



Phytoliths from soil surfaces and water reservoirs of the Brazilian semi-arid *Caatinga*

Francisco Rony Gomes Barroso^{a,*}, Vaneicia dos Santos Gomes^a, Carlos Eduardo Carvalho^a, Marie Pierre Ledru^b, Charly Favier^b, Francisca Soares Araújo^a, Laurent Bremond^b

^a Department of Biology, Federal University of Ceará – UFC, 60440-900, Fortaleza, CE, Brazil

^b Institut des Sciences de l'Évolution de Montpellier (ISEM), EPHE, PSL Research University, Université de Montpellier, CNRS, IRD, Place Eugène Bataillon, CC 065, 34095 Montpellier, France

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ABSTRACT

Understanding processes that explain phytolith assemblages and their concentration in the soil and sediments is essential to interpret long-term ecological changes. The present study shows modern phytolith assemblages and their relationship with the vegetation cover in the *Caatinga* biome, state of Ceará, northeastern Brazil. We collected recent samples from soil surfaces, in 2015, in three different vegetation covers (open shrubby *Caatinga*, dense shrubby *Caatinga*, and *Caatinga* forest vegetation) and from two cores with recently deposited sediments, in Massapê (74 cm depth, 55 years old) and Varjota (50 cm depth, 58 years old). After phytolith extraction, we studied twelve samples from soils and thirteen samples from cores. The counting revealed 26 different phytolith types with some differences in the concentration of silica bodies in different vegetation covers. Phytoliths were well preserved and could be related to the presence of plants, such as Poaceae (subfamily Panicoideae and Chloridoideae), Arecaceae and Cyperaceae. In the two cores, the most common type was globular echinate and could be associated with the presence of palms in the riparian forest and open landscapes in the surroundings. In soil surfaces samples, the saddle was the most frequent type. We found a high concentration of globular granulate around Aiuaba Ecological Station, which harbors a preserved *Caatinga* area. Finally, we observed a good match between vegetation cover and the phytolith assemblages collected in soils and reservoirs.

1. Introduction

Phytoliths, pollen, and charcoals are commonly used proxies for paleoenvironmental and paleoecological studies in the paleobotany field. Phytoliths are very interesting proxies for local records in dry environments because they resist oxidizing conditions, unlike pollen, which is preserved only under anoxic conditions, being more useful for regional analysis (Barboni et al., 1999; Coe et al., 2012; Gosh et al., 2011; IPCC, 2011; Piperno, 1991). The production and record of charcoals depend on the vegetation flammability and can feature the regional or local vegetation, depending on the charcoal type, shape, and size (Scott and Damblon, 2010). For the use of these proxies, paleoenvironmental studies require special environments with active sedimentation conditions and rare erosive events, as they preserve contiguous layers of sediment, for example, large lakes or peat bogs (Neumann et al., 2008; Suguio, 1999).

In the state of Ceará, the presence of a perennial natural lake is not

common. Fortunately, after a series of droughts (from 1877 to the present date) in Ceará, federal-state measures were adopted to construct reservoirs (Campos, 2014). The sediments deposited and accumulated over the years in these reservoirs can contain proxies, such as phytoliths, pollen, and charcoals, as in recent sediments of natural lakes (Aleman et al., 2013). Therefore, the application of paleoecological methods to study the recent sediments of artificial reservoirs can be promising to assess recent vegetation changes resulting from climate and land-use changes. In this sense, studies of soil and reservoir surface phytoliths can provide data on how different vegetation physiognomies are spatially represented and how the reservoir sediment composition varies in tens or hundreds of years. Thus, it will be possible to understand the effect of degradation and deforestation through phytolith composition in chronosequences of few decades in two reservoirs of the Brazilian semi-arid.

In the present study, we used phytoliths as a proxy of tree cover and herbaceous composition. These microscopic opal silica particles, formed

* Corresponding author.

E-mail address: ronybarroso@hotmail.com (F.R. Gomes Barroso).

in the cells of different plant organs, are released by leaf litter deposition on the soil surface or after the plant's death (Piperno and Pearsall, 1998). Phytoliths are preserved both in soil and soaked marshes for hundreds and even thousands of years. Although phytoliths are diagnoses of specific genera or families, some have no taxonomic significance or, in other cases, different families can produce the same type of phytolith (redundancy) (Piperno, 1988; Rovner, 1971). In some plants, especially in the Poaceae family, there is a diversity of forms produced by the same species (multiplicity).

