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Reproductive phenology of *Passiflora cincinnata* Mast. in the semi-arid region of Bahia State, Brazil, based on herbarium data and IDW interpolation

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ABSTRACT – (Reproductive phenology of *Passiflora cincinnata* Mast. in the semi-arid region of Bahia State, Brazil, based on herbarium data and IDW interpolation). We investigated intensity and seasonality of the reproductive phenology of *Passiflora cincinnata* Mast. and estimated its flowering and fruiting periods by interpolation using Inverse Distance Weighting, for the first time in phenology, based on herbarium collections from Bahia State, Northeastern Brazil. Data from 249 exsiccates with flowers and/or fruits were analyzed to estimate the amplitude of flowering and fruiting and test the seasonality using the circular statistics. *Passiflora cincinnata* flowering and fruiting was greatest from October to May. The maps generated by interpolation showed greatest probability of flowering and fruiting between March and May in sites with mean annual rainfall rates between 500 and 1000 mm. Our results indicated seasonality of flowering and fruiting, with reduced intensities during the austral winter. The interpolation methodology can be used in a complementary or preliminary way, either to organize field visits and set up experiments, or to extrapolate field results for larger-scale views.
Keywords: Caatinga passion fruit, geoprocessing, seasonality

RESUMO – (Fenologia reprodutiva de *Passiflora cincinnata* Mast. na região semiárida do Estado da Bahia, Brasil, com base em dados de herbário e interpolação pelo inverso da distância – IDW). Nós investigamos intensidade e sazonalidade da fenologia reprodutiva de *Passiflora cincinnata* Mast. e estimamos seus períodos de floração e frutificação por interpolação usando a Ponderação Inversa da Distância, apresentada pela primeira vez em fenologia, com base em coleções de herbários do Estado da Bahia. Dados de 249 exsicatas com flores e/ou frutos foram analisados para estimar amplitude de floração e frutificação e testar sazonalidade usando estatística circular. A floração e frutificação de *P. cincinnata* foram maiores de outubro a maio. Os mapas gerados por interpolação mostraram maior probabilidade de floração e frutificação entre março e maio em locais com índices pluviométricos médios anuais entre 500 e 1000 mm. Nossos resultados indicaram sazonalidade de floração e frutificação, com intensidades reduzidas durante o inverno austral. A metodologia de interpolação pode ser utilizada de forma complementar ou preliminar, seja para organizar visitas a campo e montar experimentos, seja para extrapolar resultados de campo para visualizações em maior escala.
Palavras-chave: geoprocessamento, maracujá da Caatinga, sazonalidade

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Introduction

Phenology refers to the timings of cyclical or seasonal biological events, such as migration, egg laying, flowering, and hibernation (Warren et al. 2021). As an integrative science, plant phenology investigates the timing of cyclical biological events and their implications for agronomy and silviculture and the maintenance of ecosystem services (Morellato et al. 2016, Williams-Linera & Meave 2002). Phenology not only has cascading effects on the fitness of individual plants, but also on the fitness of organisms that depend on them, in multiple levels of biological organization, from individuals to ecosystems (Stucky et al. 2018).

The domain of reproductive phenology is the starting point for all plant management actions, and knowledge of the phenological patterns of species of interest must be part of any field activity planning (Morellato et al. 2010). That information can be obtained in several ways, including by consulting herbarium material, periodically monitoring populations (either on-site or remotely), or accessing traditional knowledge (Abernethy et al. 2018). Herbaria are widely recognized and valued as reliable sources of information for studies evaluating plant phenological behaviors (Ellwood et al. 2019, Banaszak et al. 2020, Lima et al. 2021, Orellana et al. 2021, Silva 2021).

Herbarium records can have all the necessary information for phenological studies if it follows the premise that an exsiccate is only fully valid as a taxonomic instrument if it contains reproductive structures (flowers and fruits) as well as the date and geographic coordinates of the collection site (Lima et al. 2021). Thus, the distribution of the numbers of exsiccates available in herbaria for each month of the year reflects the success with which the species was found in different reproductive phases during field expeditions. With that information in hand, it is also possible to estimate the reproductive seasons of plant species in places where there is no field information available through mathematical modeling – using as the input data the phenology of known populations and environmental data from the region of interest (Abernethy et al. 2018).

