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Changes in phenological patterns of a tropical Atlantic Forest tree: implications for conservation

Cambios en los patrones fenológicos de un árbol de la selva atlántica tropical: implicaciones para la conservación

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SUMMARY

The study of the phenological patterns of plants contributes to the understanding of their ecological functioning and related ecosystem services, especially of little-known species. *Manilkara salzmannii* is a tree native to the Atlantic Forest that occurs in disturbed urban expansion areas. This study aimed to characterize the phenological pattern of *M. salzmannii* and to correlate its phenophases with meteorological variables. Evaluations were carried out over three years, during which time reproductive and vegetative phenophases were observed in the sampled population. The activity and Fournier indices were initially considered, and circular statistics were later applied. For the correlation with climate, we used data corresponding to the month of observation, as well as one month and two months beforehand. The species has an annual pattern of reproductive events. However, there was variation in the phenological pattern over the three years regarding vegetative and reproductive phenophases. In 2016, there was barely any bud production and blooming, which negatively influenced fruiting events. Leaf senescence was more intense in periods of higher temperature and solar radiation. On the other hand, leaf shedding was more intense in periods of lower wind speed, higher humidity, and precipitation. Immature fruiting correlated positively with temperature and solar radiation, but negatively with humidity and wind speed. Among the implications for the conservation of *M. salzmannii*, the knowledge obtained regarding the length of the reproductive period stands out. Thus, this study's results can guide the appropriate timing of fruit collection for seedling production programs.

Keywords: Manilkara, Sapotaceae, phenology, circular statistics, meteorological variables.

RESUMEN

El patrón fenológico de las plantas contribuye a la comprensión de su funcionamiento ecológico y de los servicios ecosistémicos relacionados, especialmente, de especies poco conocidas. *Manilkara salzmannii* es un árbol nativo de la selva atlántica que se encuentra en áreas de expansión urbana perturbadas. Este estudio tuvo como objetivo caracterizar el patrón fenológico de *M. salzmannii* y correlacionar las fenofases con las variables meteorológicas. Se realizaron evaluaciones durante tres años, donde se observaron las fenofases reproductivas y vegetativas en la población muestreada. El índice de actividad y el índice de Fournier fueron los parámetros considerados inicialmente, y luego se aplicó la estadística circular. Para la correlación con el clima, se utilizaron los datos correspondientes al mes de observación, un mes antes y dos meses antes. La especie tiene un patrón anual de eventos reproductivos. Sin embargo, hubo variación en el patrón fenológico a lo largo de los tres años en lo que respecta a las fenofases vegetativa y reproductiva. En 2016, la producción de yemas y la floración prácticamente no se produjeron, influyendo negativamente en los eventos de fructificación. La senescencia foliar fue más intensa en los periodos de mayor temperatura y radiación solar. Por otro lado, la caída de hojas fue más intensa en períodos de menor velocidad del viento, mayor humedad y precipitaciones. Los frutos inmaduros se correlacionaron positivamente con la temperatura y la radiación solar, pero negativamente con la humedad y la velocidad del viento. Entre las implicaciones para la conservación de *M. salzmannii*, destaca el conocimiento obtenido sobre la duración del periodo reproductivo. En este sentido, los resultados de este estudio pueden orientar la recolección de frutos en el momento más adecuado para los programas de producción de plántulas.

Palabras clave: Manilkara, Sapotaceae, fenología, estadística circular, variables meteorológicas.

INTRODUCTION

Plant phenology is the study of the annual sequence of cyclical biological events in plant development, which respond to changes in environmental variables, usually correlated to reproductive and vegetative phenophases (Wright *et al.* 2019). Phenological knowledge is important for understanding the ecological functioning and ecosystem services of plants (Piao *et al.* 2019). Phenophase dynamics play an essential role in regulating photosynthesis, evapotranspiration, and energy fluxes. Also, they can provide indications of carbon cycles and be used as bioindicators of climate oscillations (Piao *et al*. 2019, Wang *et al.* 2019). Traditionally studied phenophases, such as flowering and fruiting events, are readily apparent and can be observed through visits with pre-established frequency (Albert *et al.* 2019). These observations generate data that assist in species conservation, because by analyzing them it is possible to determine the timing of reproductive events, and monitor changes in vegetation and other disturbances (Morellato *et al.* 2016).