Poaceae can produce grass silica short cells (GSSC) (Mulholland and Rapp, 1992). The subfamily Panicoideae produces bilobate, polylobate, and cross morphotypes, which are grasses adapted to hot and humid climates. The saddle type generally occurs in the subfamily Chloridoideae, C₄ grasses adapted to dry climates (Twiss et al., 1969; Mulholland, 1989; Fredlund and Tieszen, 1994; Kondo et al., 1994). The presence of woody dicotyledonous may be associated with the production of globular granulate, sclereid, and faceted block types (Scurfield et al., 1974; Kondo et al., 1994; Alexandre et al., 1997; Runge, 1999; Bremond et al., 2005; Neumann et al., 2001). Cyperaceae can produce papillae, and Arecaceae may originate globular echinate (Kondo et al., 1994). In general, *Caatinga* plants produce a large number of phytoliths. Some families, such as Arecaceae, Bromeliaceae, Chrysobalanaceae, Malvaceae, Anacardiaceae, and Erythroxylaceae are major producers (Coe et al., 2017).

Studies on phytoliths in Brazil are still incipient (Luz et al., 2015), but there is relevant information about different Brazilian biomes. In peat bogs of a mixed rainforest in the state of Paraná, southern Brazil, Rasbold et al. (2016) recognized drier climatic conditions 14,500 years ago, with a gradual increase in humidity starting 6000 years ago. In a restinga in Maricá, in the state of Rio de Janeiro, southeastern Brazil, Santos et al. (2015) found little production of phytoliths in soil samples from six different plant communities, except for the families Poaceae, Cyperaceae, and Arecaceae, which occurred in large quantities and diversity. In the *Caatinga* biome, in the state of Ceará, northeastern Brazil,

Ricardo et al. (2018) found large phytolith assemblages extracted from plants, in which the most prevalent were tracheids, followed by polyhedral, globular granulate, elongate, and trichomes (lanceolate hair cells). Dias et al. (2019) have studied phytoliths from soil profile, also in state of Ceará, with a predominance of bulliform, acicular and globular types. Their results showed the tree density increased in the period between 2300 and 700 years ago.

Studies carried out in the *Caatinga* biome in Ceará (Coe et al., 2017; Dias et al., 2019; Ricardo et al., 2018) did not present paleoecology data with phytoliths from cores collected in reservoirs. Our study reconstructs paleoecological and paleoenvironmental data and shows possible evidence of anthropogenic action in vegetation cover. It is essential to understand the temporal reconstruction of the *Caatinga* biome that, since the arrival of the Portuguese, has been threatened by agricultural activities, soil erosion, ecosystem degradation, and alteration in species relative abundance (Pompeu-Sobrinho, 1937). These anthropogenic pressures changed the vegetation cover, transforming closed tree vegetations into more open physiognomies, with rich herbaceous pastures suitable to livestock farming (Pompeu-Sobrinho, 1937). Our goals are: a) to study the original flora of the *Caatinga*, recorded through phytolith assemblages in three different vegetation covers; b) to retrieve the land-use history from phytoliths present in sediments of water reservoirs; and c) to reconstitute the vegetation cover dynamics.

2. Study area

The *Caatinga* Phytogeographical Domain (CPD) is a broad Brazilian natural region located in the northeastern corner of the South American continent (Ab'Sáber, 2003; IBGE, 2004). The *Caatinga sensu stricto* is the main vegetation type of the CPD, comprising approximately 800,000 km². It is also widespread in the state of Ceará (Fig. 1A). According to Veloso et al. (1991), "*Caatinga*" is a local name, and this vegetation can be called savanna.