Spatial interpolation is a procedure for estimating property values from non-sampled locations based on data values observed at known locations (Burrough 1986). Here, we present the possibility of using geospatial interpolation to estimate reproductive phenology by expanding on local field data using information from herbarium collections. The values measured at sampling points allow estimating those variables in places of interest that have not been sampled, using mathematical functions in which the independent variables are the neighboring samples (Xavier et al. 2010). Among the most used methods for interpolating spatial data are kriging, nearest neighbor, trend surface analysis, triangulation, and Inverse Distance Weighting – IDW (Li and Heap 2014).

Inverse Distance Weighting assumes that the value at an unsampled point can be approximated as the weighted average of values at points within a certain cut-off distance (Mitas & Mitasova 1999). The IDW system can be characterized as a smoothing and accurate interpolator, of the global type, that is reasonably faithful to the sampled data, with a fast-processing speed (QGIS.org 2021). IDW is a rapid method and has low operational costs without the need for post-processing with other tools and has proven to be useful in many agricultural applications, as well as for social and environmental themes (Amaral & Justina 2019, Maldaner & Molin 2020).

Passiflora cincinnata Mast. (Passifloraceae), our target species, also known as wild passion fruit or Caatinga passion fruit, is distributed in the Amazon, Caatinga, Cerrado, and Atlantic Forest domains (Bernacci et al. 2020). The plant is a vigorous vine, with grooved stems, 3-5 lobed palmate leaves, flowers purple 10 cm. wide and fruit with greenish rind and white to light yellow acidic pulp (Barbosa Santos et al. 2021). The first commercial cultivar (BRS Sertão Forte) was launched by the Brazilian Agricultural Research Corporation – Embrapa in 2016 after extensive research (Araújo et al. 2019). Virtual herbaria data (39 herbaria) show a major concentration of the species in eastern Brazil, with 49% of the 800 records (with available images) occurring in Bahia State (speciesLink 2023).

Despite its wide distribution, most studies on this species have been concentrated in northeastern Brazil, of which only a few have explored its reproductive phenology (Kiill et al. 2010, Bernardes et al. 2020). These authors studied different management techniques for *P. cincinnata* and observed that it showed constant flowering and fruiting throughout the year, although with reductions in the percentages of those phenophases in January and February, independent of the management regime (conventional or organic). Other *Passiflora* species likewise exhibit continuous flowering and fruiting, while *P. actinia* Hook., *P. bahiensis* Klotzsch, *P. malacophylla* Mast., and *P. nitida* Kunth show marked seasonalities (Esashika et al. 2018). The need for further studies of the reproductive phenologies of *Passiflora* species in the context of the semiarid region is therefore clear, especially for those with considerable agronomic potential, such as *P. cincinnata* (Dutra et al. 2019, D'Abadia et al. 2021, Rinaldi et al. 2022).

We investigated here the intensity and seasonality of the reproductive phenology of *Passiflora cincinnata* Mast. based on herbarium data for Bahia State. We also estimated flowering and fruiting seasons in areas without collected samples through interpolation by Inverse Distance Weighting. We expect our results will permit an extension of the phenological information obtained in the field to a larger scale and provide useful information for future field research planning.

Materials and Methods

Information concerning *Passiflora cincinnata* Mast. flowering and fruiting were gathered from speciesLink database (available at http://www.splink.org.br/). Data derived from exsiccates collected in Bahia State and available from the virtual collections of Brazilian and international herbaria. We identified 492 exsiccates, distributed among 26 different herbaria. We initially discarded exsiccates that did not have a collection date or a georeferenced collection point, and then samples without any visible (or recorded) reproductive phenophases; 249 samples from 14 herbaria (ALCB, ASE, CEN, ESA, FURB, HUEFS, HURB, MCCA, NYBG, RECOLNAT MNHN P, UEC, UPCB, US, VIC. Acronyms following the Index Herbariorum), collected in 45 different years remained after that filtering. The next step classified the samples into two groups: one designated as “flower” (containing samples with flowers or buds) and the other designated as “fruit” (containing the samples with immature or ripe fruits); the same voucher could appear in both groups if it displayed both phenophases. This cluster produced 223 and 110 samples in the “flower” and “fruit” groups respectively (Supplementary material, Table 2). Thus, of the 249 samples, 139 had only flowering information, 26 had only fruiting information, and 84 had both information.

We imported and converted the group data to a vector file (shapefile) in *QGIS 3.22 Bialowieza* software, and performed the interpolation using the *qgis:idwinterpolation* algorithm, based on the months of occurrence of the phenophases, resulting in a raster file. The P coefficient, an attribute that determines the power to which the distance between the points is raised, was kept standard, with a value of 2 (square of the distance) and, after processing, we applied a simple false-color band. Finally, resampling was carried out using the bilinear method to remove the knurled effect from the image and generate a map with smooth gradients between the values.