Although phenological studies have gained prominence due to the current scenarios of global climate change, implications for conservation and environmental management are still incipient (Morellato *et al.* 2016), especially when dealing with tropical tree species. Due to the rich biodiversity of tropical forests, such as the Brazilian Atlantic Forest, little is known about the dynamics of native species' phenological patterns. Moreover, deciphering the role of evolutionary history in the phenological patterns of tropical species in the Southern Hemisphere is necessary to identify species that are sensitive or resilient to climate change, especially because the available phenological data are restricted to local scales and short periods (Morellato *et al.* 2016).

The Atlantic Forest is the region with the second-highest population of the family Sapotaceae in South America (Mônico *et al.* 2017). This family consists of trees and shrubs, distributed in 53 genera and about 1,100 species (Alves-Araújo and Alves 2010), found mainly in Neotropical regions. The genus *Manilkara* has a wide distribution in Brazil, with great commercial relevance, mainly for timber and latex production (Fabris and Peixoto 2013). Despite the high economic value, there are few studies involving the ecology and conservation of its species, and several members of the genus are on the red list of threatened species, primarily due to illegal logging and timber harvesting (IUCN 2021).

Manilkara salzmannii (A.DC.) H.J.Lam is a tree species that is distributed in Atlantic Forest fragments, found in almost all the Brazilian coastal regions as well as inland regions of the state of Piauí (Alves-Araújo and Alves 2010, Alves-Araújo and Alves 2013). There are records of occurrence in disturbed areas (Alves-Araújo and Alves 2010), which may indicate the potential of the species for rehabilitation of degraded environments. *M. salzmannii* has coriaceous leaves with a glabrous abaxial surface, stems, and branches with the absence of lenticels and inflorescences with axillary position (Alves-Araújo and Alves 2010). Despite its classification in the IUCN list as of Least Concern (LC), the lowest risk category (Alves-Araújo and Alves 2013), phenological studies of the species are urgently needed to support conservation programs due to its high vulnerability.

This study aimed to characterize the phenological pattern of *M. salzmannii* trees in an Atlantic Forest fragment and to correlate its reproductive and vegetative events with meteorological variables, to understand the behavior of the species in reaction to climatic oscillations. To this end, we sought to answer the following questions: i) Does the species present seasonality in its phenophases? ii) Are its phenophases influenced by meteorological variables? iii) Does the species have synchronous reproductive events?

METHODS

The study was conducted in a remnant Atlantic Forest area with Semideciduous Lowland Seasonal Forest type vegetation, in the municipality of Macaíba, Rio Grande do Norte (figure 1). The site has a transitional climate between types As' and BSh' according to the Köppen classification (Alvares *et al*. 2013), with mean annual precipitation of 1,086.1 mm (EMPARN 2021), a rainy season in fall and winter and high temperatures throughout the year. The area has about 10 ha, located near a dam with trails and small roads, with some nearby houses and family farms. The study was registered in the National System for Management of Genetic Heritage and Associated Traditional Knowledge (*Sistema Nacional de Gestão do Patrimônio Genético e do Conhecimento Tradicional Associado – SisGen*) with code ADB6CB0. A sample of plant material was collected and deposited in the herbarium of the Federal University of Rio Grande do Norte.

We selected 19 adult individuals of *M. salzmannii* taller than 4 meters, each presenting at least one phenophase in the years evaluated. The entire methodology is depicted in the flowchart of figure 2. Evaluations were made biweekly for three years, from January 2016 to December 2018 (n = 72 observations), at the end of which the average of the observations was calculated for each month. Synchronism was determined by the activity index, and the Fournier index (Fournier 1974) was used to quantify the intensity of the phenophases. Then, circular statistics were applied using the Oriana® demo version 4.02 program (https://www.kovcomp.co.uk/oriana/index.html) to observe the seasonal behavior of the species. The months were converted into angles from the Julian calendar, with 0° being equivalent to day 1 of the year (January 1st) and so on until 360°, corresponding to day 365 of the year (December 31st), using 366 days in a leap year. The Rayleigh test (z) was used to observe the significance of the average angle and the Watson-Williams test ($P < 0.05$) was applied for comparison among the three years of evaluation.

Also, the phenophases that showed a significant mean angle ($P < 0.05$) were converted to mean date, which is the date of greatest intensity of the phenophase during the year.

