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How do meteorological factors alter the phenology of a neotropical tree species?

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ECOLOGY

ABSTRACT

Background: Neotropical species lack autecological information. Among these, are phenological studies, which help to understand forest dynamics and provide important contributions to the collection, restoration, and conservation programs. This research aimed to characterize the vegetative and reproductive phenological behavior of neotropical species *Geoffroea spinosa* Jacq. in a seasonally dry tropical forest, as well as to verify if there is a correlation between phenophases and environmental parameters. Twenty individuals were accompanied monthly for two years, to detect and tally the presence of floral buds, flowers, immature fruits, ripe fruits, leaf emergence, presence of mature leaves, and defoliation. A semi-quantitative evaluation was carried out with the Fournier method.

Results: The results showed that the population had synchrony of reproductive events, with more than 50% of the individuals blooming and fruiting during the same time interval. Furthermore, the circular statistical test indicated a high seasonality for reproductive events ($r \geq 0.50$ and $p < 0.001$). Among the vegetative events, all were classified as non-seasonal ($r < 0.5$). *G. spinosa*, showed a significant correlation ($p \leq 0.05$) for all meteorological variables evaluated.

Conclusion: The reproductive phenophases of *G. spinosa* showed strongly seasonal behavior, unlike vegetative events. the period between mid-February and the end of March was the most propitious for fruit collection. No seasonality was observed for the vegetative events. The species proved to be sensitive to *El niño* conditions. Follow-up phenological studies associated with meteorological variables are important for a better understanding of the dynamics of vegetative behavior in response to climate change.

Keywords: Fabaceae; Flooded Ground; Tropical Forest; Seasonality

HIGHLIGHTS

Meteorological oscillations affect the phenology of *Geoffroea spinosa*;
Fruit production is strongly correlated with average local temperature;
The reproductive phenophases show seasonal behavior;
El niño years can be a climatic barrier to the perpetuation of the species.

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INTRODUCTION

The phenological phenomena of forest species, such as loss of leaves, flowering, sprouting, and fruiting, are directly associated with climatic variations during the year (Liang, 2019). Thus, phenological studies help to understand how forest dynamics occur, in particular how the growth and reproduction period of the species occurs (Brito Neto et al., 2018). These studies are important because they provide information on the ecological processes, genetic variation, and reproductive strategies of the species, in addition to indicating the best period for fruit and seed collection, supporting conservation and restoration actions and providing food resources (Brito Neto et al., 2018; Morellato et al., 2016).

Several types of research point to the strong correlation existing between the reproductive and vegetative events of plants and the climatic conditions of the region. According to (Williams-Linera and Alvarez-Aquino, 2016), phenological periodicity is generally more evident in tropical dry forests, where there is strong seasonality in rainfall throughout the year, as well as in temperature and photoperiod. However, phenological patterns can present different responses depending on the species and ecosystem studied.

The search for a better understanding of species dynamics in native forests is becoming more frequent and necessary due to its high ecological and economic importance. However, despite the increased development of techniques in recent decades, there is still a lack of forestry information, especially that related to the period of flowering, collection, and germination of seeds. Thus, studies of the reproductive phenology of tree species in forest areas are essential to provide parameters for conservation and rational exploitation, reconciling sustainability with economics, especially of fruit-producing species with commercial possibilities, such as *Geoffroea spinosa* Jacq.

G. spinosa is a species belonging to the Fabaceae family, known mainly as 'umari' in Brazil, where it occurs naturally in riparian forests and periodically flooded habitats, in areas of Caatinga and Cerrado physiognomies in the states of Bahia, Ceará, Paraíba, Pernambuco, Rio Grande do Norte, Goiás and Mato Grosso do Sul. It is also found in other South American countries (Pennington, 2015). The species has high stature, deciduous leaves, fissured stems, and thorns on the branches. The leaves have a glabrous adaxial face, and during the reproductive phase, inflorescences form in panicles that produce small flowers with yellow-orange color. The drupe-like fruit is hard and fleshy, usually containing a single seed (Mendoza, 2012; Sinani et al., 2019).

As verified by (Tomchinsky and Ming, 2019) in a survey of edible plants in the 16th and 17th centuries, *G. spinosa* has been used for a long time by humans. However, despite having wide distribution, studies are still incipient related to the species' ecological and forestry aspects, as phenological studies. Overall, the phenology of tropical species is poorly understood and needs more attention (Davis et al., 2022). In this sense, this study aimed to characterize the phenological behavior of *G. spinosa* Jacq. in an area of seasonally dry tropical forest, as well as to verify if there is a correlation between phenophases andmeteorological factors (temperature, rainfall, sunstroke, and relative humidity). The following questions were evaluated: i) Are the phenological patterns seasonal? ii) Are the vegetative and reproductive phenophases influenced by meteorological variables? and iii) Does the population present synchronism of reproductive events? The answer to these questions will be the first step to understanding its ecology.