Flowering and fruiting amplitudes were qualitatively estimated by the number of specimens (249 vouchers) with flowers and fruits (Newstrom et al. 1994) and expressed as a linear graph. We examined the seasonality of herbarium phenological data using circular statistics (Morellato et al. 2010) using the R environment, with the addition of the *circular* package 3.2.3 (R Core Team, 2022). The frequency of each phenophase was calculated based on the total number of vouchers showing each phase per month. Months were converted into angles at 30° intervals. The mean angles and r vector lengths were calculated. Angle significance was tested using the Rayleigh test (z) for circular distributions (Zar 2010). The phenological events with significant mean angles ($p < 0.05$) were transformed into mean dates (Supplementary material, script 1). Phenophases whose vector lengths (r) were > 0.5, and which the Rayleigh tests indicated as significant, were considered seasonal (Morellato et al. 2010).

Results

The results confirmed our hypothesis that herbarium data would be useful for estimating phenophase amplitudes and seasonality and for extending local phenological information obtained in the field to larger scales through Inverse Distance Weighting. The analysis of the herbarium data showed that *Passiflora cincinnata* Mast. can be found in its reproductive mode throughout the year, as many *Passiflora* species, although with evident periods of greater flowering and fruiting activities from October to May (figures 1, 2). Although *P. cincinnata* flowered and fruited throughout the year, reproductive peaks showed significant seasonal patterns, with the highest mean peaks in February and March respectively (figure 1; table 1). The IDW interpolation processing showed that there is a high probability of encountering *P. cincinnata* blooming and fruiting between March and July in Bahia State (figure 3).

Table 1. Results of the circular statistical analyses of the occurrences of seasonal flowering and fruiting peaks for *Passiflora cincinnata* Mast. based on herbarium collections for Bahia State, in northeastern Brazil.

Phenophases	Observations (N)	Mean date	Mean angle	Length of the mean vector (r)	Angular standard deviation	Rayleigh test (p)
Flowering peak	223	05 feb.	35.76	0.40	77.88	< 0.01
Fruiting peak	110	03 mar.	62.89	0.33	85.10	< 0.01

