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Characterization of the geographic distribution, reproductive phenology and fruits of *Stenocereus martinezii*: a threatened columnar cactus

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Abstract. *Stenocereus martinezii* (JG Ortega) Buxb. is a columnar cactus that produces fruits with commercial relevance (pitayas) and is classified as an Endangered (En) species on the IUCN Red List. It is currently considered endemic to the state of Sinaloa, Mexico; however, it could have a wider geographic distribution that has not been detected due to low collection efforts. It is also one of the least known Stenocereus species in terms of its biology, ecology, ethnobotany and nutritional composition. The objective of this work was to update the geographic distribution of *S. martinezii*, locate sites where it is used commercially, describe its reproductive phenology, and describe the physical and chemical composition of its fruits. For its distribution, field explorations were carried out in areas of western Durango and eastern Sinaloa from 2013 through 2024 and a database was built and compared to previous reports in biological collections. Phenology was monitored in three localities in 2017 and fruit composition was quantified from fruits collected in the Arroyo Grande community. The newly detected distribution area of *S. martinezii* was considerably larger than previously reported from literature and scientific collections, and this is the first report of this species in the state of Durango. At the edge of its range, *S. martinezii* is displaced by the other two commercially important pitaya cactus species in Sinaloa: *Stenocereus montanus* in the east and *Stenocerus thurberi* in the west. Reproductive phenology was unimodal, and productivity was higher in populations where fruits are harvested. Its reproductive stage occurs later than more southern species and earlier than more northern species, making it a food bridge for migratory bird and bat species. *S. martinezii* fruits are smaller but with a similar chemical composition with other fruits of this genera with commercial value.

Keywords: *Endangered species, reproductive phenology, Stenecereus*

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Introduction

The genus *Stenocereus* (A. Berger) Riccob includes about 23 species of columnar, arborescent, shrub, or prostrate cacti distributed from the southern United States through northern South America (Alvarado-Sizzo *et al*., 2018; POWO, 2024). They are mainly found in arid and semi-arid environments of the dry tropics, such as xerophilous scrubland, thorn forest and low deciduous forest (Arreola-Nava and Terrazas, 2003).

Mexico is the main center of diversity of *Stenocereus*, containing 21 species, 18 of which are endemic of Mexico (Arreola-Nava and Terrazas, 2003; Alvarado-Sizzo *et al*., 2018). The Stenocereus genus is one of the 40 genera considered as a natural and cultural heritage due to its distribution, endemicity, nutritional and commercial value of its fruits, known as pitayas (Pimienta-Barrios and Nobel, 1994; Quiroz-González *et al*., 2018; Rzedowski, 2019).

The pitayas (*Stenocereus* spp. fruits) are one of the most consumed fruits of the Cactaceae family. They are produced during the driest season of the year, when there is a marked scarcity of resources. The pitaya harvest is an important economic activity regionally, and pitayas are the main food source for many native species of insects, birds and bats (Silvius, 1995; Flemming *et al*., 1996). They are generally sold directly on the roads near the places where they are collected or in nearby towns and cities. Although many *Stenocereus* species are cultivated and are in the process of domestication (Parra *et al*., 2010) most of the fruits are harvested from wild populations. Although most *Stenocereus* species produce edible fruits, only half of them are used commercially (species known as "*pitayeras"*). The non-commercial species produce fruits that are too few or too small to be commercially profitable. The pitaya fruits are a source of vitamin C, antioxidants phenolic compounds (*e.g.* quercetin, rutin and hydroxycinnamoyl derivatives), fiber, simple sugars and soluble pigments (betalains) (García-Cruz *et al.*, 2017); they are considered a considerable source of nutrients and phytochemicals to sustain health and have potential industrial applications as in the production of dyes.

