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Original Article

Understanding phenology and forest meteorology dynamics in a South American pharmacological tree

Compreendendo a fenologia e a dinâmica da meteorologia florestal em uma árvore farmacológica sul-americana

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Abstract

Protium heptaphyllum (Burseraceae) is a native species widely studied for its secondary metabolites, yet with limited records regarding its ecology and conservation. To address this gap, the present study describes the vegetative and reproductive phenology of the species in an Atlantic Forest fragment in Rio Grande do Norte, Brazil, examining the relationship between phenological events and meteorological variables. Twenty adult individuals (twelve females and eight males) were monitored biweekly over two years. The phenophases assessed included leaf senescence, leaf flushing, flower buds, flowers at anthesis, and immature and mature fruits, and were correlated with precipitation, temperature, relative humidity, solar radiation, and wind speed. The species exhibited a seasonal pattern, with heightened reproductive activity from October to February. Flowering was intense and synchronous, suggesting efficient pollination; however, mature fruit production was low. The findings reveal limitations in reproductive success, indicating that extreme climatic events, such as *El niño*, may influence the species' phenological behavior. Identifying periods of peak phenological activity contributes to guiding seed collection, seedling production, and restoration efforts, providing concrete insights for the conservation of *P. heptaphyllum* in its natural habitats.

Keywords: climate change, conservation, *Protium heptaphyllum*, reproductive events, vegetative changes.

Resumo

Protium heptaphyllum (Burseraceae) é uma espécie nativa amplamente estudada por seus metabólitos secundários, mas com poucos registros sobre sua ecologia e conservação. Para preencher essa lacuna, este estudo descreve a fenologia vegetativa e reprodutiva da espécie em um fragmento de Mata Atlântica no Rio Grande do Norte, relacionando os eventos fenológicos com variáveis meteorológicas. Vinte indivíduos adultos (doze fêmeas e oito machos) foram monitorados quinzenalmente durante dois anos. Foram avaliadas as fases de senescência, brotamento, botões florais, flores em antese, frutos imaturos e maduros, correlacionadas com precipitação pluviométrica, temperatura, umidade relativa, radiação solar e velocidade do vento. A espécie apresentou padrão sazonal, com maior atividade reprodutiva entre outubro e fevereiro. A floração foi intensa e sincronizada, indicando fecundação eficiente, mas a produção de frutos maduros foi reduzida. Os resultados revelam limitações no sucesso reprodutivo, sugerindo que eventos climáticos extremos, como *El niño* podem afetar o comportamento da espécie. A identificação dos períodos mais ativos da fenologia contribui para orientar a coleta de sementes, a produção de mudas e ações de restauração, fornecendo subsídios concretos para a conservação de *P. heptaphyllum* em ambientes naturais.

Palavras-chave: mudanças climáticas, conservação, *Protium heptaphyllum*, eventos reprodutivos, mudanças vegetativas.

1. Introduction

Brazil's botanical diversity comprises a large part of the globe's biodiversity (Castuera-Oliveira et al., 2020; Myers et al., 2000). This diversity is fundamental for the maintenance of ecosystems and for the distribution of environmental services related to human well-being (Martinelli and Moraes, 2013), but there is an urgent need for conservation efforts to mitigate threats of extinction. These threats are related to habitat destruction, the introduction of exotic species, and climate change (Rai and Singh, 2020). Consequently, 35 global biodiversity hotspots have been identified as highly susceptible to species loss, warranting worldwide conservation priority (Wilson et al., 2021). Two of these are in Brazil: the Cerrado and the Atlantic Forest biomes (Myers et al., 2000).

These more susceptible environments require efficient and sustainable management strategies, particularly to prevent the inappropriate exploitation of species with medicinal properties. In Brazil, although there are legal

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frameworks addressing medicinal plants, these are often embedded within broader environmental legislation and still lack specific criteria and clear definitions for appropriate use and conservation (Lindberg et al., 2023). Furthermore, in most cases, there is limited knowledge about the active compounds and conservation status of many commercially exploited species (Santos et al., 2024). This lack of regulatory specificity and scientific information is also evident at the global scale. According to the International Union for Conservation of Nature (IUCN) Red List, species such as *Protium heptaphyllum* (Aubl.) March. (Burseraceae) lacks sufficient data for formal threat categorization. Despite being recognized as a species of research and conservation interest, it remains data deficient (Martinelli and Moraes, 2013).

While *P. heptaphyllum* exhibits a broad distribution across the phytogeographic domains of the Amazon, Caatinga, Cerrado and Atlantic Forest biomes, information regarding its ecology and conservation remains limited (Daly, 2015; Rodrigues et al., 2024). The species is dioecious, meaning it possesses unisexual flowers in separate individuals, resulting in not all adult trees bearing fruit by the end of the phenophase (Daly et al., 2022). It is classified as an early secondary species, semi-deciduous (or evergreen, depending on local conditions), and zoochoric, traits that influence its regeneration strategy and ecological interactions (Carvalho, 2006). Consequently, there is a need to determine the timing of reproductive events and the intensity of phenophases within the population. The fruits are globular drupes, green when immature and red when ripe, measuring 1.3-1.5 cm × 0.8-1.5 cm (Silva et al., 2007).

P. heptaphyllum is known for its aromatic structures and frequent use in folk medicine, as described by European naturalists dating to the 19th century (Cabral et al., 2020; Breitbach et al., 2013). Various data are available on its chemical constituents and pharmacological potential, especially the resin, its most marketed product (Almeida et al., 2021). In the literature, there is information about the anti-inflammatory, analgesic and weight-loss properties of its constituents (Carvalho et al., 2017), including for the treatment of neuropathic pain (Singh et al., 2017), and orofacial pain (Siqueira-Lima et al., 2017). There are also records of anxiolytic, antidepressant, and anticonvulsant effects (Aragão et al., 2006, 2015; Dimmito et al., 2021). However, there is a lack of ecological information to effectively preserve the species' genetic resources (Freire et al., 2019).

Hence, to develop coherent conservation and management strategies, it is essential to comprehend the species' behavior in its natural environment (Costa et al., 2022; Ettinger et al., 2022; Mir et al., 2021). Assessing phenophases provides insights into plants' reproductive characteristics by observing key events such as flowering, fruiting, leaf flushing, and leaf senescence (Costa et al., 2022; Diatta et al., 2022; Menon et al., 2025). It also allows the evaluation of the relationships between phenophases and meteorological variables, generating information on the behavior of natural populations in ecosystems. Phenological studies are also relevant to identify the period of fruit and seed collection and support the sustainability of non-timber forest products, contributing to *in situ* and *ex situ* conservation (Costa et al., 2022; Ponti and Sannolo, 2023).