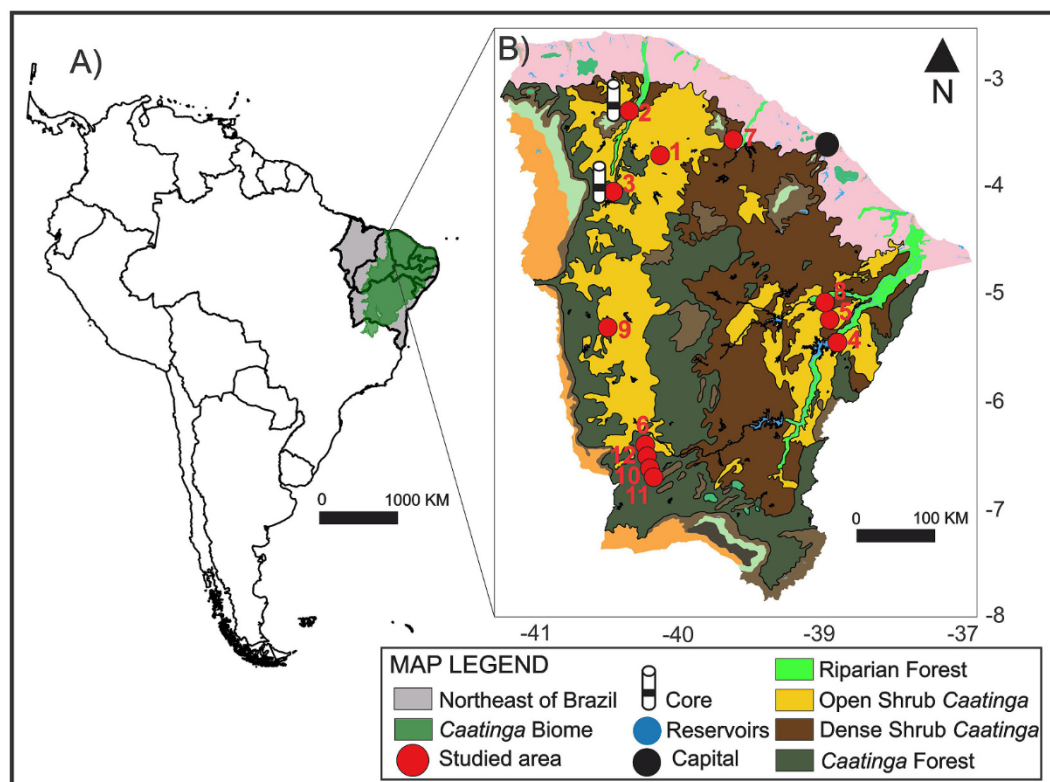


Fig. 1. Study area: A, distribution of the *Caatinga* in northeastern Brazil (Source: IBGE Instituto Brasileiro de Geografia e Estatística, 2004); B, Location of samples from the water reservoir (Acarauá Mirim {2} and Araras {3} cores) and soil surfaces (1–12), in three different vegetation covers (Source: Figueiredo, 1997).

The *Caatinga* vegetation comprises a deciduous, thorny, and succulent biome with open and grey aspect during the dry season, when almost all trees and shrubs shed their leaves. The *Caatinga* is frequently mentioned in the literature as widely variable in composition as well as in physiognomy, in response to climate and topography heterogeneity, soil types, and human influence (Andrade-Lima, 1981; Cabrera and Willink, 1973; Sampaio, 1995; Fernandes, 1998; Moro et al., 2016).

In Ceará, the predominant climatic characteristics are high average air temperatures during most of the year (Souza et al., 1992). Rains are considerably irregular throughout the year, and the rainfall concentrates in the first semester (Zanella, 2007). Cities have rainfall values ranging between 201.80 and 1700 mm, but usually within 400.01 and 600 mm (IPECE, 2015). The *Caatinga* soils are rocky and shallow, in general, with different characteristics, even within short distances (Ab'Saber, 1974; Sampaio, 1995).

The *Caatinga* comprises several physiognomies. In Ceará, the vegetation cover can be divided into eleven different types (FUNCEME, 1994). The Phytoecological Units map shows the area of occurrence of the different vegetation types found in Ceará (Fig. 1B). In general, the original vegetation was altered as a result of a disorderly and predatory human action (Antongiovanni et al., 2020).