In northwestern Mexico there are nine *Stenocereus* species, *S. alamosensis* (J.M. Coult.) A.C. Gibson and K.E. Horak, *S. eruca* (Brandegee) A.C. Gibson and K.E. Horak, *S. gummosus* (Engelm.) A.C. Gibson & K.E. Horak, *S. kerberi* (K. Schum.) A.C. Gibson and K.E. Horak, *S. martinezii* (J.G. Ortega) Buxb., *S. montanus* (Britton and Rose) Buxb., *S. standleyi* (J.G. Ortega) Buxb., *S. thurberi* (Engelm.) Buxb. and *S. quevedonis* (J.G. Ortega) Buxb.). From this species, four are used commercially, *S. gummosus* (Baja California Sur), *S. martinezii* (Sinaloa), *S. montanus* (Sinaloa and Sonora) and *S. thurberi* (Baja California Sur, Sinaloa and Sonora) (Pío-León *et al*., 2017; Coronado-García *et al*., 2022; Salomón-Montijo *et al*., 2022).

Stenocereus martinezii (Figure 1) is listed by the NOM-059-SEMARNAT-2010 (SEMARNAT, 2019) standards as subject to Special Protection (Pr) and is recognized as Endangered (En) on the IUCN Red List due to its distribution and anthropogenic pressures from cattle grazing and agriculture (Terrazas *et al*., 2013). *Stenocereus martinezii* is one of the most important species in terms of bio-cultural and economic relevance and is a priority species for conservation of the tropical dry forest of northwest Mexico (Cué-Bar *et al*., 2006; Pío-León *et al*., 2023). *Stenocereus martinezii* fruits are harvested between spring and summer and are the main economic income for local communities during these seasons. Despite its described relevance, this species has been the least studied in the genus in terms of geographic distribution, ecology, phenology, uses, and fruit nutritional composition. Currently, it is considered endemic in Sinaloa, where it is found in the central region of the State. However, there has been limited collection effort (DRGU, 2024; Enciclovida, 2024) and its geographic distribution is suspected to be larger. This is evidenced by a large number of photographic records on the iNaturalist platform (2024) (over 1400 until October 2024). Unfortunately, since it is a protected species, the geolocation from iNaturalist records is hidden and it is not feasible to precisely determine the limits of its geographic distribution from these data.

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Figure 1. *Stenocereus martinezii*: (A and B) habit; (C) plant branches with immature fruits; (D) flower; (E) ripe fruit.

In this study, the area of the geographic distribution of *S*. *martinezii* was defined and compared it with previous records from scientific collections, document populations where its fruits are commercially harvested, estimate its reproductive phenological period, and carry out a physicochemical and nutritional description of its fruits.

Materials and Methods

Study Area

The State of Sinaloa is located in northwestern Mexico. Its orography is flat in the Coastal Plains, with increasing elevations heading east through the Sierra Foothills and finally, with notable elevation in the Sierra Madre Occidental (INEGI, 2021). The main types of vegetation are low deciduous forest

(50%, 27,568 km^2), thorn forest (29%, 15,612 km^2) and mixed pine and oak-pine forests (16%, 8681 km^2), in addition to aquatic and semi-aquatic vegetation on the shorelines (Figure 2) (Wiken *et al.*, 2011).