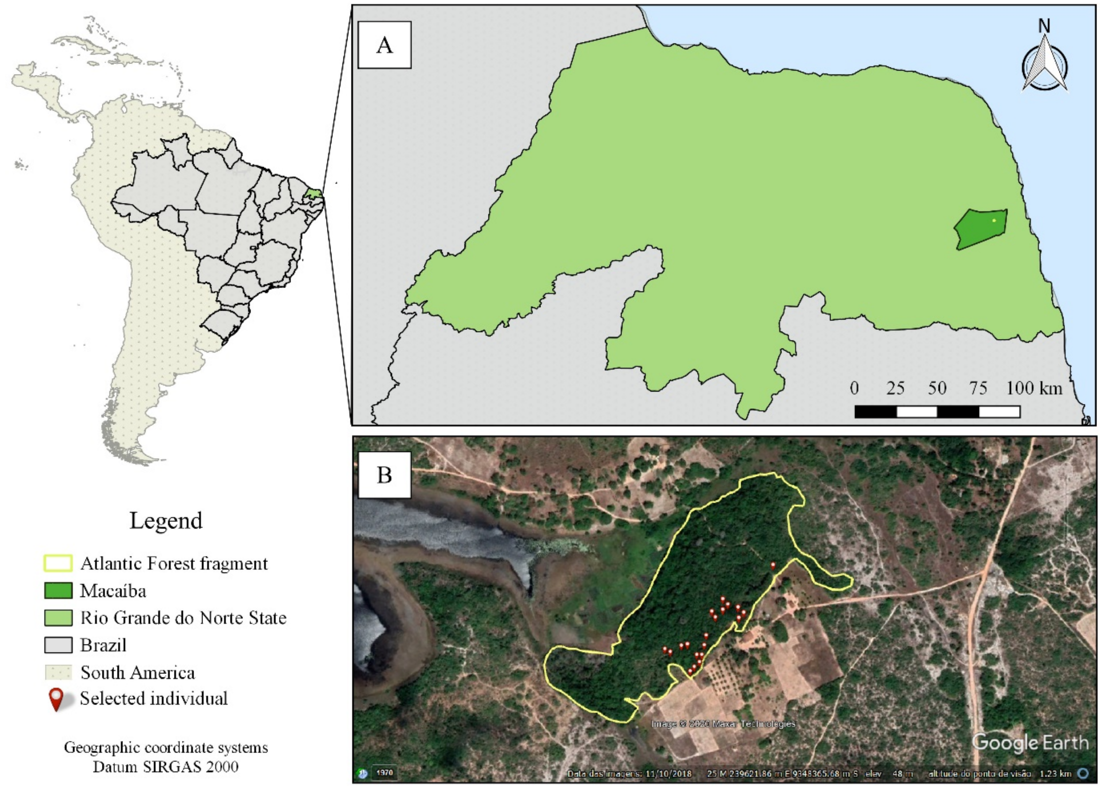

Figure 1. Location of the study site in the state of Rio Grande do Norte, municipality of Macaíba (A) and the population of *Manilkara salzmannii* in an Atlantic Forest fragment (B).

Localización del sitio de estudio en el estado de Rio Grande do Norte, municipio de Macaíba (A) y la populación de *Manilkara salzmannii* en un fragmento de Mata Atlántica (B).

Meteorological data were obtained from the automatic climatological station of the National Institute of Meteorology in the city of Natal, approximately 20 km from the study area. Data corresponding to the month of the phenological event (m_0), one month before (m_1), and two months before (m_2) were used. Finally, the Lilliefors test was employed to analyze deviations from a normal distribution of the phenological data, which indicated the use of nonparametric Spearman correlation in Bioestat 5.0® (Ayres et al. 2007).

RESULTS

In 2016, leaf senescence was frequent during all months, with no peak in a particular period (figure 3), while the peak of leaf loss in 2017 was in March, and in 2018 was in January. The leaf flushing showed variation during all months in the three years of evaluation, with the average vector close to May-June. The reproductive events of bud production and blooming barely occurred in 2016, influencing the fruiting events which consequently did not occur in the following months. The peak bud production occurred in August 2017 and 2018, and blooming was most intense in October 2017 and September 2018. The presence of immature fruits was least pronounced in 2016 but showed peaks in December 2017 and January 2018 (two consecutive months). Moreover, the production of mature fruit peaked in February 2016 and 2018.