MATERIAL AND METHODS

Study area

The study was conducted in a fragment classified as a seasonally dry tropical forest, called Mata do Olho D'agua, located inside an area used for research by the Specialized Agricultural Sciences Academic Unit of Federal University of Rio Grande do Norte, belonging to the municipality of Macaíba in the state of Rio Grande do Norte (5° 53' S and 35° 23' W). With an area of approximately 270 ha, the fragment has points of anthropization, with the removal of vegetation to produce wood stakes and poles by the local people, besides the opening of roads, removal of sandbanks, and raising of ruminant animals. The forest is located in a transition zone between the Caatinga and Atlantic Forest biomes, with an average tree height of 6 meters, uncompacted canopy, and 80% deciduousness at the end of the dry period. The local climate is tropical savannah with dry summer ('As' on the Köppen scale), with the dry season lasting from September to December and the rainy season falling in May and June. The average annual rainfall is approximately 1,300 mm with an average annual temperature of 26 °C (Figure 1).

Data Collection

Twenty adult individuals were selected from a population of *G. spinosa* present in the Mata do Olho D'água fragment (Figure 2). For selection, the phytosanitary state was observed, and those with apparent disease and/or an infestation of parasites were not included. The method adopted for the observation of phenological events was the trails approach (D'eça-Neves and Morellato, 2004), and to homogenize the adversities of the area, the individuals were divided into two subpopulations (P1 and P2), 10 located on the margins of the existing path and 10 in thickly forested places, both in microsites with water formation favoring the development of the species. All individuals were identified with platelets and the subpopulations were georeferenced, spaced approximately 600 meters apart.

Data were collected monthly from November 2015 to October 2017, totaling 24 observations. During the visits, the reproductive phenophases were evaluated, related to the presence of floral buds (F_1), flowering (F_2), immature fruits (F_3), and ripe fruits (F_4), while the vegetative phenophases were noted regarding defoliation (F_5), leaf emergence (F_6) presence of mature leaves (F_7). The fallen fruits, flowers, and leaves found below the trees were also tallied to serve as indicator parameters of the phenological activity of the species.

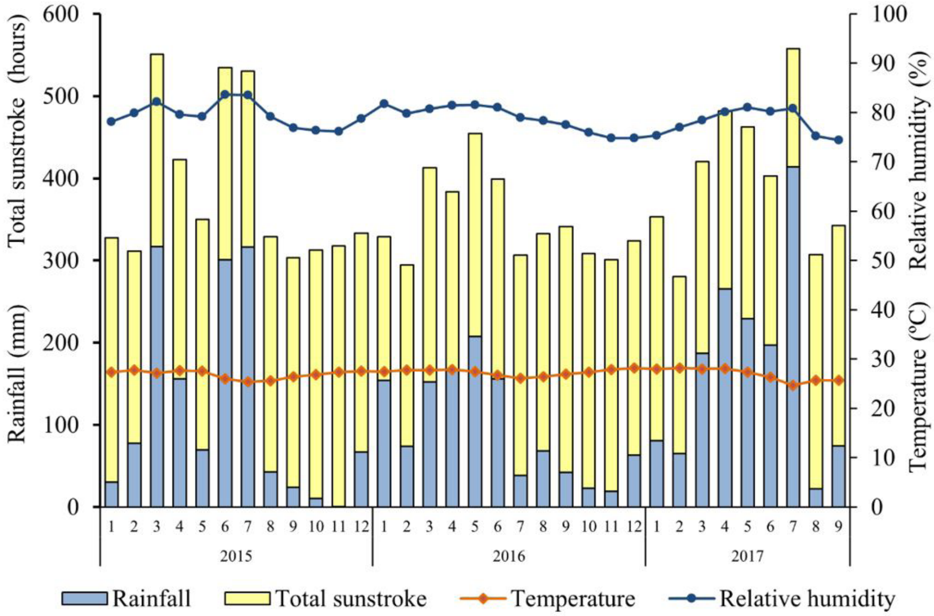

Figure 1. Environmental variables of the study area. Climatogram of accumulated rainfall, average monthly relative humidity; total sunstroke, and average monthly temperature (Source: INMET).