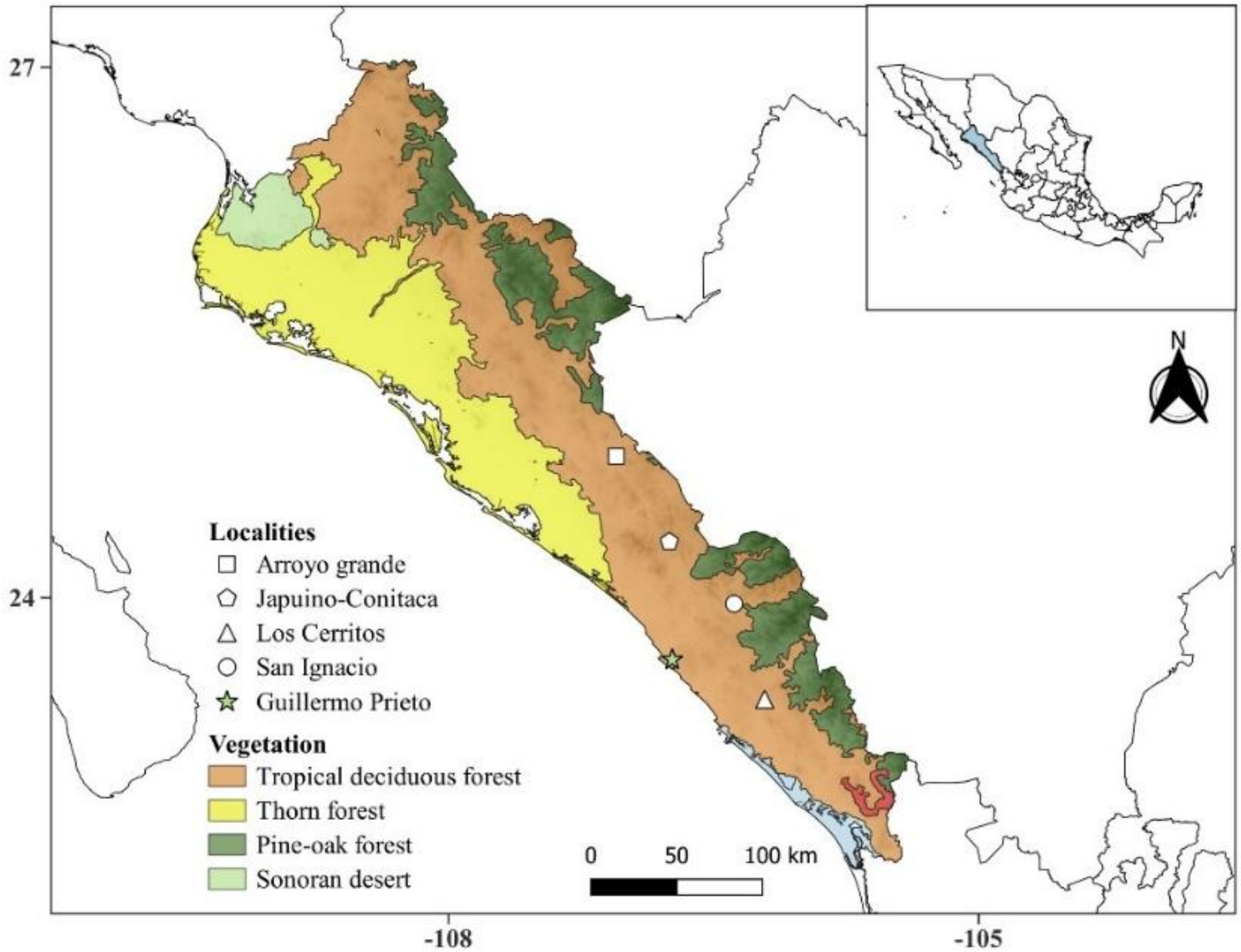

Figure 2. Main types of vegetation in Sinaloa, México, and localities where the fruits of *Stenocereus martinezii* are commercially harvested (except in Guillermo Prieto).

Stenocereus martinezii distribution

The geographic distribution of *S. martinezii* was defined through explorations to search for the species in Sinaloa and the adjacent State of Durango between 2013 and 2024. Simultaneously, while performing the explorations, the populations were documented where fruits are commercially harvested. The efficiency of the exploration was improved did interviewing local residents about the sites where fruits are harvested. Also, iNaturalist records were used to inform this search. Since *S. martinezii* is a protected species, iNaturalist does not provide exact geolocation points, but rather a randomly selects a point within a 10 km radius of the actual point of the record ("obscured" observations). Thus, we did not have access to the exact points of the records, but we did use the obscured record coordinates as starting points for searches in those areas. Each *S. martinezii* population detected was georeferenced. A data base was constructed with collected data as well as the available records from the National Herbarium MEXU (DGRU, 2024) and the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO) (Enciclovida, 2024).

Phenology

The reproductive phenology of *S. martinezii* was registered in three communities from February to August 2017. These included two communities where fruits are harvested commercially (Arroyo Grande and Japuino-Conitaca) and a third community (Guillermo Prieto) where fruits are harvested for self-consumption only (Figure 2) in order to detect differences that may be due to commercial harvest. Three reproductive stages were recorded following the Campbell scale, buds, flowers and fruits (Rondón, 1994). The bud stage was considered from the time buds were visible until pre-anthesis. The flower stage was defined when all flowers were partially or totally open. The fruits were counted from the incipient stage (dehydrated flowers after pollination on the plant) until dehiscence. In each site, 50 reproductive plants were chosen randomly, georeferenced and marked with aluminum tags. The stages were recorded every two weeks from the beginning of flowering until the end of the fruit stage. After August, records were taken monthly to record potential anomalous bud and/or flower production and detect the start of the following reproductive season.