The phenophase was unimodal, with data around the mean vector, while the r-value was greater than 0.50, and a value lower than 0.50 was observed in the vegetative phenophases (table 1). For the reproductive events, this did not occur in the bud production and blooming phenophases in 2016, precisely the year in which there were barely any such events. The seasonality of the phenophases was confirmed by the Rayleigh test ($P < 0.05$), which showed a specific period of greatest intensity in all years except 2016. This year did not experience significant seasonality of leaf senescence, bud production, or blooming. The Watson-Williams test ($P < 0.01$) indicated the distinction of the phenophases between the years, showing similar vegetative phenophases between 2017 and 2018. Such similarity occurred in 2016 and 2017 for bud production, and in 2017 and 2018 for bud immature fruit production, with divergences occurring between the years for the rest of the events.

The species has an annual pattern of reproductive events, showing synchrony of bud production and blooming, which occur at nearly the same time (figure 4). The production of immature and mature fruits also occurred during close

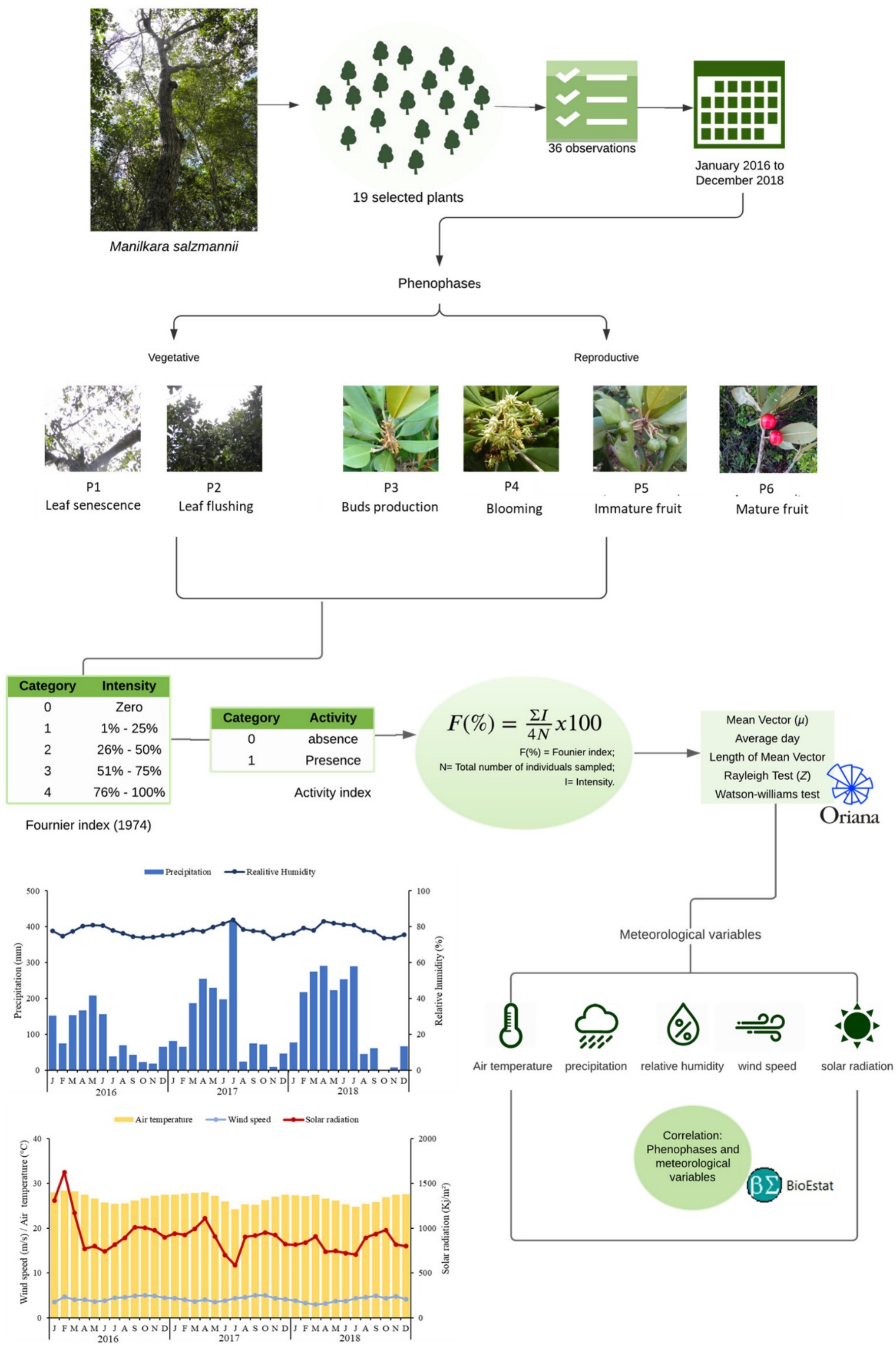

Figure 2. Phenological analysis of a population of *Manilkara salzmannii* in an Atlantic Forest fragment.