In a forest physiognomy, the treetops touch each other during the rainy season, the favorable season for plants in the semi-arid region. *Schinopsis brasiliensis* Engler (Anacardiaceae) and *Astronium urundeuva* (M. Allemão) Engl. (Anacardiaceae) are some of the species present in the *Caatinga* Forest. The degradation of the *Caatinga* Forest results in the appearance of the Shrubby *Caatinga* characterized by the smaller size and twisted and whitish stems. The greater or lesser density of individual members of the community results in Dense Shrubby *Caatinga* or Open Shrubby *Caatinga* (FUNCEME, 1994). According to Andrade-Lima (1981), the Open Shrubby *Caatinga* occupies small, dispersed areas in the *Caatinga*, with predominantly small species, including some herbs in open spaces. The Dense Shrubby *Caatinga* is the vegetation type that occupies the largest area nowadays. The most frequent species in Shrubby *Caatingas* are *Mimosa tenuiflora* (Willd.) Poir, *Cenostigma bractosum* (Tul.) Gagnon & G.P. Lewis, *Mimosa caesalpiniiifolia* Benth (Fabaceae), *Croton sonderianus* Müll. Arg. (Euphorbiaceae), and *Cereus jamacaru* DC (Cactacea) (IPLANCE, 1995). Those three vegetations comprise the “Crystalline *Caatinga*”, a unique phytoecological unit with a cohesive flora (Moro et al., 2015).

There are larger forests along semi-arid river courses (riparian forests) than in the surrounding vegetation. The riparian forest and “Carnaubais” cover the interior and follow the Acaraú River. *Copernicia prunifera* (Mill.) H.E. Moore (Arecaceae) stands out in riparian forests. The typical soils of these areas are sandy and can reach great depths, allowing the development of riparian forests associated with *Copernicia prunifera* (Carnaúba Palm), forming “Carnaubais”. The riparian forest associated with “Carnaubais” occurs in semi-arid areas from the interior of Ceará to sub-humid coastal areas associated with riverbeds, lagoons or periodically flooded regions (Moro et al., 2015).

3. Material and methods

3.1. Study sites

We analyzed phytoliths from three vegetation types in the Crystalline *Caatinga*: open shrubby, dense shrubby, and forest vegetation. There were two different analyses: 12 soil samples and 2 cores (in different places). We took 12 soil samples from areas with different vegetation cover, in eight cities of Ceará (Table 1). We have collected sediments in two reservoirs for core analysis in the Open Shrubby *Caatinga*, surrounded by riparian forests. The Acaraú-Mirim and Araras dam reservoirs, in Massapê and Varjota, respectively, are part of the Acaraú River Basin in northern Ceará. The Araras reservoir is near the Sierra Ibiapada sedimentary plateau at the east, whereas the Acaraú-Mirim reservoir is next to high granitic mountains known as Sierra Meruoca. The criteria

Table 1

Description and location of samples from soils and water reservoirs.

Vegetation cover	Samples	Cities
Open Shrubby <i>Caatinga</i> -OSC	1	Sobral
	2	Massapê
	3	Varjota
	4	Alto Santo
	5	Morada Nova
	6	Aiuaba
Dense Shrubby <i>Caatinga</i> -DSC	7	Umirim
	8	Morada Nova
<i>Caatinga</i> Forest-CF	9	Independência
	10	Aiuaba
	11	Aiuaba
	12	Aiuaba

for choosing the 12 points from soil surfaces in different vegetation covers was the minimum count of 200 phytoliths morphotypes per sample. For the chosen reservoirs, the criteria was the period of construction, being the both oldest in the State of Ceará.

3.2. Sampling and sediment dating

During the sediment sampling for phytolith extraction, three field expeditions were carried out in the state of Ceará as part of the activities of the project “Evolution of biodiversity loss in areas under degradation processes” (CNPq process # 400890/2014–3), initiated in 2014, based on a partnership between the Federal University of Ceará and the University of Montpellier, France.

The sediments were collected with a Kajak-Brinkhurst sampler (KB) in the middle of the reservoir (2 replicates per reservoir). The KB sampling method allows collecting a few tens of centimeters of unaltered sediments at the water-sediment interface, representing the last decades. Two cores were collected in two older dams in Ceará: Aracarú-Mirim, built in the year 1907, and Araras, built in 1958 (Ledru et al., 2020). Samples were collected contiguously in 1 cm deep layers for phytolith analyses.

A chronological framework was established to date sediments using short-lived radionuclides measurements. Age–depth models are fully described in Ledru et al. (2020). The base of lake sediment dated to 1963 ± 8.5 yr AD, in the Acaraú-Mirim reservoir, and 1959.5 ± 11.5 yr AD (facies 1 and 2) in the Araras reservoir. The topmost sample is described in soil analysis.