This study aimed to describe the vegetative and reproductive phenology of *P. heptaphyllum*, investigating potential correlations between phenophases and meteorological variables. The primary question guiding this research is: What are the seasonal patterns in the timing of vegetative and reproductive events for this species, and what environmental factors influence these patterns?

2. Material and Methods

The study was carried out in an Atlantic Forest fragment (5°53'30" S, 35°21'30" W, 50 m a.s.l.; Figure 1). The vegetation is classified as Semideciduous Lowland Seasonal Forest (Costa et al., 2022), exhibiting a transitional climate between Köppen's classification types As' and BSh' (Alvares et al., 2013). The average annual rainfall in the region in 2015 and 2016 were 1127.9 mm and 903.8 mm, respectively (EMPARN, 2021), with high temperatures throughout the year and rainy season from autumn to what is typically considered winter. A voucher specimen with registration number 26577 was collected and deposited in the herbarium of the Federal University of Rio Grande do Norte. Additionally, this study is registered in the Brazilian SisGen platform with the code A0FBC35.

We followed the methods of Freire et al. (2022), where adult individuals of *P. heptaphyllum* with a height above five meters were selected. To increase the chances of observing reproductive events in *P. heptaphyllum*, a dioecious species, adult individuals from both sexes were sampled (twelve females and eight males). The evaluations were conducted biweekly for two years, from January 2015 to December 2016, resulting in 48 observations. Due to the accessibility and proximity of individuals, observations were carried out without the need for visual tools. Subsequently, the monthly averages of the observations were computed. In the context of our study, leaf senescence represents the natural ageing process of leaves in *P. heptaphyllum*, culminating in shedding. Conversely, leaf flushing denotes the emergence of new leaves, typically associated with the growth season.

The production of flower buds begins with the formation of nascent buds, marking the start of the reproductive phase, and continues until these buds mature into fully developed flowers in anthesis. Flowering (flowers in anthesis) designates the phase when flowers open. Immature fruits characterize the developmental stage post-fertilization before reaching full size and maturity. Finally, ripe fruits indicate the fruit's readiness for dispersal. We analyzed synchronicity using an activity index that measured the presence or absence of a phenological event (Rocha et al., 2020). The Fournier (1974) index, which employs a quantification scale, was used to evaluate the intensity of phenophases (Figure 2).

Following data collection, the Oriana® demo version 4.02 (Kovach Computing Services, 2020) was employed to compute the circular statistics. To aid in the analysis, we converted the months into angles using the Julian calendar.

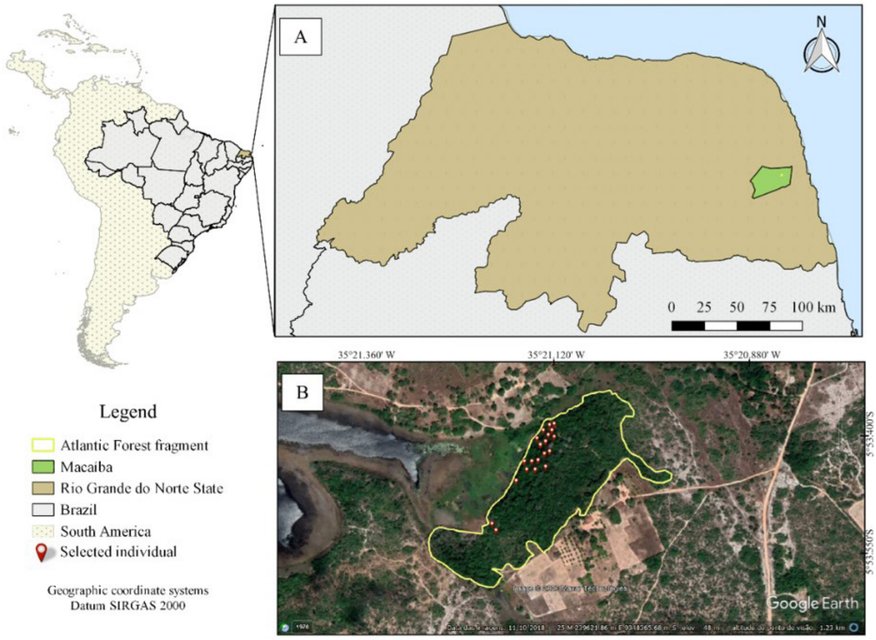

Figure 1. Location of the forest studied in the Rio Grande do Norte state, municipality of Macaíba (A) and the population of *Protium heptaphyllum* in an Atlantic Forest fragment (B).

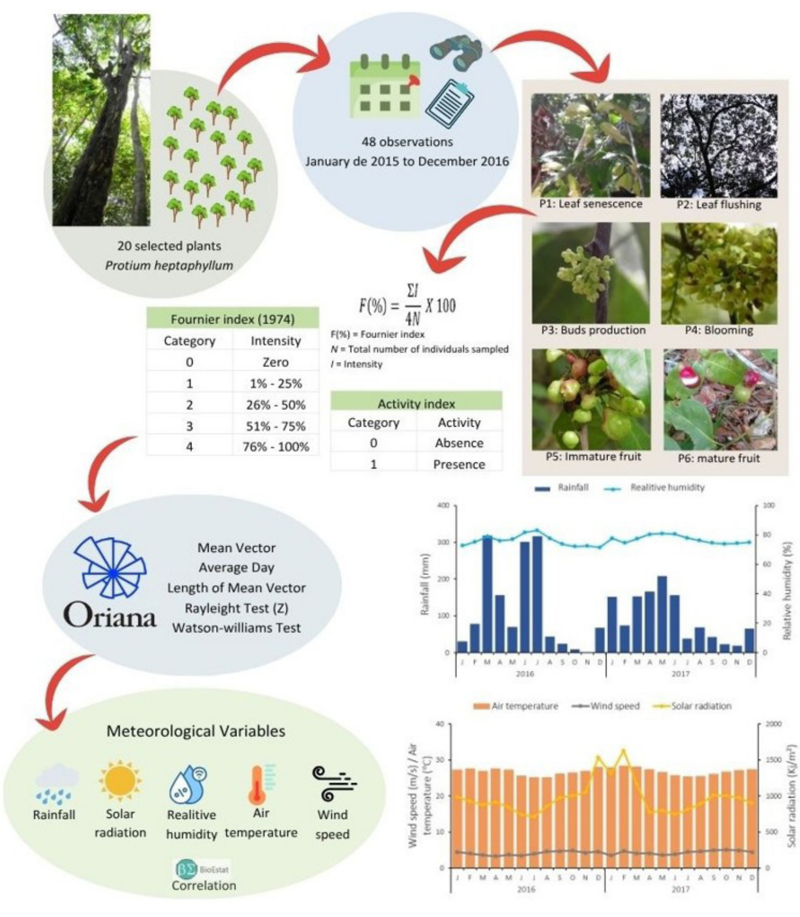

Figure 2. Experimental design and analysis of a population of *Protium heptaphyllum* in an Atlantic Forest fragment.