Análisis de la fenología de una populación de *Manilkara salzmannii* en un fragmento de Mata Atlántica.

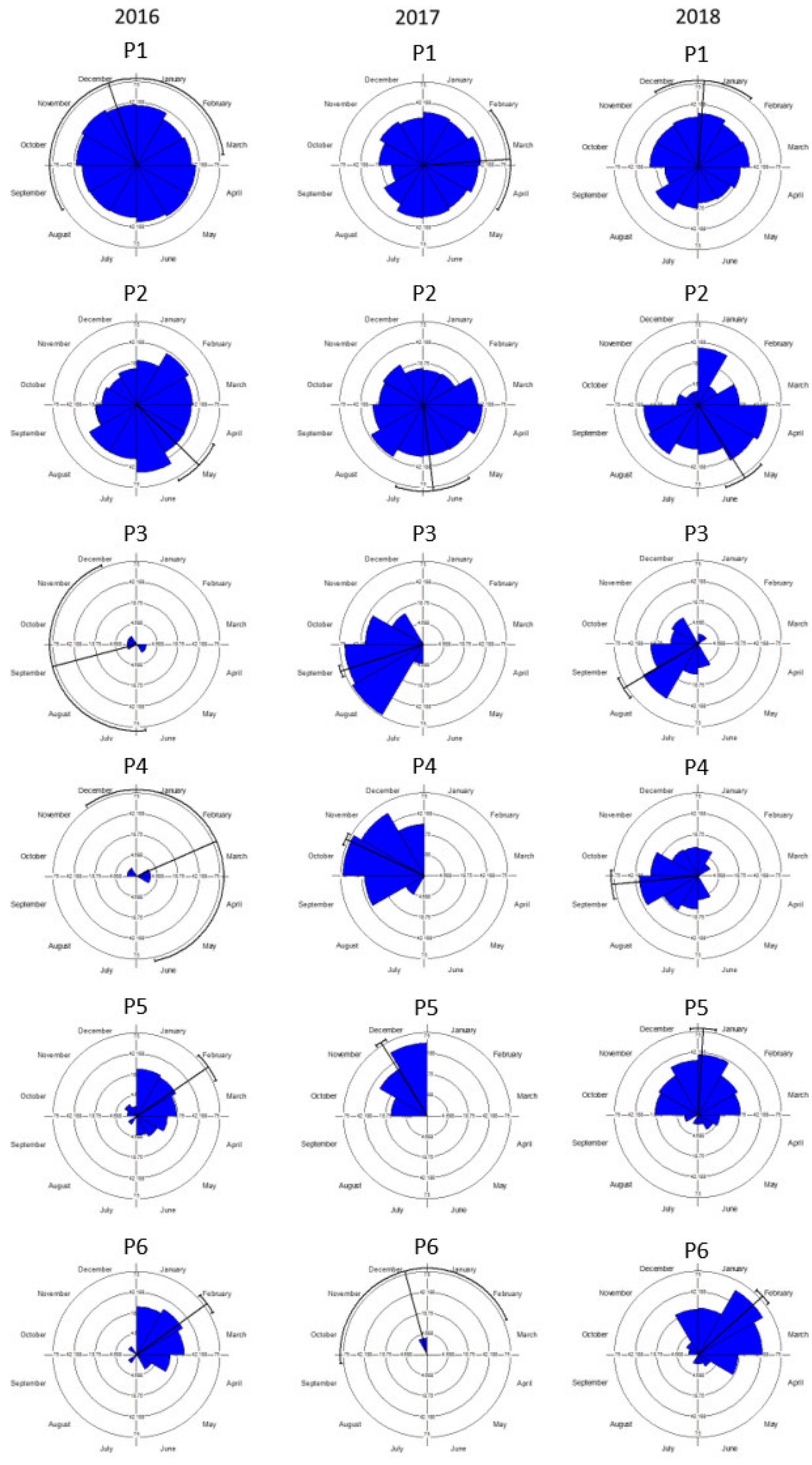

Figure 3. Phenological behavior of a population of *Manilkara salzmannii* in an Atlantic Forest fragment. P1 = leaf senescence; P2 = leaf flushing; P3 = bud production; P4 = blooming; P5 = immature fruit; and P6 = mature fruit.