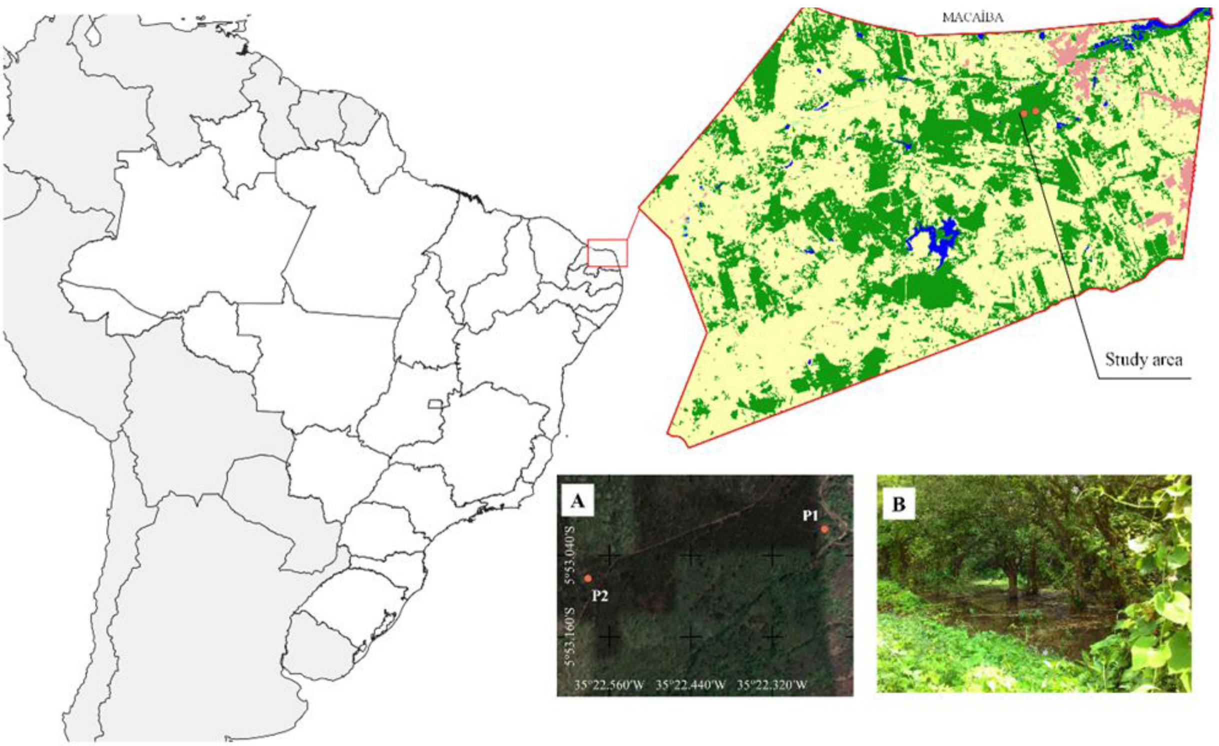

Figure 2. Location of the study area, Mata do Olho D'Água fragment in the municipality. of Macaíba, Rio Grande do Norte, Brazil. (A) *Geoffroea spinosa* Jacq. populations and (B) seasonal flooding on the soil.

Phenological analysis

The analysis of the synchronism of phenological activities was determined from the activity index. This is a qualitative method that consists of evaluating the presence or absence of phenophase differences, indicating only the number of individuals in the sampled population that are manifesting some phenological event.

The Fournier index (1974) was used to quantify the intensity of phenophases. This method seeks to characterize phenophases as fruiting, flowering, sprouting, and leaf fall, in addition to determining the intensity of these events. Thus, the following scale was adopted: 0 (zero) - absence of the phenomenon; 1- occurrence from 1 to 25%; 2- occurrence from 26 to 50%; 3- occurrence from 51 to 75%; 4- occurrence from 76 to 100%. After the monthly collections, the data were organized to calculate the Fournier index (Equation 1).

$$F(\%)=(\sum I /4N)\times 100 \qquad (1)$$

Where:
F(%) = Fournier index;
N= Total number of individuals sampled;
I= Intensity.