3.3. Phytolith extraction and counting

We extracted phytoliths from 3 g sediment samples using the following protocol (Aleman et al., 2013): (1) deflocculation of the sediment with NaPO_3 , (2) dissolution of carbonates using HCl, (3) oxidation of organic matter with H_2O_2 , (4) removal of clay by gravity, (5) drying of the residue with ethanol, and (6) densimetric separation of phytoliths in a dense solution of ZnBr_2 ($d > 2.3$). We mounted the recovered fraction on microscope slides in immersion oil 518 (Carl Zeiss™ Immersol™) for 3D observation and counted phytoliths at a 600X magnification. We deposited the slides in the Laboratory of Phytogeography of the Federal University of Ceará (UFC). We counted a minimum of 200 grass silica short cells (GSSC). We made phytolytic diagrams using the PSIMPOLL program (Bennett, 2005).

3.4. Phytolith classification

We described phytoliths according to their three-dimensional shape and classified them following the international phytolith nomenclature code (Madella et al., 2005).

We calculated three phytolith indices for each sample. 1. *Aridity index (Iph)* indicates the dominance of short-grass or tall-grass savannas based on the proportion of Chloridoideae (saddle type) to the sum of

Chloridoideae and Panicoideae (saddle, cross, and bilobate) phytoliths (Bremond et al., 2008). 2. *D/P index* (ratio of woody dicotyledon to Poaceae phytoliths) was also calculated as the ratio of globular granulate and decorated phytoliths to the GSSC (Bremond et al., 2008). 3. *Palm Tree Cover index (Pa/P)*, which is the ratio between the phytolith type characteristic of *Arecaceae* (Globular echinate) and the sum of phytolith types of *Poaceae* (Bulliform cuneiform + Bulliform paralepipedal + Short cells + Acicular) (Coe et al., 2017).

4. Results

4.1. Phytoliths of soil surfaces

We identified 24 types of phytoliths (Figs. 2 and 3). The saddle was the most frequent (39%), followed by other morphotypes, such as the

globular granulate (15%), bilobate (14%), globular echinate (11%), and papillae (3%) (Fig. 3A). Sample 12 showed the highest number of phytoliths and sample 9, the lowest. They both came from the *Caatinga* Forest.

In the Open Shrubby *Caatinga*, samples 1, 4, 5, and 6 showed a high frequency of saddle, followed by bilobate types. Samples 2 and 3 showed mostly globular echinate, saddle, and bilobate types. In the Dense Shrubby *Caatinga*, sample 7 showed mainly bilobates, followed by saddle and papillae types, whereas sample 8 had a predominance of saddle and similar values of bilobate, globular echinate, and globular granulate types. Finally, in the *Caatinga* Forest, sample 12 was the only one with a high frequency of globular granulate (57%). Samples 9, 10, and 11 showed mainly saddle, followed by bilobate types.

We calculated phytolith indices for each vegetation cover (Fig. 3A). The mean *D/P index* was 0.2; the highest value (2.7) occurred in sample