Comportamiento fenológico de una población de *Manilkara salzmannii* en un fragmento de bosque atlántico. P1 = senescencia de las hojas; P2 = enrojecimiento de las hojas; P3 = producción de brotes; P4 = floración; P5 = frutos inmaduros; y P6 = frutos maduros.

Table 1. Mean vector (μ), several observations of phenophase occurrence (N), mean vector concentration (r), Rayleigh (Z), and Watson-Williams tests of *Manilkara salzmannii* phenophases in the years 2016, 2017, and 2018.

Vector medio (μ), número de observaciones de aparición de la fenofase (N), concentración media del vector (r), Rayleigh (Z) y pruebas de Watson-Williams de las fenofases de *Manilkara salzmannii* en los años 2016, 2017 y 2018.

Phenophases	Year	μ	Mean date	N	*r*	*Z*	*Watson-Williams test*	
leaf senescence	2016	341.01°	-	424	0.04	ns	2016/2017	< 0.001
	2017	85.96°	28/Mar	316	0.13	< 0.001	2017/2018	ns
	2018	3.91°	04/Jan	266	0.14	< 0.001	2016/2018	< 0.001
leaf flushing	2016	134.33°	16/May	327	0.26	< 0.001	2016/2017	< 0.001
	2017	173.28°	25/June	306	0.18	< 0.001	2017/2018	ns
	2018	147.53°	30/May	275	0.33	< 0.001	2016/2018	< 0.001
bud production	2016	255.00°	-	5	0.20	ns	2016/2017	ns
	2017	251.83°	12/Sept	192	0.89	< 0.001	2017/2018	ns
	2018	238.93°	30/Aug	103	0.79	< 0.001	2016/2018	< 0.001
blooming	2016	66.21°	-	6	0.40	ns	2016/2017	< 0.001
	2017	295.09°	26/Oct	200	0.88	< 0.001	2017/2018	< 0.001
	2018	264.27°	25/Sept	125	0.64	< 0.001	2016/2018	< 0.001
immature fruit	2016	55.37°	25/Feb	88	0.70	< 0.001	2016/2017	< 0.001
	2017	327.96°	29/Nov	103	0.94	< 0.001	2017/2018	< 0.001
	2018	3.23°	03/Jan	166	0.63	< 0.001	2016/2018	< 0.001
mature fruit.	2016	53.73°	24/Feb	96	0.83	< 0.001	2016/2017	< 0.001
	2017	345.00°	16/Dec	3	1.00	< 0.001	2017/2018	ns
	2018	47.84°	16/Feb	172	0.79	< 0.001	2016/2018	< 0.001

ns = not significant.

periods. Synchrony was evidenced quantitatively, as all reproductive events decreased in 2016 and 2017, showing that if one event was affected, the others were as well.

The leaf senescence was more intense in periods of higher temperature and solar radiation, as well as in periods of lower precipitation and humidity. Leaf flushing was positively influenced by precipitation and humidity in all the months evaluated, as well as by periods of lower wind speed. Bud production was negatively and significantly correlated with temperature in the three months evaluated, and the same occurred with blooming in the two months before the event. There was a positive and significant correlation between humidity with bud production and a negative correlation between solar radiation with bud production in the penultimate month before the event. Also, there was a negative and significant correlation between blooming and precipitation in the same month. There was a positive and significant correlation between wind speed in the same month as well as one month before the bud production and blooming events.

DISCUSSION

The occurrence of leaf flushing and leaf senescence throughout the observation period showed that *M. salzmannii* follows the pattern of a perennial species (Almeida Jr *et al*. 2010), with budding, defoliation, and growth of new leaves during the annual cycle. This pattern is an ecological strategy that optimizes the use of environmental resources by the plant. Leaf senescence was higher in periods with higher temperatures and lower precipitation, corroborating the data on litter contribution observed for a primary forest community (Barlow *et al*. 2007). In a study with *Manilkara hexandra*, precipitation was found to play a key role in the production of new leaves. However, its pattern of leaf senescence was different from that observed for *M. salzmannii*, as it occurred during the wet season (Gunarathne and Perera 2014).

Our observations indicate that *M. salzmannii* is classified as a species with an annual reproductive pattern, meaning that the bud production, blooming, and fruiting events occur only once a year (Newstrom *et al*. 1994). This pattern was expected for the species, as it has been previously observed for some of the other species of the genus, such as *Manilkara hexandra, Manilkara subsericea,* and *Manilkara amazonica* (Gomes *et al*. 2008, Gunarathne and Perera 2014). Another factor that influences this reproductive pattern is the fleshy nature of the fruits, which require more time to complete the maturation process and attract dispersers.