To understand the seasonal behavior of the species between each of the 7 phenophases, circular statistical analysis was applied through the Oriana® program. For each year of observation, the Fournier index was calculated monthly per occurrence of phenological events in the population, thus estimating the frequency. The months were converted to angles from the Julian calendar, being 0° = day 1 of the year (January 1st), successively until 360° = day 365 of the year (December 31st), and in the leap year, although 366 days were used for conversion. The mean angle, the angular standard deviation, and the length of the r-vector were calculated, and the significance of the angle was determined using the Raleigh (z) test for circular distributions. Phenophases with significant mean angles ($p < 0.05$) were converted to mean date, i.e., the date of greatest phenophase intensity during the year.

Correlation with meteorological variables

Four monthly meteorological variables were used: total sunstroke, total rainfall, average relative humidity, and average temperature. Thus, we obtained meteorological data for the first (m1) and second month (m2) that preceded the observation, to verify the influence of environmental conditions on the evaluated phenophases. To verify if there was a relationship between the variables and the occurrence of each phenophase, deviations from normality were evaluated by the Lilliefors test followed by a calculation of Spearman's nonparametric correlation. For this, data were obtained from the automatic climatological station of the National Institute of Meteorology located in Natal, 20 km away in a straight line from the study area. The data were tabulated and submitted to statistical analysis by the BioEstat5.0®

RESULTS

The results showed that in the first year of evaluation, the peak of floral budding and flowering occurred in the same month, in January 2016. In the second year, the peak blooming occurred in the month following that of budding. In the first year, the production of immature fruits occurred in four months, from February to May 2016. However, ripe fruits were only observed in February, indicating there was some interference in the ripening of the fruits produced by the trees sampled. This could have been due to problems involving the mother plant itself or the occurrence of some anthropic factor. The problem with the ripeness of the fruits did not occur or was less intense in the second year since the ripe fruits occurred in more than one month. However, even though occurring in more than one month, there was a gap between the immature fruits observed in the initial months of 2017, which leads to the belief that the fruiting was aborted (Figure 3).

The species presented an annual pattern of the reproductive phenophases, with only one cycle in the year (Newstrom et al., 1994). We observed a smaller proportion of ripe fruits in relation to immature ones, which might have been related to the climatic variables or the environment itself. Moreover, the population presented synchrony in reproductive events, with more than 50% of the individuals blooming and fruiting during the same time interval. Regarding the vegetative events, the phenophases presented wide variation in the evaluated period, with peaks and mean angles in distinct periods of the year (Figure 4), thus demonstrating a continuous pattern (Newstrom et al., 1994). This behavior can be influenced by environmental variables, as well as by the genetic characteristics of the plants.

The results of the circular statistical test indicated high seasonality for reproductive events, regardless of the year of observation ($r \geq 0.50$ and $p<0.001$). Also, the phenophases floral budding, flowering, and immature fruits presented total aggregation of data around the mean angle ($r = 1$) for the evaluation conducted in 2015 and 2016 (Table 1). In general, the intensity of the reproductive phenophases did not vary between years. Only, blooming (F_2) presented average dates corresponding to the same month. The average dates corresponding to ripe fruit (F_4) indicated that the best period for fruit collection is from mid-February to the end of March. Among the vegetative events, all were classified as non-seasonal ($r < 0.5$) since they remained frequent throughout the year.

With respect to the relationship between phenophases and meteorological variables (mean temperature, total rainfall, total sunstroke, and mean relative humidity), *G. spinosa*, showed a significant correlation ($p \leq 0.05$) for the four abiotic variables in at least one of the phenophases studied (Table 2). The data indicated a positive correlation between the presence of flowers and the mean temperature, as well as a strong positive correlation between the presence of immature fruits, indicating that the increase in temperature, observed in the previous month (m_1), corresponded directly to an increase in the subsequent flowering and fruiting.