In this method, we assigned 0° to the first day of the year (January 1), and the scale progressed to 360°, representing the 365th day of a standard year (December 31). However, in the case of a leap year, we extended the scale to 361° to account for the additional day. This approach enabled a consistent representation across both standard and leap years. The significance of the mean angle was analyzed using Rayleigh's test (z), which assesses the uniformity of circular data. Additionally, the Watson-Williams test was employed to compare mean angles between the two years, with significance determined at $p < 0.05$, and the length of the vector r was calculated, which indicates unimodality, with data around the average vector, when the value is greater than 0.50. In circular graphs, the value of the mean angle is represented by a black line, with an arc that is smaller as the data is more concentrated to the mean vector.

Phenophases with significant mean angles ($p < 0.05$) were transformed into mean dates, representing the peak intensity of each phenophase during the year. Meteorological data were obtained from the "*Instituto Nacional de Meteorologia* - INMET" climatological station, approximately 20 km from the forest fragment studied. The meteorological variable included air temperature, rainfall, relative humidity, wind speed, and solar radiation. The meteorological data used included: a) data from the event month (m0), b) data from one month before the event (m1), and data from two months before the event (m2). We used the Lilliefors test to check for deviations from normality in the phenological data. Since the data were non-parametric, we applied Spearman's non-parametric correlation method.

3. Results

The leaf senescence of *P. heptaphyllum* frequently occurred throughout the year, with a low concentration around the mean vector, with *r* values below 0.5 (Figure 3 – P1). The leaf flushing also presented a low concentration around the mean vector (Figure 3 – P2). Flower buds exhibited minimal intensity throughout most of the observed period, with peaks in late October 2015 and early November 2016 (Figure 3 – P3). The peak flowering was noted in early November 2015 and late November 2016, just after the periods of flower buds (Figure 3 – P4). The peaks of immature fruits intensity occurred in December 2015 and February 2016 (Figure 3 – P5), while ripe fruits peaked in January 2015 and February 2016 (Figure 3 – P6). Hence, reproductive events manifested on a modest scale every month, with the highest intensity observed from October to February.

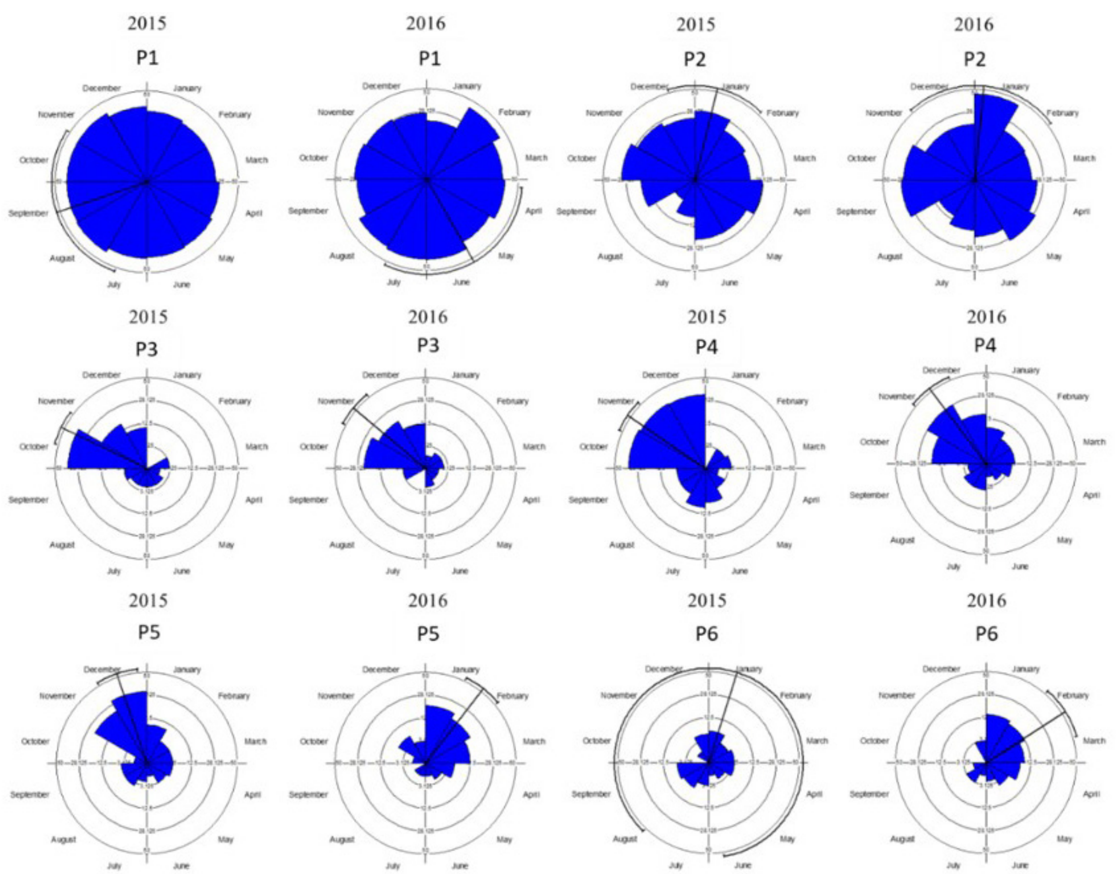

Figure 3. Phenological traits of a population of *Protium heptaphyllum* within an Atlantic Forest fragment. The codes indicated as follows: P1 (leaf senescence); P2 (leaf flushing); P3 (flower buds); P4 (flowering); P5 (immature fruits); and P6 (ripe fruits).

Synchrony between the reproductive events (Figure 4) was evident, with phenophases occurring sequentially: flower buds, flowering, formation of immature fruits, and development of ripe fruits. However, our observation through the activity index revealed a discrepancy; the number of immature fruits resembled that of flowers, suggesting successful fecundation, but fewer ripe fruits were observed. This phenomenon was primarily attributed to insect attacks observed at the site, causing fruit degradation and loss, with many seeds dispersed in the soil (personal observation).

Our analysis using the circular statistics revealed that no unimodal distribution ($r < 0.50$) was observed for vegetative phenophases or ripe fruits in 2015. This indicates the data for these phenophases were not concentrated around a single mean direction (vector concentration, r). In contrast, Rayleigh's test ($p < 0.05$) confirmed seasonality for immature fruits in 2015, flower bud production in 2015 and 2016, flowering in 2015 and 2016, and immature fruits in 2015 (Table 1). Regarding vegetative events, only leaf flushing showed seasonality in 2015 according to the Rayleigh test (Z). The other phenophases had similar frequency throughout the year, without significant changes in intensity in a given period, i.e. the lower the degree of seasonality, the longer the occurrence of phenophase. According to the Watson-Williams test ($p < 0.01$), only bud and immature fruits production did not exhibit significant differences between the two years under evaluation.