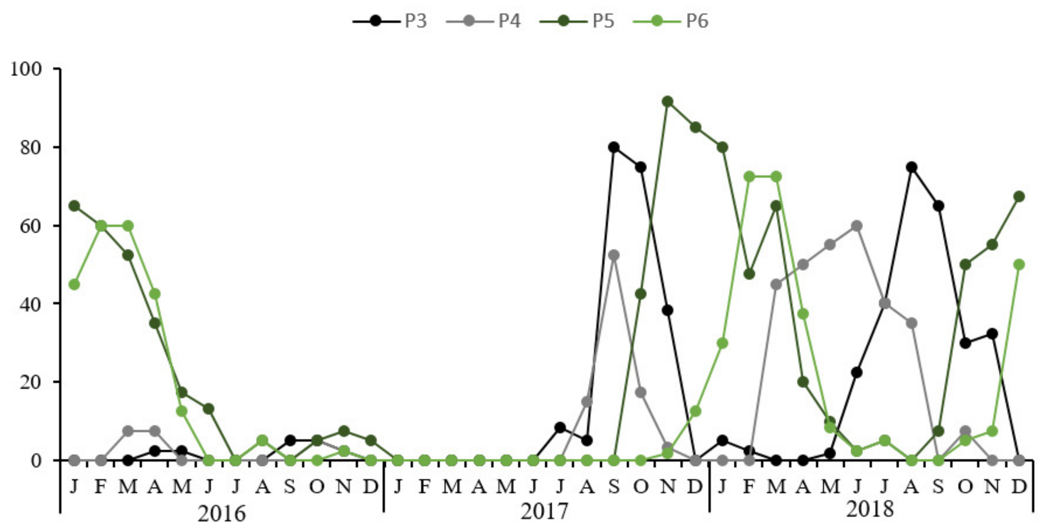

Figure 4. Index of activity of bud production (P3), blooming (P4), immature fruits (P5), and mature fruits (P6) of a population of *Manilkara salzmannii* in an Atlantic Forest fragment.

Índice de actividad de producción de brotes (P3), floración (P4), frutos inmaduros (P5) y frutos maduros (P6) de una populación de *Manilkara salzmannii* en un fragmento de Bosque Atlántico.

Table 2. Spearman correlation (rs) between the vegetative and reproductive events of a population of *Manilkara salzmannii* and meteorological variables in the same month (m_0), previous month (m_1), and two months previously (m_2).

Correlación de Spearman (rs) entre los eventos vegetativos y reproductivos de una población de *Manilkara salzmannii* y las variables meteorológicas en el mismo mes (m_0), el mes anterior
221 (m_1) y dos meses antes (m_2).

Variables/months		Phenophases					
		leaf senescence	leaf flushing	bud production	blooming	immature fruit	mature fruit
Air temperature	m_0	0.4109*	-0.2238	-0.5543*	-0.2176	0.4050*	0.4084*
	m_1	0.4433*	0.0437	-0.6789*	-0.4447*	0.2714	0.4547*
	m_2	0.3789*	0.3129	-0.6458*	-0.6431*	0.0018	0.3377*
Precipitation	m_0	-0.0654	0.3681*	-0.3147	-0.4199*	-0.1292	0.2443
	m_1	-0.2370	0.5956*	-0.0006	-0.3024	-0.3523*	-0.0810
	m_2	-0.4701*	0.5376*	0.2137	0.0216	-0.4317*	-0.2600
Relative humidity	m_0	-0.2028	0.5310*	-0.0888	-0.3163	-0.2987	-0.0460
	m_1	-0.3713*	0.6247*	0.2449	-0.1170	-0.4332*	-0.2438
	m_2	-0.5738*	0.3412*	0.4756*	0.2640	-0.4244*	-0.4116*
Wind speed	m_0	-0.0539	-0.2149	0.5000*	0.4171*	-0.1898	-0.4279*
	m_1	0.1813	-0.5315*	0.3539*	0.4748*	0.1446	-0.2209
	m_2	0.2869	-0.5598*	0.1039	0.2882	0.3142	-0.0860
Solar radiation	m_0	0.2960	-0.1666	-0.0669	0.0040	0.0187	-0.0748
	m_1	0.4011*	-0.2452	-0.2880	-0.0431	0.2585	0.1383
	m_2	0.5407*	-0.1197	-0.4759*	-0.2834	0.3216*	0.3314*

* Significant correlation ($P < 0.05$).