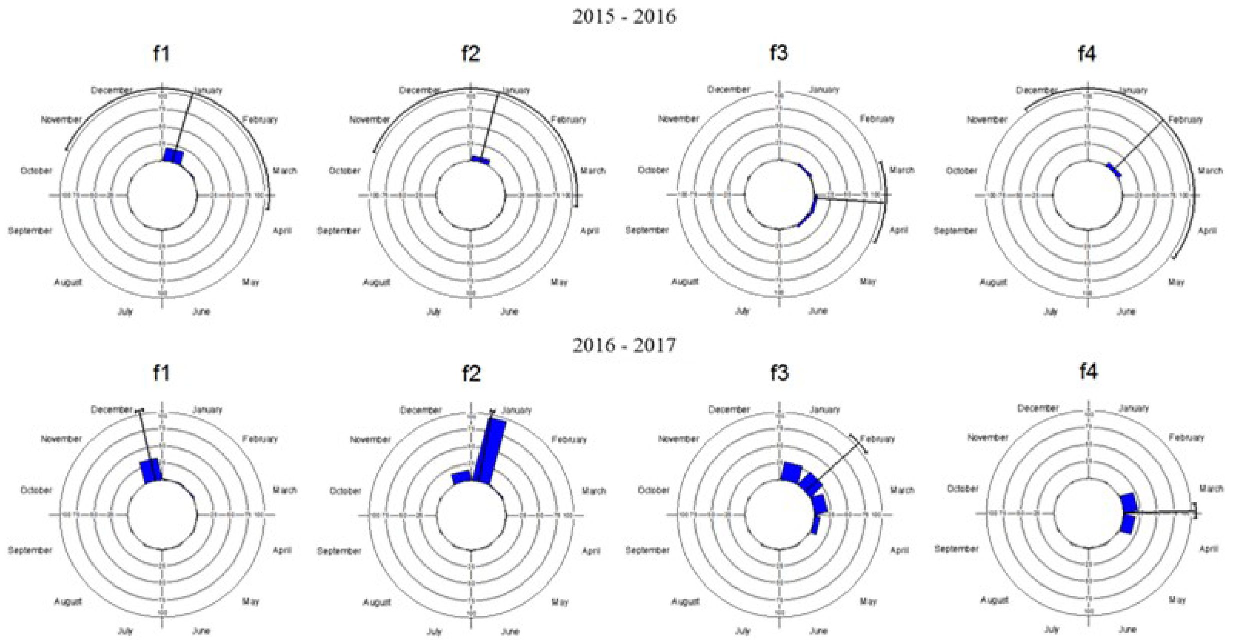

Figure 3. Histograms of distributions of floral budding (F_1), flowering (F_2), immature fruits (F_3) and ripe fruits (F_4) of *Geoffroea spinosa* Jacq. in Mata do Olho D'água fragment in the municipality of Macaíba, Rio Grande do Norte, Brazil.