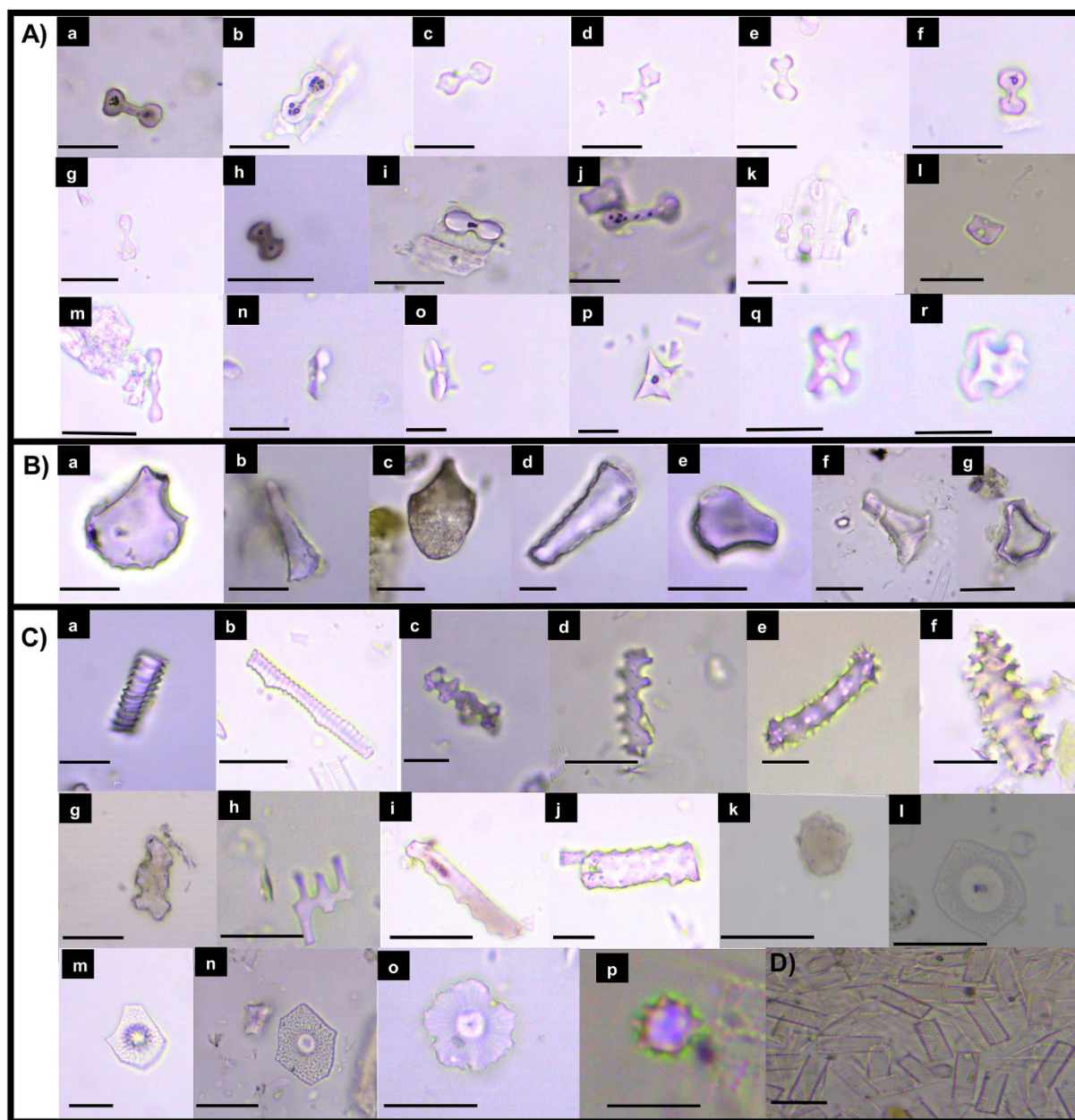


Fig. 2. Phytolith morphotypes found on the soil surface and sedimentary cores of reservoirs. (A) GSSC morphotypes: a-k, bilobate; l, saddle; m, polylobate; n, trapeziform; o, rondel bilobate; o-p, rondel bilobate; q-r, cross. (B) a-g cuneiform bulliform. (C) Other morphotypes: a-b, tracheid; c, elongate crenate; d, elongate crenate; e, rod-shaped; f, elongate dendriform; g, elongate crenate?; h, elongate tuberculate; i, elongate sinuate; j, elongate sinuate; k, globular granulate; l-o, papillae; p, globular echinate; (D), diatom. The scale bar is 20 μ m.

