnerable to climate change, due to its hydrological deficit, poor soils, and the lack of perennial rivers, which are all vulnerable to changes in phytogeography, and economic and social practices (Nobrega and Santiago 2016).

The chronology of *S. brasiliensis* indicated a strong correlation between tree growth in the Brazilian semi-arid zone and both ENSO and TSA events, and local downpours. Complementary long-term studies or expanded analyses of timbers used in buildings will also be important for a more definitive understanding of the dynamics of the climate of the Caatinga, and the implications of these anomalies in rainfall patterns for the survival of the rural populations that depend on the exploitation of local natural resources for their subsistence.

Author contribution statement FCN conducted the fieldwork and analyses, established the chronology, and prepared the manuscript. MAP conducted the fieldwork and analyses and prepared the manuscript. FAR supervised the research and the tree ring analyses. CSL supervised the research and the tree ring analyses. ASR supervised the research and the statistical analyses.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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