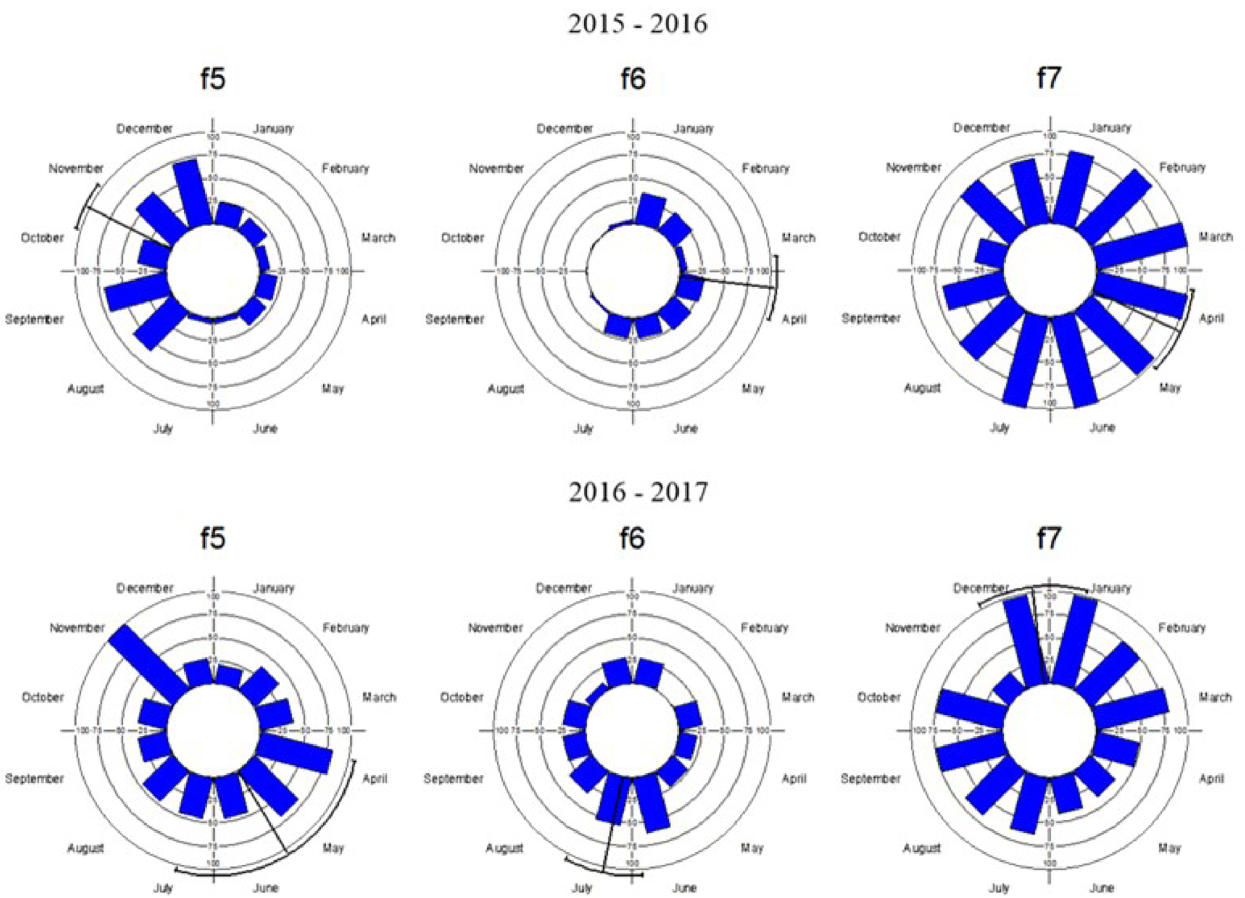

Figure 4. Histograms of the distribution of defoliation (F_5), presence of leaf emergence (F_6) and mature leaves (F_7) in a natural population of *Geoffroea spinosa* Jacq. in the municipality of Macaíba, Rio Grande do Norte, Brazil.

The total rainfall presented a negative correlation for floral budding (F_1) and flowering (F_2). This means the species invest in phenophases associated with flowering during periods of lower rainfall. This relationship can be a strategy to attract pollinators. Following this line, the relative humidity also presented a negative correlation with the floral production, adding further evidence to this hypothesis. The production of new leaves (F_6) had a positive correlation with total rainfall, which may indicate that the growth of the species is limited by the availability of water in the soil. Periods of greater sunshine also positively influence the production of floral buds and flowers.

Table 1. Mean of the vector (μ), number of observations of the occurrence of phenophases (N), concentration of the mean vector (r) and Rayleigh test (Z) for circular uniformity between the phenophases of *Geoffroea spinosa* Jacq. from November 2015 to October 2017, present in the municipality of Macaíba, Rio Grande do Norte, Brazil.

Phenophases	Years	Datas				
		μ	Average day	N	*r*	*Z*
F_1	2015 - 2016	16.44°	17/jan	20	1.00	< 0,001
	2016 - 2017	347.28°	18/dec	35	0.99	< 0,001
F_2	2015 - 2016	15.00°	15/jan	8	1.00	< 0,001
	2016 - 2017	11.32°	11/jan	111	0.99	< 0,001
F_3	2015 - 2016	94.24°	06/apr	13	0.82	< 0,001
	2016 - 2017	48.59°	18/feb	79	0.88	< 0,001
F_4	2015 - 2016	45.00°	15/feb	6	1.00	< 0,001
	2016 - 2017	89.19°	31/mar	38	0.98	< 0,001
F_5	2015 - 2016	297.43°	29/out	391	0.40	< 0,001
	2016 - 2017	147.99°	-	563	0.07	ns
F_6	2015 - 2016	96.99°	08/apr	171	0.45	< 0,001
	2016 - 2017	191.90°	14/jul	325	0.27	< 0,001
F_7	2015 - 2016	115.62°	27/apr	987	0.14	< 0,001
	2016 - 2017	353.62°	24/dec	777	0.13	< 0,001

Table 2. Spearman's correlation (r_S) between meteorological variables from the first month (m_1) and second month (m_2) before the phenological observations of the vegetative and reproductive events of *Geoffroea spinosa* Jacq. present in the municipality of Macaíba, Rio Grande do Norte, Brazil.

Variables /months		Phenophases						
		F_1	F_2	F_3	F_4	F_5	F_6	F_7
Average temperature	m_1	-	0.4439*	0.7111*	-	-	-	-
	m_2	-	-	-	-	-	-	-
Total rainfall	m_1	-	-	-	-	-	0.3444*	-
	m_2	-0.5078*	-0.5235*	-	-	-	-	-
Total sunstroke	m_1	-	-	-	-0.4054*	-	-0.5291*	-
	m_2	0.4575*	0.4439*	-	-	-	-	-
Average relative humidity	m_1	-	-0.4468*	-	-	-	-	-
	m_2	-	-0.5771*	-	-	-	-	-

DISCUSSION

As observed in Figure 3, the species has a short yearly period with floral activities, which can influence the success of pollination and fecundation, directly associated with the demand and supply of the appropriate pollinators (Barrios and Ramírez, 2020). According to (Pereira Cabrera et al., 2020), *G. spinosa* flowers are mainly visited by native bees, more so in the dry season. This dependence on specific pollinators can be a negative aspect for plant reproduction, mainly due to the anthropic effects suffered by Caatinga habitats. In this respect, bee populations have been reduced due to factors such as environmental fragmentation, use of pesticides, and pest infestations in hives (Rosa et al., 2019).