The correlation analysis between phenophases and meteorological variables (Table 2) revealed that leaf senescence exhibited a positive and significant correlation with rainfall (m_2= 0.5787*). Similarly, leaf senescence demonstrated a positive and significant correlation with relative humidity (m_1= 0.5129*; m_2= 0.4653*).

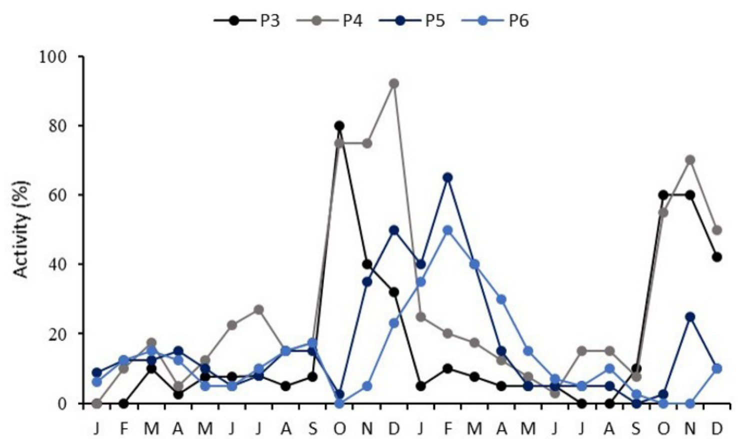

Figure 4. Activity index of the flower buds (P3), flowering (P4), immature fruits (P5) and ripe fruits (P6) of a population of *Protium heptaphyllum* within an Atlantic Forest fragment.

Table 1. Mean vector (µ), number of observations of phenophase occurrence (N), mean vector concentration ®, Rayleigh (Z), and Watson-Williams tests of *Protium heptaphyllum* phenophases in the years 2015 and 2016 within an Atlantic Forest fragment.

Phenophases	Year	µ	Mean date	N	*r*	*Z*	Watson-Williams test
P1	2015	251.26°	-	406	0.08	ns	84.28*
	2016	150.39°	-	392	0.07	ns	
P2	2015	13.63°	13/jan	245	0.17	< 0.001	0.66*
	2016	5.39°	-	280	0.1	ns	
P3	2015	295.87°	26/oct	78	0.70	< 0.001	3.48^{ns}
	2016	309.99°	10/nov	65	0.71	< 0.001	
P4	2015	304.25°	04/nov	140	0.59	< 0.001	4.88*
	2016	322.92°	23/nov	96	0.54	< 0.001	
P5	2015	341.19°	11/dez	89	0.59	< 0.001	36.50*
	2016	37.67°	-	68	0.67	ns	
P6	2015	17.37°	-	40	0.08	ns	1.45^{ns}
	2016	57.12°	-	56	0.58	ns	

The phenophases mean P1 (leaf senescence); P2 (leaf flushing); P3 (flower buds); P4 (flowering); P5 (immature fruits); P6 (ripe fruits); ns (not significant); *significant.

Table 2. Spearman correlation (rs) between the meteorological variables and the same month (m0), previous month (m_1) and second previous month (m_2) to the vegetative and reproductive events of a population of *Protium heptaphyllum* in an Atlantic Forest fragment.

Variables/months		**Phenophases**					
		P1	**P2**	**P3**	**P4**	**P5**	**P6**
Air temperature (°C)	m_0	-0.3873	0.3869	0.0058	0.0297	**0.6876***	**0.5228***
	m_1	-0.3589	0.3067	-0.2131	-0.1403	**0.4441***	**0.4820***
	m_2	-0.0502	0.0292	-0.4397	-0.3759	0.2245	**0.4465***
Rainfall (mm)	m_0	-0.1666	-0.1732	**-0.4482***	**-0.3899***	-0.0296	0.3961*
	m_1	0.2918	-0.2726	-0.3971*	**-0.5157***	-0.2713	0.2162
	m_2	**0.5787***	**-0.4571***	-0.1629	-0.3304	**-0.4468***	-0.0583
Relative humidity (%)	m_0	0.0454	-0.3669	**-0.4648***	-0.3571	-0.2924	0.1364
	m_1	**0.5129***	**-0.5474***	-0.2131	**-0.4688***	**-0.4688***	0.0259
	m_2	**0.4653***	**-0.3673***	-0.0256	-0.2124	**-0.6417***	-0.2921
Wind speed (m/s)	m_0	0.2852	-0.0340	**0.4451***	0.3593	-0.1081	-0.2908
	m_1	-0.3271	0.2591	**0.4500***	**0.4755***	0.1173	-0.2483
	m_2	-0.2830	**0.3991***	0.4567	0.3728	0.2845	-0.1465
	m_0	-0.1413	**0.4462***	0.3060	0.3497	**0.5213***	0.2228
Solar radiation (Kj/m^2)	m_1	-0.2830	**0.4580***	0.2710	0.3781	**0.6157***	0.2886
	m_2	-0.3698	0.3577	-0.0126	0.1259	**0.6320***	**0.4255***

The phenophases mean P1 (leaf senescence); P2 (leaf flushing); P3 (flower buds); P4 (flowering); P5 (immature fruits); P6 (ripe fruits); *significant.

The two correlations that occurred were significant only with data from two months before the event. Conversely, leaf flushing exhibited a negative and significant correlation with rainfall (m_2= -0.4571*), with consistent patterns observed in the previous and subsequent months. Additionally, leaf flushing displayed a positive and significant correlation with wind speed two months before the event (m_2= 0.3991*), and with solar radiation in both the same month and the preceding month (m_0= 0.4462*; m_1= 0.4580*).

Flower buds negatively correlated with rainfall in the same month and the previous month (m_0= -0.4482*; m_1= -0.3971*). Additionally, flower buds negatively correlated with relative humidity in the same month (m_1= -0.4688*). Higher wind velocity in the same month and the previous month was associated with increased flower buds (m_0= 0.4451*; m_1= 0.4500*). Flowering negatively correlated with rainfall in the same month and the previous month (m_0= -0.3899*; m_1= -0.5157*). Flowering was more prominent when relative humidity was lower (m_1= -0.4688*), and wind speed was higher in the previous month (m_1= 0.4755*).