Physico-chemical and proximate characterization of fruits

The variation in the weight, volume and number of seeds were analyzed in 390 fruits at commercial maturity during 2017, 2018 and 2019 (130 fruits per year) from the Arroyo Grande population. Ten fruits were collected weekly between May 15th and July 15th. The weight was recorded on a Mettler Toledo analytic balance (Switzerland). To estimate volume, the equatorial and polar diameters with a digital caliper (Truper, CALDI-6MP; 14388) was measured and calculated the volume using the spheroid equation:

$$V = \left(\frac{4}{3}\right)\pi a^2 b$$

where a = polar (major) diameter, b = equatorial (minor) diameter.

The seeds were separated from the pulp by agitating in water, after which the seeds were rinsed and filtered through a 1 mm^2 mesh. The floating seeds were considered vain or inviable and were discarded from the analysis. The number of seeds per fruit was extrapolated based on an aliquot of 100 seeds using the formula:

$$NS = \left(\frac{100 \times w100}{WS}\right)$$

Where NS = number of seeds, w100 = weight of 100 seeds, and WS = weight of total seeds. The pH was measured with a Hanna (HI9813-5) potentiometer and total soluble solids content (°Brix) levels were estimated with a Sper Scientific refractometer. Both, pH and °Brix were taken from the juice of the fruits (Guillén-Enríquez *et al.,* 2022)

The proximate fruit pulp content was measured using the Association of Official Analytical Chemist (AOAC, 2005) methodologies. For the total protein content, a conversion factor of 6.25 was used. The carbohydrates were estimated by subtraction, total carbohydrates = 100 – protein – lipids – ash – raw fiber. For the macronutrient conversion, was assumed 4 kcal per gram of protein or carbohydrates and 9 kcal for gram of lipids.

Statistical analysis
An analysis of variance was performed and a Tukey *post-hoc* (*P*<0.05) was used to establish significant differences among populations for each of the measured variables. The differences in the measured fruit traits, interannual variation was considered as the independent factor.

Results and Discussion

Distribution of Stenocereus martinezii
Stenocereus martinezii is distributed from the south-center to north-center region in the State of Sinaloa, as well as a small population in Tamazula, Durango municipality (Figure 3). Prior to this work, this species was considered to be endemic to Sinaloa (Terrazas *et al*., 2013; Pío-Léon *et al*., 2023; Vega-Aviña *et al*., 2021). Thus, this study expands the understanding of its biogeography. *Stenocereus martinezii* inhabits the Sierra Foothills region of Sinaloa with tropical deciduous forest (Wiken *et al*., 2011) (Figure 3), from around sea level to 400 m. Its distribution is delimited in the west by the thorn forest of the Coastal Plains of Sinaloa, where it is displaced by *S*. *thurberi*. To the east, its distribution is delimited by Oak-Pine and Pine forests, but it is displaced by *S*. *montanus* since 400 m of the tropical deciduous forest. These three species of the *Stenocereus* genera are used commercially in Sinaloa (Salomón-Montijo *et al*., 2022); these species are allopatric and only rarely coincide at the edges of their distributions (Figure 3B).

The area of distribution of *S*. *martinezii* described here is much larger than the areas previously reported by Arreola-Nava and Terrazas (2003) and by scientific collections (Figure 3A) but is similar to the area estimated by current records of iNaturalist (2024). The small number of records in scientific collections might be due to the impractical collecting procedures for columnar cacti; these plants do not possess vegetative structures that can be easily collected and preserved, so photographic records or direct observation may be a good alternative. As of October 2024, there were 1460 research quality records of *S*. *martinezii* on iNaturalist.

The species that are most commonly associated with *S*. *martinezii* are elements of the tropical deciduous forest such as *Lysiloma divariacata* (Jacq) J.F. Macbr, *Ipomoea arborescens* Sweet, *Pachycereus pecten-aboriginum* Britton & Rose, *Senna atomaria* (L.) H.S. Irwin & Barneby and *Stenocereus alamosensis,* as well as some species that are frequent in thorn forest: *Bromelia pinguin* L., *Colubrina heteroneura* Standl., *Fouquieria macdougaalii* Nash and *Haematoxylum brasiletto* H. Karst.