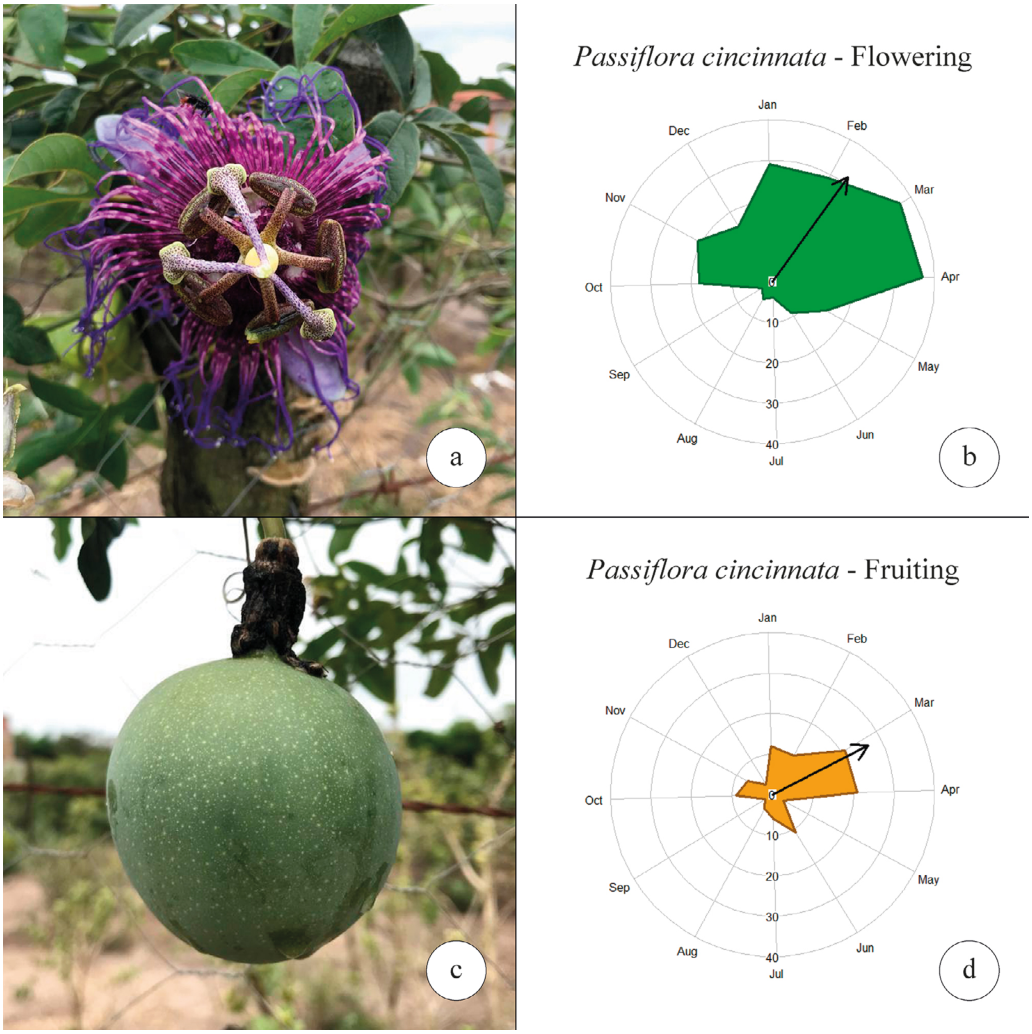

Figure 1. *Passiflora cincinnata* Mast. reproductive phenology in Bahia State, northeastern Brazil, based on herbarium collections. a. flower. b. flowering circular histograms based on the record monthly frequency. c. fruit. d. fruiting circular histograms based on the record monthly frequency. Black arrows: observed mean angle (mean phenophase date). For analysis details, see Table 1.

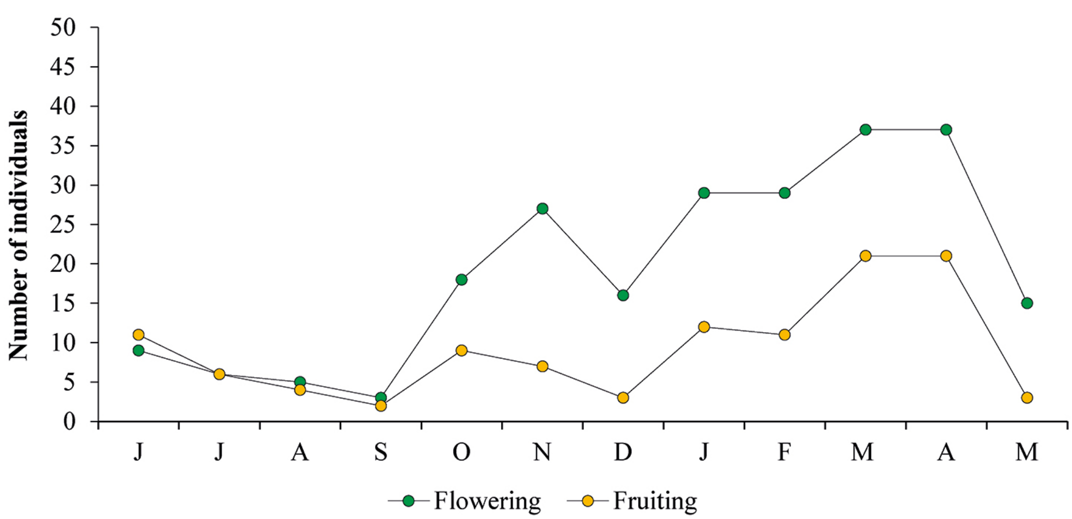

Figure 2. Amplitude of flowering (green dots) and fruiting (yellow dots) of *Passiflora cincinnata* Mast. based on data of 249 herbarium specimens available online.