Increased immature fruits production was observed when there was reduced rainfall two months before the event (m_2= -0.4468*), and lower relative humidity in the previous two months (m_1= -0.4688*; m_2= -0.6417*). Additionally, immature fruits production showed a positive and significant correlation with air temperature in the same month and previous month (m_0= 0.6876*; m_1= 0.4441*), as well as with radiation in all the months evaluated before the phenophase (m_0= 0.5213*; m_1= 0.6157*; m_2= 0.6320*). The rate of ripe fruits demonstrated a positive and significant correlation with air temperature in the three months evaluated (m_0= 0.5228*; m_1= 0.4820*; m_2= 0.4465*), rainfall in the same month (m_0= 0.3961*), and radiation two months before the event (m_2= 0.4255*).

4. Discussion

Frequent leaf senescence was observed throughout the year, without a proportional production of new leaves, characteristic of semideciduous species, which typically lose 20% to 50% of their foliage (IBGE, 2012). The highest intensity of new leaf emission occurred around January, so it is the best period for collecting plant material since younger tissues produce more secondary metabolites (Tak and Kumar, 2020). Interestingly, all the climatic variables were significantly correlated with leaf flushing, except for the air temperature, showing the meteorological effects on the species, a common fact in Atlantic Forest species that can create adaptation mechanisms to changes in meteorological variables (Macedo et al., 2021; Silva et al., 2020).

In general, there is a positive correlation between solar radiation and the production of phenolic compounds (Del Valle et al., 2020). These findings suggest that weather variability can influence not only phenological events but also the biosynthesis of compounds (Inouye, 2022). For example, the absence of seasonality in the leaf flushing observed in 2016 appears to reflect environmental changes and the recurrent annual seasonal calendar of events (Inouye, 2022).

Although most trees evaluated in this study had female flowers, fruiting occurred less than expected. Thus, the maintenance of the species in the forest fragment may be affected by the low rate of fructification of the individuals observed, in which it is common for part of the flowers not to convert into fruit (Bera et al., 2024). Another factor to be considered is the meteorological effects on the reproductive events, in which the influence of low rainfall and relative humidity on flower buds and flowering stood out. Additionally, there was an influence of increased temperature and solar radiation on the formation of immature and ripe fruits. Such results indicate that fluctuations in meteorological conditions may disrupt the temporal distribution of phenophases, despite their occurrence in nearly every month assessed.

The low intensity of reproductive events may have been caused by the effects of *El niño*, which might have altered fruiting and other seasonal phenophase events. *El niño* is an oceanographic phenomenon that influences atmospheric circulation, affecting rainfall and temperature in several regions of the world (Cai et al., 2020). In 2015-2016, *El niño* was considered strong, and in Brazil the anomaly caused a rainfall deficit in the Amazon (North), Northeast and Midwest regions (Pereira et al., 2017). In the case of the region where the *P. heptaphyllum* population is located, despite not changing the annual averages of rainfall that much, months were observed with values different from historical data.

El niño also caused prolonged leaf senescence in other species (Kaewthongrach et al., 2020), which can explain the behavior of *P. heptaphyllum*, which showed constant shedding during 2015 and 2016. This behavior is expected in stressful situations, since *P. heptaphyllum* is a species classified as semideciduous, losing its leaves in stressful situations. Besides this, the leaf flushing was higher with lower rainfall and higher solar radiation, indicating the phenomenon may have influenced the absence of seasonality in 2016.

Phenology is an environmental science necessary to understand plant responses to climate changes (Pérez-Ramos et al., 2020). Previous studies have shown that phenological sensitivity under experimental heating provides important justification for the continuity of this type of monitoring, since the information obtained may be useful to identify species at risk of decline (Zhang et al., 2023). According to the Intergovernmental Panel on Climate Change Report - IPCC (2013), South America will tend to have higher temperatures and reduced water availability. Thus, climate change is likely to cause severe impacts on plant communities found at high altitudes and in riparian areas within tropical forests (Zhang et al., 2023), which could affect populations of the species in our study, given their presence in vulnerable areas susceptible to impacts.

Climate change generates more extremely unfavorable periods and probably affects fruitification, causing immature fruits production at the end of the dry season. This is an adaptive strategy for seed dispersal during the favorable periods (Simão et al., 2021). Another advantageous strategy for the species was the synchrony of flowering, since individuals flowering at the same time attract more floral visitors, increasing pollen transport (Costa et al., 2022). Since *P. heptaphyllum* is a dioecious species, this favors pollination.

A negative correlation between flowering and rainfall is consistent with the species' pollination strategy, as rain limits the activity of flying insects. A study of the identification of pollen grains in honey from bees in the Amazon reported the pollen frequency of *P. heptaphyllum*, showing that the flowers of the species are an attraction for bees because they are good sources of nectar (Souza et al., 2020).

An abundance of *P. heptaphyllum* pollen grains in honey was also reported between January and March, indicating that in the Amazon the species presents a phenological pattern of flower production in a different period from that found in this study. In this context, another phenological study of *P. heptaphyllum* in the Pantanal in the state of Mato Grosso do Sul observed that the emission of leaf buds, flowers, and fruits had a positive relationship with rainfall (Domene et al., 2010). These differences, likely driven by geographic distance and variations in phytogeographic domains, underscore the need for more comprehensive studies, including long-term phenological monitoring across multiple populations.

In contrast to other climatic variables, wind speed showed no significant correlation with phenological events. This lack of association is explained by the zoochorous dispersal syndrome of *P. heptaphyllum* (Carvalho, 2006), which relies on animals rather than wind for pollination and seed dispersal. Furthermore, the dense canopy structure characteristic of forest fragments acts as a physical barrier that reduces wind penetration, limiting its influence as a phenological trigger.

The vegetative aspects of *P. heptaphyllum* found in this study suggest the optimal time for leaf collection, as this aromatic plant contains valuable chemical constituents. However, medicinal plants are often harvested unsustainably, potentially leading to their extinction (Applequist et al., 2020). Typically, plants of the same species in different environments tend to present significant differences in the production of secondary metabolites, under the influence by environmental factors, since the biosynthesis of these compounds can be related to environmental responses (Espinosa-Leal, et al., 2022).

Moreover, seasonal variations influence the number of phenolic compounds (Inouye, 2022), and phenophases are also related to the production of these compounds, with lower amounts found when the plant invests in reproductive events (Gomes et al., 2021). This information implies that *P. heptaphyllum*, due to its wide distribution throughout Brazil and other South American countries, may be directly affected by abiotic environmental variables, such as those presented in this study, which consequently can affect the production of secondary metabolites, especially resin, which has important pharmacological constituents.

5. Conclusions

Protium heptaphyllum exhibits seasonality in the phenophases of leaf flushing (January), flower buds (October and November), flowering (November), and immature fruits (December). This indicates optimal periods for observing or collecting vegetative and reproductive structures, with January to March being the most favorable for fruit collection.