The commercial harvest of *S. martinezii* fruits was recorded in four communities, Arroyo Grande, Japuino-Conitaca, San Ignacio and Los Cerritos (Figure 1). These communities are located near the eastern edge of the species' distribution, in the low hills of the Sierra Madre. Some communities no commercial harvesting pitaya fruits near the coast were found. Then, it was hypothesized that the inland populations of *S. martinezii* are more vigorous and productive than the coastal populations, such that harvesting is profitable in terms of cost and benefit per collection effort. The greatest potential for use of germplasm and establishment of cultivation of the species is likely in the areas around communities where the fruits are already commercially harvested, as occurs in the other species of *Stenocereus* in south-central Mexico (Parra *et al*., 2012; Casas *et al*., 2016).

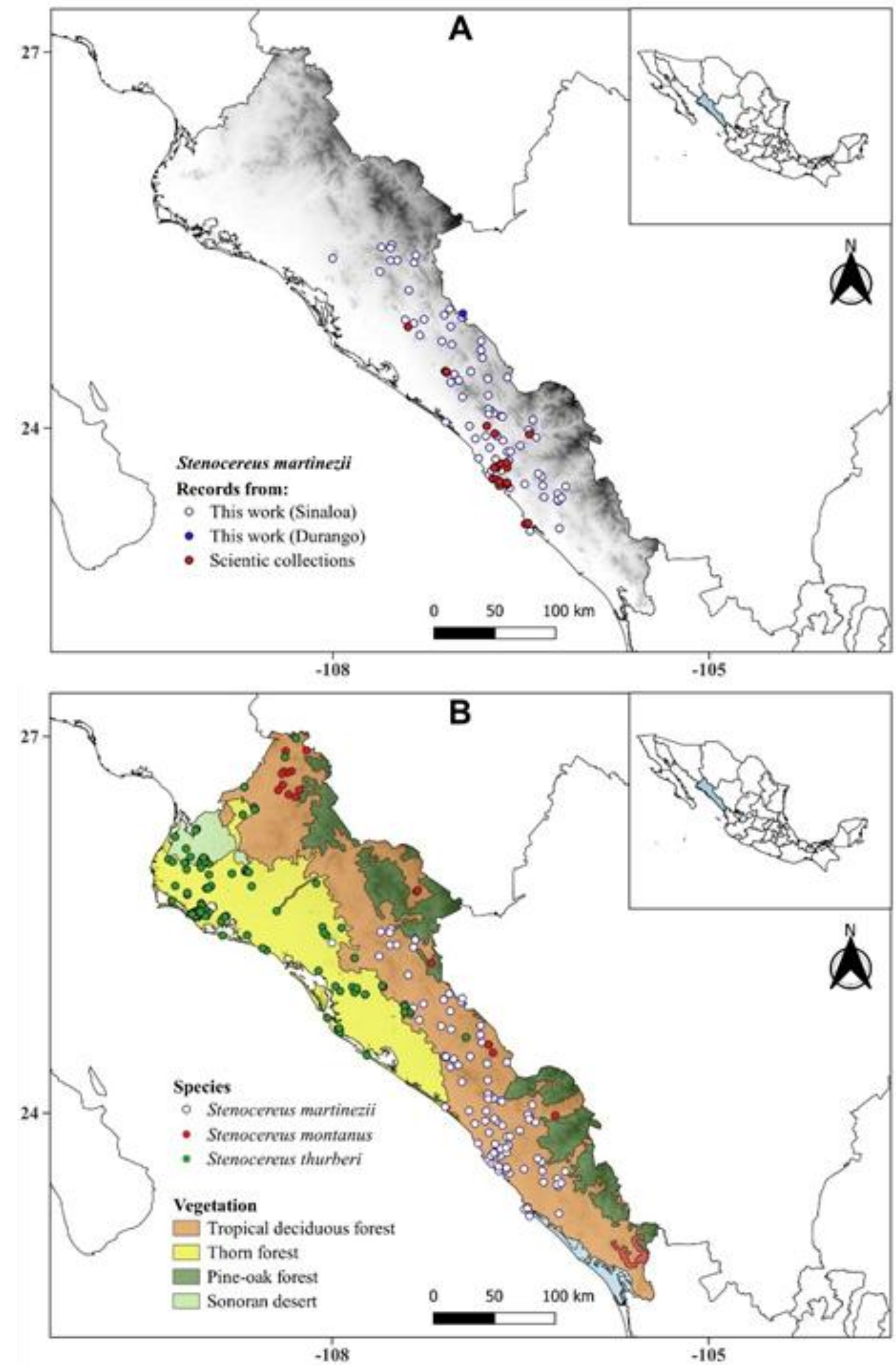

Figure 3. Distribution of *Stenocereus martinezii*: (A) from scientific collections and records from this work; (B) compared with the other two pitaya species of commercial importance in Sinaloa.

Phenology

The reproductive stage of *S. martinezii* lasted six months (February – July) in the three surveyed populations (Figure 4). The numbers of buds, flowers and fruits were much higher in populations where there was commercial use (Japuino and Arroyo Grande) compared to Guillermo Prieto where fruits are only occasionally harvested. This also suggests that the fruits are harvested in localities where fruit yield is high enough to be economically profitable.