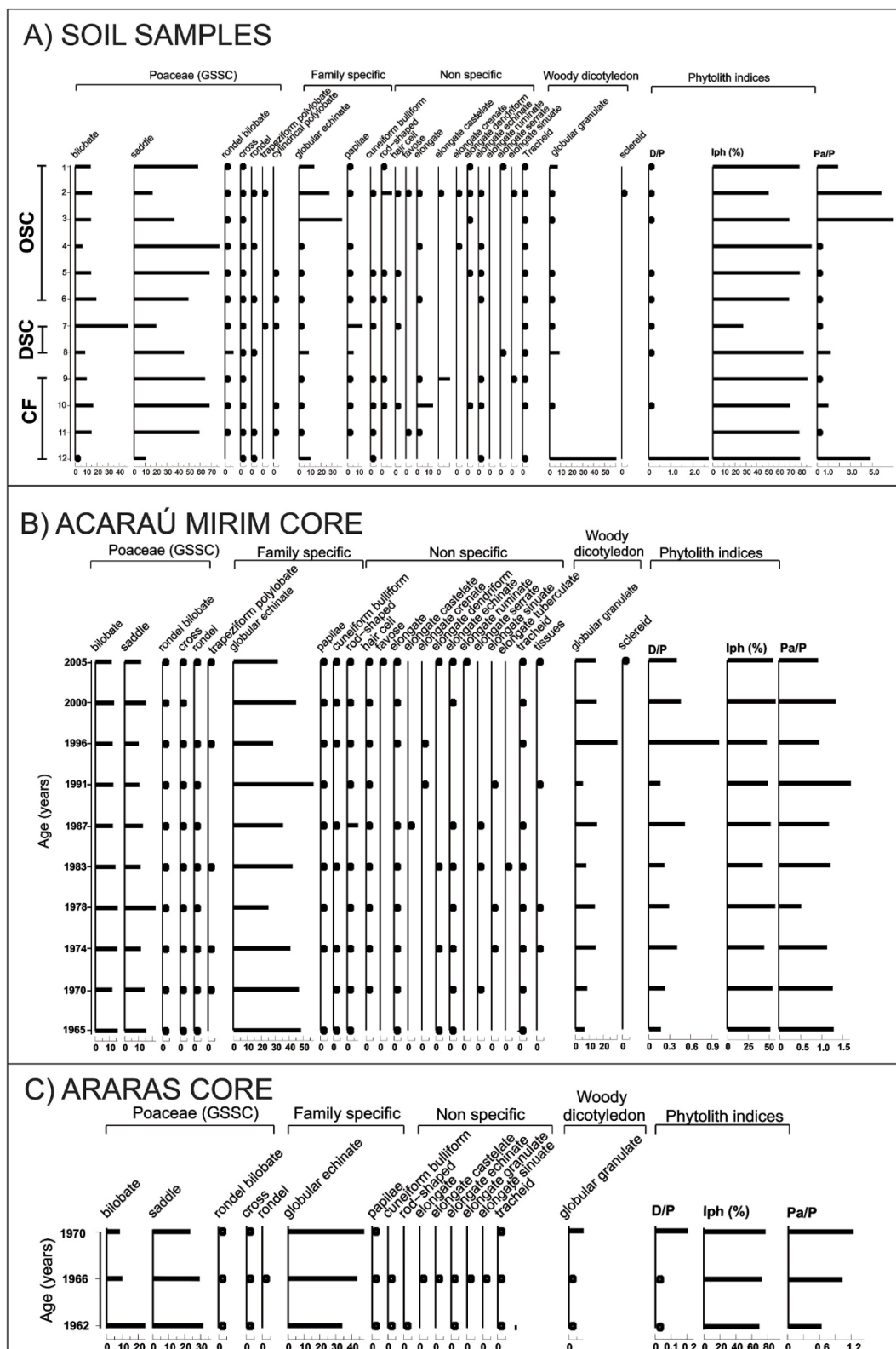


Fig. 3. Phytolith diagram. A, soil surface samples; B, samples from the Acaraú Mirim core (Massapé City); C, samples from the Araras core (Varjota City). GSSC: grass silica short cell. The dot indicates values for percentages $\leq 5\%$. Acronyms: CF, *Caatinga* Forest; DSC, Dense Shrubby *Caatinga*; and OSC, Open Shrubby *Caatinga*.

12 (*Caatinga* Forest) and the lowest (0.005) in sample 8 (Open Shrubby *Caatinga*). The value was null for samples 4 (OSC), 9 (CF), and 11 (FC). The mean Iph index (%) was 72%; the highest value (90%) occurred in sample 4 (OSC) and the lowest (28%) in sample 7 (Dense Shrubby *Caatinga*). The mean Pa/P index was 0.194 and varied from 0.004

(Sample 4) to 0.693 (Sample 3).

4.2. Phytoliths from reservoir sediments

We identified 25 phytolith types in the Acaraú Mirim core (Fig. 3B).