The species is affected by climatic effects, particularly the strong influence of *El Niño* on the phenophases in the observation period. The vegetative phenophases of *P. heptaphyllum* were negatively influenced by rainfall during the respective months of the event occurrence. Low rainfall correlated with increased leaf sprouting and reduced shedding. Additionally, decreased rainfall in the months surrounding the observation period led to heightened flower buds, flowering, and immature fruits production. Conversely, a positive correlation was observed between ripe fruit production and rainfall, indicating that rainfall facilitates fruit ripening.

The population exhibited synchrony in reproductive events, which represents an advantage of the dioecious system. This synchronous strategy can be considered efficient, as evidenced by the intensity of immature fruits, similar to the values observed for flowering, indicating successful fecundation. However, the low production of ripe fruits raises the hypothesis that the ripening process may be affected by intrinsic factors (such as resource allocation or physiological constraints) or by external pressures, possibly related to climatic anomalies such as *El Niño.* Although this remains to be verified, such interference may hinder the species' natural regeneration. To mitigate these effects, actions such as seedling production and the restoration of degraded areas where the species occur could contribute to preserving its genetic resources and maintaining the availability of its bioactive compounds.

Acknowledgements

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Data Availability Statement

"Research data is available at: https://figshare.com/articles/dataset/Phenology_of_Protium_heptaphyllum_-_research_data_xlsx/30070198?file=57731092

References

ALMEIDA, M.D.C., SILVA, J.A.P., TAVARES, F.F.C., ARAUJO, L.L., ZEFERINO, J.S. and SANTANA, R.M.C., 2021. Development of a bio-based adhesive from *Protium heptaphyllum* resino. *Polímeros*, vol. 31, no. 2, e2021014. http://doi.org/10.1590/0104-1428.10020.

ALVARES, C.A., STAPE, J.L., SENTELHAS, P.C., GONÇALVES, J.L.M. and SPAROVEK, G., 2013. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, vol. 22, no. 6, pp. 711-728. http://doi.org/10.1127/0941-2948/2013/0507.

APPLEQUIST, W.L., BRINCKMANN, J.A., CUNNINGHAM, A.B., HART, R.E., HEINRICH, M., KATERERE, D.R. and VAN ANDEL, T., 2020. Scientists' warning on climate change and medicinal plants. *Planta Medica*, vol. 86, no. 1, pp. 10-18. http://doi.org/10.1055/a-1041-3406. PMid:31731314.

ARAGÃO, G.F., CARNEIRO, L.M.V., FROTA-JUNIOR, A.P., VIEIRA, L.C., BANDEIRA, P.N., LEMOS, T.L.G. and VIANA, G.S.B., 2006. A possible mechanism for anxiolytic and antidepressant effects of alpha- and beta-amyrin from *Protium heptaphyllum* (Aubl.) March. *Pharmacology, Biochemistry, and Behavior*, vol. 85, no. 4, pp. 827-834. http://doi.org/10.1016/j.pbb.2006.11.019. PMid:17207523.

ARAGÃO, G.F., CARNEIRO, L.M.V., FROTA-JUNIOR, A.P., BANDEIRA, P.N., LEMOS, T.L.G. and VIANA, G.S.B., 2015. Alterations in brain amino acid metabolism and inhibitory effects on PKC are possibly correlated with anticonvulsant effects of the isomeric mixture of α- and β-amyrin from *Protium heptaphyllum. Pharmaceutical Biology*, vol. 53, no. 3, pp. 407-413. http://doi.org/10.3109/13880209.2014.923001. PMid:25471298.

BERA, B.J., SAMANTA, A. and KARMAKAR, P., 2024. Reproductive ecology of a threatened medicinal plant *Canscora alata* (Roth) Wall. *Brazilian Journal of Botany*, vol. 47, no. 2, pp. 485-500. http://doi.org/10.1007/s40415-024-00994-0.

BREITBACH, U.B., NIEHUES, M., LOPES, N.P., FARIA, J.E.Q. and BRANDÃO, M.G.L., 2013. Amazonian Brazilian medicinal plants described by C.F.P. von Martius in the 19th century. *Journal of Ethnopharmacology*, vol. 147, no. 1, pp. 180-189. http://doi.org/10.1016/j.jep.2013.02.030. PMid:23500885.

CABRAL, R.S.C., ALVES, C.C.F., BATISTA, H.R., SOUSA, W.C., ABRAHÃO, I.S., CROTTI, A.E.M., SANTIAGO, M.B., MARTINS, C.H.G. and MIRANDA, M.L.D., 2020. Chemical composition of essential oils from different parts of *Protium heptaphyllum* (Aubl.) Marchand and their in vitro antibacterial activity. *Natural Product Research*, vol. 34, no. 16, pp. 2378-2383. http://doi.org/10.1080/14786419.2018.1536659. PMid:30499330.

CAI, W., MCPHADEN, M.J., GRIMM, A.M., RODRIGUES, R.R., TASCHETTO, A.S., GARREAUD, R.D., DEWITTE, B., POVEDA, G., HAM, Y.-G., SANTOSO, A., NG, B., ANDERSON, W., WANG, G., GENG, T., JO, H.-S., MARENGO, J.A., ALVES, L.M., OSMAN, M., LI, S., WU, L., KARAMPERIDOU, C., TAKAHASHI, K. and VERA, C., 2020. Climate impacts of the El Niño–southern oscillation on South America. *Nature Reviews Earth & Environment*, vol. 1, no. 4, pp. 215-231. http://doi.org/10.1038/s43017-020-0040-3.

CARVALHO, P.E.R., 2006. *Protium heptaphyllum* (Aubl.) March. – Almecegueira. In: P.E.R. CARVALHO, ed. *Espécies arbóreas brasileiras*. Brasília: Embrapa Informação Tecnológica, vol. 2, pp. 79-87.

CARVALHO, K.M.M.B., MELO, T.S., MELO, K.M. and SANTOS, F.A., 2017. Amyrins from *Protium heptaphyllum* reduce high-fat diet-induced obesity in mice via modulation of enzymatic, hormonal and inflammatory responses. *Planta Medica*, vol. 83, no. 3-04, pp. 285-291. http://doi.org/10.1055/s-0042-114222. PMid:27525508.

CASTUERA-OLIVEIRA, L., OLIVEIRA-FILHO, A.T. and EISENLOHR, P.V., 2020. Emerging hotspots of tree richness in Brazil. *Acta Botanica Brasílica*, vol. 34, no. 1, pp. 117-134. http://doi.org/10.1590/0102-33062019abb0152.

COSTA, T.L.N., LUCAS, F.M.F., SILVA, B.R.F., CHAGAS, K.P.T., FREIRE, A.S.M., UCELLA-FILHO, J.G.M., SANTANA, J.A.S. and COSTA, M.P., 2022. How do meteorological factors alter the phenology of a neotropical tree species? *Cerne*, vol. 28, e103098. http://doi.org/10.1590/01047760202228013098.