The buds were first counted in mid-February and ended in May, with a peak on March 15th in all three populations (Figure 4 A). The flowering anthesis peaked on March 15th in Arroyo Grande and April 1st in Guillermo Prieto and Japuino (Figure 4B). The fruit production began in the last two weeks of March and ended in July with a peak in May (Figure 4C). The populations of Japuino and Arroyo Grande showed a peak on May 1st, while in Guillermo Prieto fruit production was rather scarce and did not show a clear peak.

Comparing with other arborescent *Stenocereus* species, the reproductive stage of *S. martinezii* occurs a month later than that of *S. queretaroensis* (F.A.C. Webber) Buxb in Jalisco (Pimienta-Barrios and Nobel, 1994) and a month before *S. thurberi* in northern Sinaloa (Salomón-Montijo *et al*., 2016). The clinal phenological patterns of these congeneric species can be attributed to the timing of migration of bats that pollinate them (Flemming *et al*., 2001). So, *S. martinezii* constitutes as a food bridge for migratory fauna moving south to north.

The production of reproductive structures was unimodal in the three populations, similar to other columnar cacti species (Flemming *et al*., 2001; Pavón and Briones, 2001: Bustamante and Búrquez, 2008). The reproductive structure production was also asynchronous, since plants with buds, flowers and fruits were found simultaneously. This phenomenon has been interpreted as an ecological strategy to minimize the risk that an entire reproductive stage could be completely lost due to adverse biological conditions (pests) or physical factors (rainfall or drought), allowing the three stages reproductive parts to complete the entire reproductive process (Pimienta-Barrios and Nobel, 1994). Leon de la Luz and Domínguez-Cadena (1991) established that the asynchrony of phenological processes is a response of populations to unpredictable and completely random environmental conditions such as alternating rainfall and dry periods in arid environments.