According to (Barrios and Ramírez, 2020), the species is hermaphrodite, has a high pollen-ovule ratio, and does not present dichogamy, herkogamy or spontaneous reproduction. Thus, individuals tend to be self-incompatible, so the fecundation of flowers only occurs with the transfer of pollen from a flower to the stigma of another individual.

Other aspects observed by (Barrios and Ramírez, 2020) are that the species has two ovules per flower, one seed per fruit, and a low number of aborted seeds (0.04) per fruit, indicating that our observation may be a consequence of a factor other than physiological. However, those authors observed a low fertility value for the species (0.00), besides a seed to ovule ratio of 0.50, a value considered intermediate, since the species invests part of its energy to attract dispersers. Also, *G. spinosa* has two types of seed dispersal syndrome, hydrochory and mammalichory, the latter being the main one (Barrios and Ramírez, 2020). All these factors directly affect the efficiency of the species' reproductive processes.

Intra-population synchrony was observed for reproductive events, which can be a strategy of the species to attract pollinators and dispersers. According to the study conducted by (Freitas and Bolmgren, 2008), the synchrony of flower opening can affect the quality and quantity of the offspring, since the increase in the visual display of flowers attracts more potential pollinators. The same explanation applies to seed dispersion: since mammalichory is one of its types of dispersal syndrome, increasing the availability of food for fauna through synchronization of fruit production increases the likelihood of colonizing new areas. According to (Burgess et al., 2006), environmental variables and the number of mature flowers are the main factors responsible for the pollinator visitation rate, and information about the response of pollinators in fragmented environments help to predict if the fragmentation will bring positive or negative effects for plant reproduction in specific cases.

The diversity of behavior existing in a community reflects the strategies that each species has to obtain ecological success. In a study conducted by (Luna-Nieves et al., 2017) with 14 native species in a seasonally dry tropical forest in Mexico, three phenological strategies were identified to signify reproductive events: i) flowering and fruiting exclusively in the rainy season, ii) flowering in the rainy season and fruiting exclusively in the dry season, and iii) flowering and fruiting exclusively in the dry season. Unlike those strategies reported, in this study we observed that even under the influence of *El niño*, *G. spinosa* starts the production of floral buds during the end of the dry season and fruit production during the rainy season.

Knowledge about the phenology of arboreal plants has numerous applications. (Buisson et al., 2017) explained the importance of phenology for restoration, especially for the harvesting of seeds in tropical forests, since a calendar can be prepared of fruiting with a description of the populations and places of reference in relation to environmental conditions and interaction with fauna. Thus, knowing the time of fruiting is important to ascertain the appropriate period for fruit collection, both for consumption and to obtain seeds, especially to be used in forest restoration projects, in which native species are paramount. In this respect, *G. spinosa* has occurrence restricted to certain habitats and may be vulnerable to extinction due to anthropic actions. However, remedial actions are hampered by the lack of data on the species (Souza et al., 2011).

We also observed that the immature fruits present in 2016 (Figure 3) practically did not reach the ripening stage, which may have been caused by the abortion of the mother plant, probably for lack of the necessary resources for development, due to the strong influence of the *El niño* climatic phenomenon (Figure 1). *El niño* is responsible for the increase of the minimum and maximum temperatures, besides causing droughts that mainly affect the North and Northeast regions of Brazil, which consequently affects the dynamics of the vegetation types present in these environments. In 2015 and 2016, a strong *El niño* event produced extreme droughts in the study area.

Pua (2016) found several nutrients important to human nutrition in *G. spinosa* leaves, which demonstrates the high investment in nutrients for foliar production. Thus, phenological monitoring is advantageous since it helps to identify the appropriate period for leaf collection because the vegetative stage alters the chemical composition and environmental conditions influence the emission of sprouts. However, according to (Pua, 2016), *G. spinosa* is not a demanding plant from an agroclimatic point of view, so it is tolerant of adverse conditions. (Silva et al., 2015), studying a floodplain community, found *G. spinosa* to be the most versatile species, being farmed by the community as used for timber, fodder, medicinal purposes and construction. In this way, developing strategies to increase the consumption of its leaves and fruits can be advantageous for economic development and ecological conservation.