DALY, D.C., 2015 [viewed 19 June 2024]. *Burseraceae*. In: JARDIM BOTÂNICO DO RIO DE JANEIRO, ed. *Lista de Espécies da Flora do Brasil* [online]. Rio de Janeiro: JBRJ. Available from: http://floradobrasil2015.jbrj.govol.br/jabot/floradobrasil/FB6593

DALY, D.C., PERDIZ, R.O., FINE, P.V.A., DAMASCO, G., MARTÍNEZ-HABIBE, M.C. and CALVILLO-CANADELL, L., 2022. A review of Neotropical Burseraceae. *Brazilian Journal of Botany*, vol. 45, no. 1, pp. 103-137. http://doi.org/10.1007/s40415-021-00765-1.

DEL VALLE, J.C., BUIDE, M.L., WHITTALL, J.B., VALLADARES, F. and NARBONA, E., 2020. UV radiation increases phenolic compound protection but decreases reproduction in *Silene littorea. PLoS One*, vol. 15, no. 6, e0231611. http://doi.org/10.1371/journal.pone.0231611. PMid:32555603.

DIATTA, O., DIALLO, A.M., SANOGO, D., NIELSEN, L.R., RAEBILD, A., KJAER, E.D. and HANSEN, J.K., 2022. Variation in phenology of *Acacia senegal* (L.) Wild. in relation to origin and ploidy level: implications for climatic adaptationo. *Global Ecology and Conservation*, vol. 33, e01957. http://doi.org/10.1016/j.gecco.2021.e01957.

DIMMITO, M.P., STEFANUCCI, A., DELLA VALLE, A., SCIOLI, G., CICHELLI, A. and MOLLICA, A., 2021. An overview on plants cannabinoids endorsed with cardiovascular effects. *Biomedicine and Pharmacotherapy*, vol. 142, pp. 111963. http://doi.org/10.1016/j.biopha.2021.111963. PMid:34332376.

DOMENE, V.D., MATTOS, P.P. and SALIS, S.M., 2010. *Fenologia e crescimento de almécega no Pantanal da Nhecolândia.* Corumbá: Embrapa Pantanal.

EMPRESA DE PESQUISA AGROPECUÁRIA DO RIO GRANDE DO NORTE – EMPARN [online], 2021 [viewed 13 January 2021]. Available from: http://www.emparno.rno.govol.br/Index.aspp

ESPINOSA-LEAL, C.A., MORA-VASQUEZ, S., PUENTE-GARZA, C.A., ALVAREZ-SOSA, D.S. and GARCÍA-LARA, S., 2022. Recent advances on the use of abiotic stress (water, UV radiation, atmospheric gases and temperature stress) for the enhanced production of secondary metabolites on in vitro plant tissue culture. *Plant Growth Regulation*, vol. 97, no. 1, pp. 1-20. http://doi.org/10.1007/s10725-022-00810-3.

ETTINGER, A.K., CHAMBERLAIN, C.J. and WOLKOVICH, E.M., 2022. The increasing relevance of phenology to conservationo. *Nature Climate Change*, vol. 12, no. 4, pp. 305-307. http://doi.org/10.1038/s41558-022-01330-8.

FOURNIER, L.A., 1974. Un método cuantitativo para la medición de características fenológicas em árboles. *Turrialba*, vol. 24, no. 4, pp. 422-423.

FREIRE, A.S.M., FAJARDO, C.G., CHAGAS, K.P.T., PINHEIRO, L.G., LUCAS, F.M.F. and VIEIRA, F.A., 2019. Genetic diversity in forest populations from conservation units in the Atlantic Rainforest in northeast Brazil. *Agrária*, vol. 14, no. 1, pp. 1-7. http://doi.org/10.5039/agraria.v14i2a5640.

FREIRE, A.S.M., CHAGAS, K.P.T., LUCAS, F.M.F., MEIRELES, A.C. and VIEIRA, F.A., 2022. Changes in phenological patterns of a tropical Atlantic Forest tree: implications for conservationo. *Bosque*, vol. 43, no. 3, pp. 267-275. http://doi.org/10.4067/S0717-92002022000300267.

GOMES, A.C., ANDRADE, F.H.D., LACERDA, A.V. and MACEDO, R.O., 2021. Reproductive phenology in the standardization of tannins in plant drugs of specimens of *Sideroxylon obtusifolium* (Roem. & Schult.) TD Penno. *Revista Brasileira de Botanica. Brazilian Journal of Botany*, vol. 44, no. 3, pp. 561-573. http://doi.org/10.1007/s40415-021-00726-8.

INOUYE, D.W., 2022. Climate change and phenology. *Wiley Interdisciplinary Reviews: Climate Change*, vol. 13, no. 3, e764. http://doi.org/10.1002/wcc.764.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA – IBGE, 2012. *Manual técnico da vegetação brasileira.* 2. ed. Rio de Janeiro: IBGE.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE – IPCC, 2013. *Fifth Assessment Report (AR5).* Cambridge: Cambridge University Press, pp. 10-12.

KAEWTHONGRACH, R., CHIDTHAISONG, A., CHARUCHITTIPAN, D., VITASSE, Y., SANWANGSRI, M., VARNAKOVIDA, P., DILOKSUMPUN, S., PANUTHAI, S., PAKOKTOM, T., SUEPA, T. and LECLERC, M.Y., 2020. Impacts of a strong El Niño event on leaf phenology and carbon dioxide exchange in a secondary dry dipterocarp forest. *Agricultural and Forest Meteorology*, vol. 287, no. 1, pp. 1-11. http://doi.org/10.1016/j.agrformet.2020.107945.

KOVACH COMPUTING SERVICES, 2020 [viewed 6 March 2025]. *Oriana (version 4.02)* [online]. Available from: https://www.kovcomp.co.uk/oriana/index.html

LINDBERG, K., MARTVALL, A., LIMA, M.G.B. and FRANCA, C.S.S., 2023. Herbal medicine promotion for a restorative bioeconomy in tropical forests: a reality check on the Brazilian Amazono. *Forest Policy and Economics*, vol. 155, pp. 103058. http://doi.org/10.1016/j.forpol.2023.103058.

MACEDO, T.M., COSTA, W.S., BRANDES, A.F.N., VALLADARES, F. and BARROS, C.F., 2021. Diversity of growth responses to recent droughts reveals the capacity of Atlantic Forest trees to cope well with current climatic variability. *Forest Ecology and Management*, vol. 480, no. 1, pp. 118656. http://doi.org/10.1016/j.foreco.2020.118656.

MARTINELLI, G. and MORAES, M.A., 2013. *Livro vermelho da flora do Brasil.* 1. ed. Rio de Janeiro: Instituto de Pesquisas Jardim Botânico do Rio de Janeiro.