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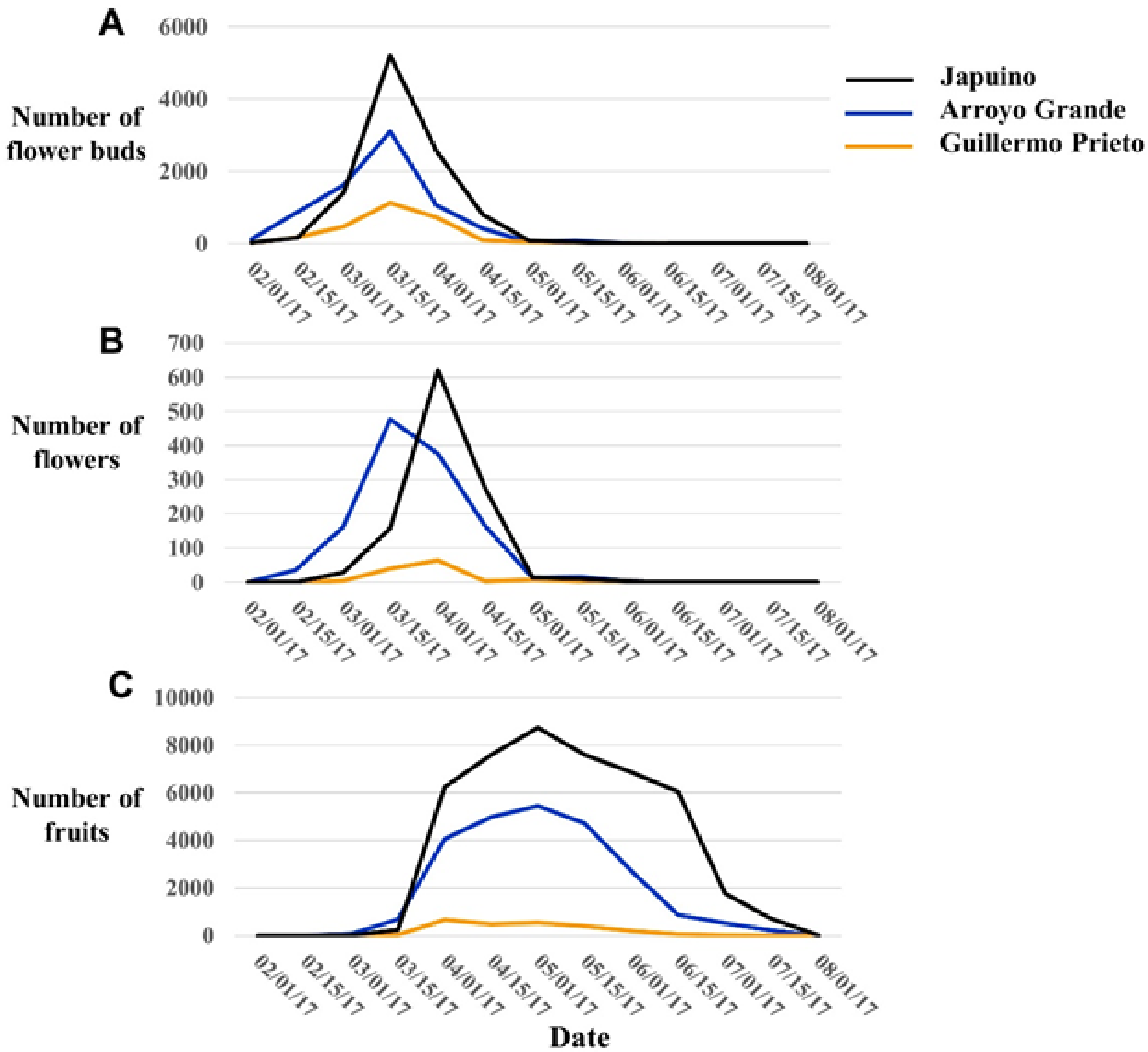

Figure 4. The reproductive phenology of flower buds, flowers and fruits of *Stenocereus martinezii* during 2017 in three different localities of Sinaloa, Mexico.

Physico-chemical and proximate characterization of fruits

All measured fruit traits showed significant differences among study years (Table 1). In 2017, fruits had lower weight, volume, sugar content, and number of seeds per fruit, but higher pH. On average, *S*. *martinezii* fruits were smaller and lighter (36.4 g) than other commercially used species such as *S*. *griseus* (Haw) Buxb (63-290 g), *S. pruinosus* (Otto) Buxb (86-300 g) (Quiroz-González *et al*., 2018), *S*. *queretaroensis* (97-165 g) (Pimienta-Barrios and Nobel, 1994) and *S*. *thurberi* (76 g) (Rodríguez-Félix *et al*., 2019). Hence, its harvest implies a larger effort. However, weight and volume of *S*. *martinezii* fruits remain relatively constant throughout the reproductive season, in contrast to these other species with larger fruits, in which weight and volume tend to increase towards the end of the season (Bustamante, 2003; Orozco, 2007).

Table 1. Physicochemical and proximate characterization of *Stenocereus martinezii* fruits collected from Arroyo Grande, Sinaloa in three consecutive years (2017–2019).