Espinosa et al. (2018) found that *G. spinosa* responded positively to humid, cold, and cloudy conditions in the hottest and moderately hot spots, but the most intense response to drought was observed in the driest location studied. According to them, the individuals presented negative correlations with temperature in a specific period of the year, and temperature played an important role in the growth of the trunk diameter of *G. spinosa*, probably increasing evapotranspiration rates and increasing water stress. While the positive correlation with rainfall was related to growth and wood formation, they observed that individuals were sensitive to water stress when it occurs near the growth season (Espinosa et al., 2018).

Despite recognizing that climate is the main factor for phenological modification and regulation, studies of the relevance and implications for conservation of plant species are incipient (Morellato et al., 2016), making it necessary to understand meteorological influences on a smaller scale. According to the statistical test performed, we observed that *G. spinosa* presented low correlation with abiotic factors, which adds further support for the versatility of the species. This behavior can occur when the plant is distributed in flooded regions.

The species showed a negative correlation between flower production and rainfall and relative humidity, indicating that *G. spinosa* invests in this reproductive event during dry periods. This behavior can be a strategy of the species since small, winged insects are more frequent in the forest in periods of low rainfall and the permanence of flowers on trees during the rainy season can be difficult (Veena and Nampy, 2019). According to (Cortés-Flores et al., 2017), entomophilous pollination is the most observed syndrome in woody and herbaceous plant species in seasonally dry tropical forests, as an important regulatory element of plant behavior.

The leaf shedding showed a positive correlation with rainfall, similar to other deciduous Caatinga species (Japiassú et al., 2016), which during drought defoliates (Figure 5C), reduce their metabolic activities and new leaves (Figure 5D). This response plays an important role in resuming photosynthetic production. A positive correlation between total sunstroke and flower production was also observed, where the increase in luminosity enabled greater energy production through photosynthesis, providing the necessary resources for flowering (Figure 5A).

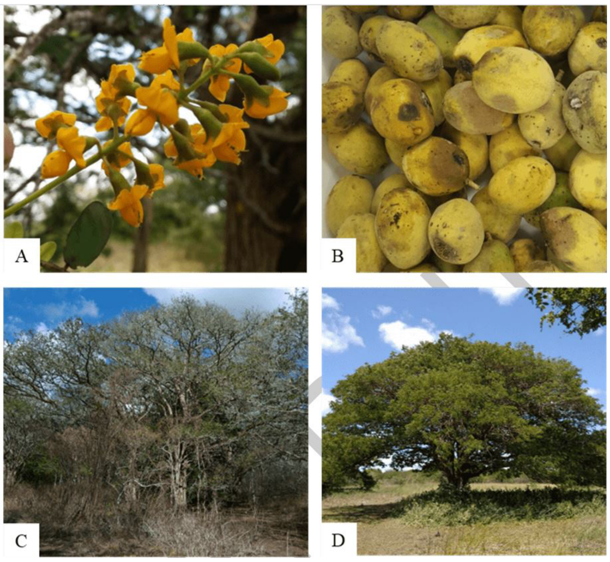

Figure 5. Phenophases of the *Geoffroea spinosa* Jacq. (A) flowers; (B) fruits; (C) defoliation and (D) leaf emergence.

CONCLUSION

In general, the data found in this study are useful to understand the reproductive and vegetative phenology, associated with the climatic oscillations, contributing to efforts for conservation and regeneration of the species, besides supporting the proper management and use of its seeds. The reproductive phenophases of *Geoffroea spinosa* showed strongly seasonal behavior, unlike vegetative events. Despite the weak correlation between these events and the meteorological variables, the species was sensitive to the *El niño* climatic phenomenon during the study period. This was a possible cause of the presence of aborted fruits. The population presented synchrony of reproductive events; the period between mid-February and the end of March was the most propitious for fruit collection. No seasonality was observed for the vegetative events. Follow-up phenological studies associated with meteorological variables are important to a better understanding of the dynamics of vegetative behavior in response to climate change.

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AUTHORS' CONTRIBUTIONS

Project Idea: TLNC, FMFL
Database: BRFS
Processing: TLNC, FMFL, BRFS
Analysis: TLNC, FMFL, KPTC, ASMF
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Review: JGMUF, JASS, MPC.

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