MENON, D., BEHERA, D. and AYYAPPAN, N., 2025. Phenological trends and associated climate drivers of a tree community in lowland dipterocarp forest, Western Ghats, India. *International Journal of Biometeorology*, vol. 69, no. 1, pp. 177-193. http://doi.org/10.1007/s00484-024-02802-6. PMid:39432080.

MIR, A.Y., YAQOOB, U., HASSAN, M., BASHIR, F., ZANIT, S.B., HAQ, S.M. and BUSSMANN, R.W., 2021. Ethnopharmacology and phenology of high-altitude medicinal plants in Kashmir, Northern Himalaya. *Ethnobotany Research and Applications*, vol. 22, pp. 1-15. http://doi.org/10.32859/era.22.17.1-15.

MYERS, N., MITTERMEIER, R.A., MITTERMEIER, C.G., FONSECA, G.A.B. and KENT, J., 2000. Biodiversity hotspots for conservation priorities. *Nature*, vol. 403, no. 6772, pp. 853-858. http://doi.org/10.1038/35002501. PMid:10706275.

PEREIRA, H.R., REBOITA, M.S. and AMBRIZZI, T., 2017. Characteristics of the atmosphere in the austral spring during the El Niño 2015/2016. *Revista Brasileira de Meteorologia*, vol. 32, no. 1, pp. 293-310. http://doi.org/10.1590/0102-77863220011.

PÉREZ-RAMOS, I.M., CAMBROLLÉ, J., HIDALGO-GALVEZ, M.D., MATÍAS, L., MONTERO-RAMÍREZ, A., SANTOLAYA, S. and GODOY, Ó., 2020. Phenological responses to climate change in communities of plants species with contrasting functional strategies. *Environmental and Experimental Botany*, vol. 170, pp. 103852. http://doi.org/10.1016/j.envexpbot.2019.103852.

PONTI, R. and SANNOLO, M., 2023. The importance of including phenology when modelling species ecological niche. *Ecography*, vol. 2023, no. 4, e06143. http://doi.org/10.1111/ecog.06143.

RAI, P.K. and SINGH, J.S., 2020. Invasive alien plant species: their impact on environment, ecosystem services and human health. *Ecological Indicators*, vol. 111, pp. 106020. http://doi.org/10.1016/j.ecolind.2019.106020. PMid:32372880.

ROCHA, É.C., OLIVEIRA, L.M., FANTINEL, V.S., DIAS, R.A.R. and BAGATINI, K.P., 2020. Phenological analysis of *Gymnanthes klotzschiana* Müll. Arg belonging to two atlantic forest biome formations. *Floresta e Ambiente*, vol. 27, no. 3, e20170922. http://doi.org/10.1590/2179-8087.092217.

RODRIGUES, M.I.A., SANTOS, E.M.G., NICOLAI, J. and RODRIGUES, T.M., 2024. Leaf traits and herbivory in a resin-producing plant species growing in floodable and non-floodable areas of the pre-Amazonian white-sand forest. *Rodriguésia*, vol. 75, e01382023. http://doi.org/10.1590/2175-7860202475010.

SANTOS, A.E.D., FAJARDO, C.G., SOUSA, V.R.B. and VIEIRA, F.A., 2024. Exploring the therapeutic potential of *Amburana cearensis*: a scientometric study on an endangered medicinal tree. *International Journal of Forestry Research*, vol. 2024, no. 1, pp. 1699607. http://doi.org/10.1155/2024/1699607.

SILVA, P.D., LEAL, I.R., WIRTH, R. and TABARELLI, M., 2007. Harvesting of *Protium heptaphyllum* (Aubl.) March. seeds (Burseraceae) by the leaf-cutting ant *Atta sexdens* L. promotes seed aggregation and seedling mortality. *Revista Brasileira de Botânica*, vol. 30, no. 1, pp. 553-560. http://doi.org/10.1590/S0100-84042007000300019.

SILVA, D.A., PFIFER, M., PATTISON, Z. and VIBRANS, A.C., 2020. Drivers of leaf area index variation in Brazilian Subtropical Atlantic Forests. *Forest Ecology and Management*, vol. 476, pp. 118477. http://doi.org/10.1016/j.foreco.2020.118477.

SIMÃO, C.H., ALVES, F.M., BARROS, A., SIMÃO, P.M., POTT, A. and AOKI, C., 2021. Reproductive phenology of aquatic macrophytes in the Cerrado-Pantanal ecotone. *Acta Botanica Brasílica*, vol. 35, no. 1, pp. 92-103. http://doi.org/10.1590/0102-33062020abb0364.

SINGH, H., BHUSHAN, S., ARORA, R., BUTTAR, H.S., ARORA, S. and SINGH, B., 2017. Alternative treatment strategies for neuropathic pain: role of Indian medicinal plants and compounds of plant origin: a review. *Biomedicine and Pharmacotherapy*, vol. 92, no. 1, pp. 634-650. http://doi.org/10.1016/j.biopha.2017.05.079. PMid:28578258.

SIQUEIRA-LIMA, P.S., SILVA, J.C., QUINTANS, J.S.S. and QUINTANS-JÚNIOR, L., 2017. Natural products assessed in animal models for orofacial pain: a systematic review. *Brazilian Journal of Pharmacognosy*, vol. 27, no. 1, pp. 124-134. http://doi.org/10.1016/j.bjp.2016.06.005.

SOUZA, R.R., PIMENTEL, A.D.A., NOGUEIRA, L.L., ABREU, V.H.R. and NOVAIS, J.S., 2020. Resources collected by two *Melipona* Illiger, 1806 (Apidae: Meliponini) species based on pollen spectrum of honeys from the amazon basino. *Sociobiology*, vol. 67, no. 1, pp. 268-280. http://doi.org/10.13102/sociobiology.v67i2.4617.

TAK, Y. and KUMAR, M., 2020. Phenolics: a key defence secondary metabolite to counter biotic stress. *Plant Phenolics in Sustainable Agriculture*, vol. 1, pp. 309-329. http://doi.org/10.1007/978-981-15-4890-1_13.

WILSON, O.J., MAYLE, F.E., WALTERS, R.J., LINGNER, D.V. and VIBRANS, A.C., 2021. Floristic change in Brazil's Southern Atlantic forest biodiversity hotspot: from the last glacial maximum to the late 21st century. *Quaternary Science Reviews*, vol. 264, pp. 107005. http://doi.org/10.1016/j.quascirev.2021.107005.

ZHANG, X., CI, X., HU, J., BAI, Y., THORNHILL, A.H., CONRAN, J.G. and LI, J., 2023. Riparian areas as a conservation priority under climate change. *The Science of the Total Environment*, vol. 858, no. Pt 2, pp. 159879. http://doi.org/10.1016/j.scitotenv.2022.159879. PMid:36334670.