Variable	**2017**	**2018**	**2019**	**Overall**
	n = 168	n = 122	n =100	N = 390
Weight (g)	33.14 ± 0.7[b]	39.70 ± 1.0[a]	37.96 ± 1.0[a]	36.43 ± 0.5
Volume (cm^3)	30.53 ± 1.2[b]	37.10 ± 1.2[a]	37.31 ± 1.0[a]	34.32 ± 0.7
pH	6.24 ± 0.02[a]	5.67 ± 0.06[b]	5.77 ± 0.03[b]	5.94 ± 0.03
Soluble solids (Brix)	8.19 ± 0.2[b]	10.6 ± 0.20[a]	10.4 ± 0.2[a]	9.47 ± 0.13
Number of seeds	584.4 ± 14.5[b]	895.1 ± 23.4[a]	923.2 ± 28.2[a]	768.5 ± 14.5
Proximate (%)				
Water	84.4	ND	ND	
Protein	2.3	ND	ND	
Fat	0.6	ND	ND	
Ash	0.7	ND	ND	
Crude fiber	1.8	ND	ND	
Carbohydrates	10.2	ND	ND	
Kcal/100g	55.4	ND	ND	

Different superscript letters indicate significant differences between years (Tukey, $P \leq 0.05$).

Stenocereus martinezii fruit pH was similar to other pitaya fruits in Mexico (5.7-6.2), with the exception of fruits from 2017 and *S*. *stellatus*, which has more acid values (3.3) (Quiroz-González *et al*., 2018). *Stenocereus martinezii* soluble solids content (8.1-10.6 Brix) was lower than those reported for *S*. *montanus* (12.4; reported as *S*. *thurberi* in Hinojosa-Gómez and Muy-Rangel, 2023); *S*. *pruinosus* (9.5-10.3), S. *queretaroensis* (10-11) (Quiroz-González *et al*., 2018) and *S*. *thurberi* (12.2) (Rodríguez-Félix *et al*., 2019) which could mean a less sweet taste. The fruits from 2017 had the lowest concentration of soluble solids, but pH increased slightly, which compensates the sweet/acid ratio to maintain a similar flavor across years. Most of the other pitaya species produced fruits with different colors (white, yellow, red and purple) that also showed variation in its sugar contents, pH, pigments; however, *S*. *martinezii* nearly always produced red fruits, with sporadic white fruits.

The proximate analysis in 2017 indicated that the main components aside from water content, are carbohydrates (10.2%), followed by proteins (2.3%) and fiber (1.8%). These values are similar to those reported for other pitaya fruits, where the carbohydrates values range from 8 to 11%. The protein content was slightly higher than the results for another *Stenocereus* species (1.0-1.5%) (Quiroz-González *et al*., 2018), which can be caused by a larger proportion of seeds relative to pulp in *S*. *martinezii*; however, the concentration of this nutrient is still low and not significant for human consumption.

Conclusions

Stenocereus martinezii is categorized as threatened, but little information is available regarding the distribution and ecology of this species. Its geographic distribution is larger than was previously described, and now the presence in the state of Durango, Mexico is reported. It is found exclusively in the Sierra Madre Foothills ecoregion in Sinaloa, in tropical deciduous forest. It is clearly replaced at the edges of its range by the other two pitaya species of the region, *S*. *thurberi* to the west and *S*. *montanus* to the east. Its reproductive phenology is unimodal and occurs later than southern columnar cacti and before northern populations of Sonora, making this species a food bridge for migratory fauna as they move northward. Its fruits are smaller than other economically important *Stenocereus* species, but its food values are similar.

ETHICS STATEMENT

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF SUPPORTING DATA

All data generated or analyzed during this study are included in this published article.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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AUTHOR CONTRIBUTIONS

Conceptualization, B.S.M., J.F.P.L., G.M.S. and J.S.D.; B.S.M., G.M.S. and J.S.D; formal analysis, B.S.M., J.F.P.L., A.A.G. and C.E.R.H.; investigation, B.S.M., G.M.S. and J.S.D.; data curation, B.S.M., J.F.P.L., A.A.G. and C.E.R.H.; writing—original draft preparation, B.S.M. and J.F.P.L.; writing—review and editing, B.S.M., J.F.P.L., A.A.G., J.S.D. and C.E.R.H.

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