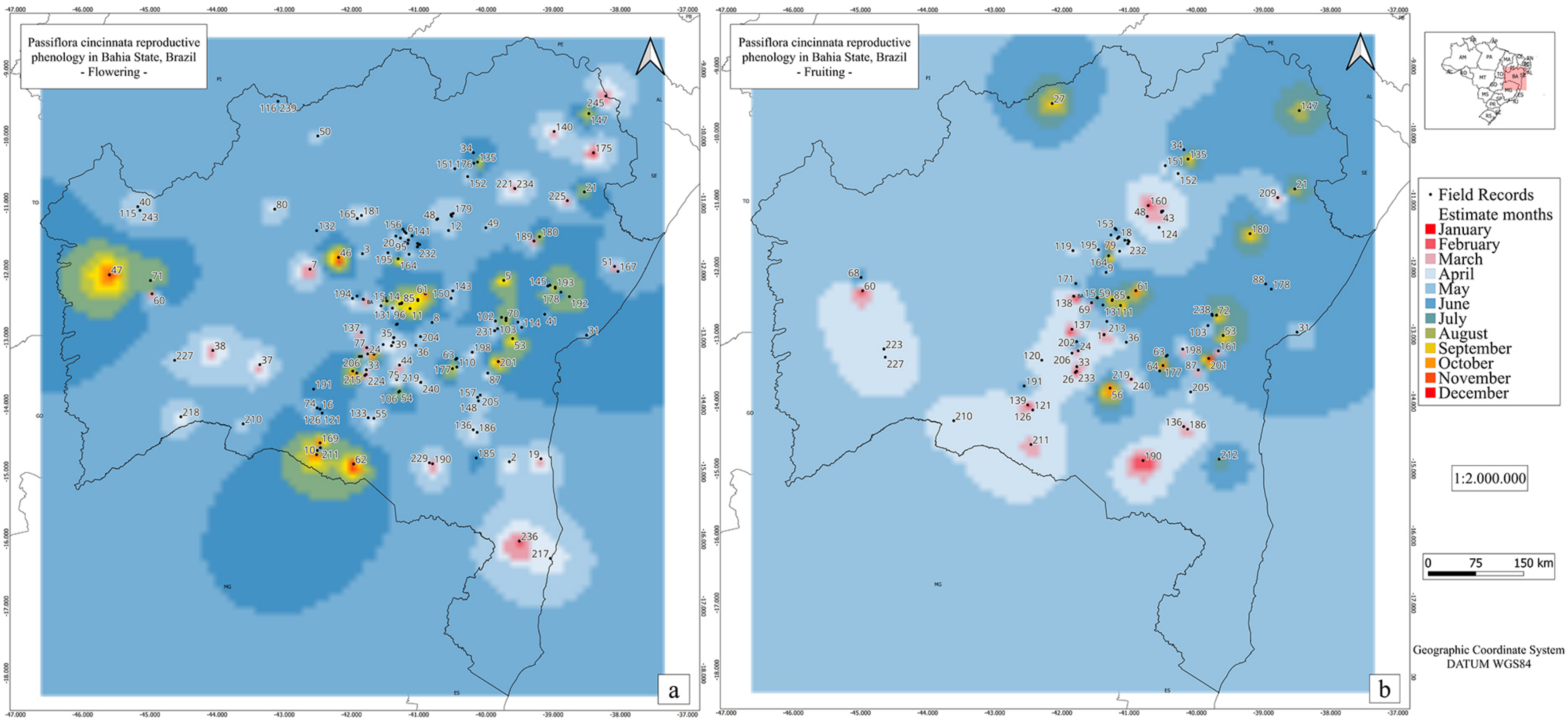

Figure 3. Probable *Passiflora cincinnata* Mast. flowering (a) and fruiting (b) months according to IDW interpolation. Colors indicate the best months for field trips. Black dots and numbers represent herbarium records (see Supplementary available at 10.6084/m9.figshare.23969931).

Discussion

Plant reproductive phenophases in seasonal tropical ecosystems are modulated by variations in abiotic factors (Orellana et al. 2021) and their flowering peaks usually occur at the end of the dry season or at the beginning of the rainy season reflecting adjustments (especially) to water availability (Neves et al. 2017). Esashika et al. (2018) showed that most *Passiflora* species produce flowers and fruits throughout the year, although some species are more seasonal and have shorter flowering cycles (e.g., *P. actinia*, *P. bahiensis,* and *P. nitida*), while Bernardes et al. (2020) analyzed the phenological traits of *Passiflora* and observed that *Passiflora cincinnata* Mast. had a long flowering period starting in October and extending to June, with its fruiting period from February to June. Silva et al. (2022) studied the phenology of *P. maliformis*, *P. cincinnata,* and *P. setacea*, and found that their flowering occurred continuously throughout the year, although with reductions between June and August, coinciding with the austral winter period and diminishing day length. We likewise identified reductions in the flowering and fruiting intensities of *P. cincinnata* during the dry season in inland areas of Bahia State (from June to October), thus expanding the field information published by Silva et al. (2022). Our study evidenced the same patterns for both phenological parameters, confirming that the examination of herbarium specimens of *P. cincinnata* is useful for determining its reproductive phenological cycles in the field, following the same techniques used by Ramirez-Parada et al. (2022), Williams et al. (2021) and Orellana et al. (2021).