The results of this study show the strong influence of meteorological variables on the phenology of the species, especially on reproductive events. The absence of bud production and consequently of blooming and fruiting in certain periods affects the timing of the species' propagation. Almeida Jr. *et al*. (2010) reported that the species has a low seed germination rate. In fact, in the area of this study, we found the species to have low and slow seedling emergence rates (Unpublished data). Furthermore, Almeida Jr (2012) observed that even though *M. salzmannii* is not classified as endangered, conservation measures are needed to prevent the species from becoming threatened in the future. In other words, in addition to *in situ* conservation measures, actions are needed to mitigate the effects of climate change.

Climate change produces damage on a global scale, with long-term negative effects, including the possibility of irreversible damage to ecosystems and biodiversity (Legagneux *et al.* 2018). We observed that during the analyzed period, the findings for 2016 deviated from the phenological pattern, probably influenced by the strong El Niño effect. This climatic event was considered very strong in 2015-2016, causing a precipitation deficit in the Amazon and Northeast and Midwest regions of Brazil (Pereira *et al*. 2017). In addition to drought, it is also responsible for causing increased temperatures, affecting mainly the North and Northeast regions of Brazil (Penereiro *et al*. 2018). Thus, it is likely that El Niño had an influence on the study area, altering the reproductive phenological behavior of *M. salzmannii,* also observed for other species (Wright and Calderon 2005; Wright *et al*. 2016, Menezes *et al*. 2018).

We found no studies regarding the phenology of *M. salzmannii* in the literature, and only a few regarding other species of the family and genus. *Manilkara subsericea*, for example, in the resting area of Maricá, state of Rio de Janeiro, showed annual and regular seasonal flowering (in the less humid and cooler season of the year) from 2003 to 2005 (Gomes *et al.* 2008). According to the authors, annual and regular fruiting was observed, occurring during the season with the heaviest rainfall and highest temperatures, with a 90 % fruit abortion rate. *M. salzmannii* showed similar results, with flowering events during the period of lowest humidity and temperature and fruiting during periods of higher temperatures, with precipitation influencing fruit maturation. The fact that the bud production and blooming phenophases occurred during periods of lower temperature and solar radiation may have influenced the low rate in 2016, and consequently the sparse fruit production.

A study with *Manilkara hexandra* in Sri Lanka showed that higher air humidity and precipitation, as well as low temperature, wind speed, and solar radiation, provided optimal conditions for flowering (Gunarathne and Perera 2014). However, the authors noted that sudden climate variations favored the abortion of flowers and fruits, which decreased seed production and the perpetuation of the species. These reports show how much climate influences the species of the genus, a factor that should be observed in future ecological research. We found that fruiting started in a period of low rainfall and continued into a period of higher rainfall, showing the importance of rainfall on fruit maturation. Similar data were also found for the species *Manilkara paraenesis* in the state of Amapá, with blooming occurring in the period of lowest rainfall, and fruiting beginning at the end of the period of low rainfall and continuing into the period of higher rainfall (Freitas *et al*. 2015).

In general, the fruits of the species of the genus are sensitive to the influence of climate, and in some cases have difficulties completing the maturation process. This characteristic needs to be studied further, because in addition to the timber potential (negative for conservation) there is ethnobotanical potential (conservationist), with implications for seed collection, seedling production, and conservation (Lamarca *et al.* 2020). There are also implications for the use of non-timber forest products of the species, such as the edible fruits of *M. salzmannii*. However, this consumption is not widespread and is not taken into consideration in most studies. The fruits of two other species of the genus, *Manilkara elata* (Allemão ex Miq.) and *Manilkara excelsa* (Ducke) Standl., are also classified as edible. Additionally, when performing sensory analysis of *Manilkara bidentata* (A.DC.) A.Chev., the fruits were found to be sweet and tasty, as well as having antimicrobial bioactive potential (Teixeira *et al.* 2019).

CONCLUSIONS

The phenophases of *M. salzmannii*, especially reproductive, varied over the years, demonstrating that this species is influenced by climate oscillations. The species presents synchrony, where bud production and blooming occur at practically the same time. Understanding the reproductive period and the impact of variations in climate on the production of plants is essential for the establishment of successful ecological strategies, as the fruits can be collected at the appropriate time and thus be used for seedling production and planting for reforestation.

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