Park et al. (2022) and Davis et al. (2022) examined the phenologies of several neotropical species through studies of herbarium collections and found congruence between herbarium records and field observations, similar to those reported for temperate biomes and, thus should be considered a consistent tool for accessing tropical phenology and responses to seasonal cues and climate change. Willis et al (2017) presented a full discussion concerning recent advances in the use of herbarium specimens for accessing plant phenology and how the development of new technologies that integrate different approaches and data sources would expand its relevance for research on plant taxonomy and geographic distribution, climate change responses, plant interaction synchrony and local species extinctions. Examples of innovative tools include the establishment of a standardized terminology (Plant Phenology Ontology – PPO) that allows data integration and processing on a global scale and the application of Machine Learning (ML) for automated phenological character detection of herbarium specimens (Stucky et al. 2018, Pearson et al. 2020). In this regard, geoprocessing techniques represent a relevant addition to this growing tool set, as in addition to essential locational information, data can be transmitted through powerful visual charts.

Based on a reliable dataset from herbarium specimens, the hypothesis of this study, that the IDW interpolation would be useful for inferring plant phenological statuses where samples were not collected, could be confirmed. The raster processing extended the probable flowering and fruiting timings to all of Bahia State, with colors tending to point to the best month for field surveys to collect reproductive botanic material (figure 3). The light blue hues covering most of the maps suggest that *P. cincinnata* can be found blooming or fruiting with greater probability between March and May, in accordance with related studies. It is necessary to point out that a robust set of records is desired for reasonable processing results. The accordance between our results and available bibliography shows that for *P. cincinnata* in Bahia, the collection was satisfactory.

Despite the new technologies mentioned above, field exploration and herbarium specimens are still compose the basic structure of botanic research as these perennial collections of dried plants are a keystone element for plant taxonomy and its development and the lack of resources devoted to activities represent a limiting factor to the expansion of the understanding of the tropical flora (Roughan & Gaudeul 2013). Prance et al. (2000) and Schatz (2002) discussed how the tropical floras continues largely understudied, with most species known by less than ten exsiccates and hundreds still only known only by their type collection. Accordingly, Lagomarsino & Frost (2020) observed that to fill these extensive gaps, continued systematic and replicable collection of fertile specimens must proceed and thus, demand permanent funding.

The IDW interpolation methodology was found to be extremely useful as it allows a spatial visualization of plant phenology based on herbarium records and provides indications of when to search for reproductive plants where they have not yet been collected. This analysis could be particularly useful for searches for under-collected plants or for expeditions into hard to access areas, thus optimizing neotropical plant taxonomy efforts in under-surveyed sites, especially when resources are limited. The Inverse Distance Weighting interpolation method can become a prior analysis tool in plant phenology and taxonomy research, supporting field activities scheduling, providing comparative basis for field observation data, and allowing more efficient uses of funding resources.

Conclusions

The results of the analysis of the herbarium collections indicated a tendency towards seasonality of flowering by *Passiflora cincinnata* Mast., although that behavior was not found to be as pronounced for fruiting. Although flower and fruit production are maintained throughout the year, the flowering and fruiting activities of *P. cincinnata* are not constant, for there is an evident reduction in flowering during June, July and August (the austral winter period).

The use of herbarium data for IDW interpolation proved to be very useful for extrapolating the reproductive phenology of the species, as it accurately reflected field studies. This methodology can therefore be used in complementary or preliminary steps to organize field visits, set up experiments, or to extrapolate the results obtained in local research to wider or regional scales.

Supplementary material

Supplementary data for this article include metadata for the *Passiflora cincinnata* Mast. herbaria specimens used in the IDW interpolation and the R script for penology circular statistics are available at 10.6084/m9.figshare.23969931

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Declaration of Conflict of Interests

The authors declare no conflict of interest.

Credit Authorship Contribution Statement

Luiz Victor de Almeida Dantas: methodology, visualization, writing, original draft preparation, formal analysis, data curation.

Vitor Alberto de Matos Pereira: methodology, visualization, writing, original draft preparation, formal analysis, data curation.

Isiara Silva Menezes: data curation, formal analysis, writing, review, image edition.

Lia d'Afonsêca Pedreira de Miranda: writing, review.

Ligia Silveira Funch: Conceptualization, review and editing, supervision.

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