The predominant types were globular echinate (41%), followed by bilobate (14%), saddle (13%), and globular granulate (13%). The level with the highest number of phytoliths corresponded to the year 2000, and the lowest to 1970. There was not enough phytolith for counting corresponding to the year 2009.

The globular echinate type was dominant in nine out of ten samples, only in the sample of the year 1996, globular granulate showed the highest number. The presence of bilobate and saddle types has changed along the core. Between 1965 and 1978, there was a continuous decrease in globular echinate and an increase in globular granulate phytoliths. In 1991, globular echinate phytoliths were highest in the core, and we found the lowest level of saddle and globular granulate types.

The mean D/P index was 0.4, with the highest value (1.0) found in 1996, and the lowest value (0.2) in 1991, 1983, 1970, and 1965. The mean Iph (%) index was 50%, with the highest value (57%) found in the year 2000, and the lowest (42%), in 1983.

We identified 16 types in the Araras reservoir (Fig. 3C), which varied along the sedimentary sequence. We prepared twelve samples for this core, but only three showed enough material for analysis, including the years 1962, 1966, and 1970. The predominant morphology was globular echinate (43%), followed by saddle (28%), bilobate (13%), and globular granulate (4%). The year 1962 showed the highest number of bilobate and saddle phytoliths and the lowest presence of globular echinate. In 1966 and 1970, there was a greater production of granular echinate and a lower number of bilobate and saddle types. The D/P index was 0.004 in 1962 and 1966 and 0.2 in 1970. The Iph (%) index was 70%, 73%, and 78% in 1962, 1966, and 1970, respectively. The Pa/P index was 0.58, 0.95, and 1.15 for 1962, 1966, and 1970, respectively.

5. Discussion

5.1. Phytolith from soils

In the present study, the saddle morphotype (Poaceae family) was very frequent in soil samples. Our data on soil phytolith assemblages differed from the analyzed phytolith of the most common plants in the *Caatinga* (other families), in which the prevalent types were tracheids, followed by polyhedral, globular granulate, elongate, and trichomes (lanceolate hair cells) (Ricardo et al., 2018). A study on five soils sampled in *Caatinga* described globular granulate and globular echinate as the two more abundant morphotypes in the total assemblage (Coe et al., 2017). Dias et al. (2019) have found phytoliths well preserved, collected in dunes in the state of Ceará and they have inferred a relatively wetter climate, with a higher tree density than the current semi-arid, about 2200 years ago.

Although the saddle was the most frequent morphotype in the total assemblages, there was a different assemblage for each vegetation cover studied. The saddle was the main component in four (1, 4, 5 and 6) out of six samples from the Open Shrubby *Caatinga*. This morphotype is linked to dry and warm conditions and occurs predominantly in the Chloridoideae subfamily (C₄ grasses). However, the globular echinate is dominant in the assemblages of samples 2 and 3. Palms (Arecaceae family) and some bromeliads (Bromeliaceae family) produce this morphotype. In the surroundings of sample 2, *Attalea speciosa* Mart. ex Spreng. (Arecaceae) is the predominant palm species of secondary ecological successions (Souza and Oliveira, 2006), whereas *Copernicia prunifera* have been present in the riparian forest with “Carnauba” palm, surrounding the area of samples 2 and 3 (FUNCEME, 1994; Mesquita et al., 2016) (Fig. 1). Therefore, the riparian forest with Carnauba can contribute to the influx of globular echinate in the soil of the Open Shrubby *Caatinga*.

In the Dense Shrubby *Caatinga*, the bilobate morphotype was the most frequent in sample 7, being mainly produced by the Panicoideae subfamily (C₄ grasses), with records associated with warm and humid environments. The presence of papillae morphotypes is characteristic of

the occurrence of Cyperaceae (Piperno, 2006). Cyperaceae is a speciose, cosmopolitan family often found, but not exclusively, associated with poorly drained plant formations, such as swamps, lakes, riverbanks, and other water bodies (Judd et al., 2009). Besides showing a high saddle percentage, sample 8 had similar values for bilobate, globular echinate, and globular granulate phytoliths, the second most representative types in this sample. In the state of Paraná, the gradual increase of the bilobate morphotype was observed during the transition from arid to more humid conditions (Rasbold et al., 2016). The rainfall rate in this site is 600.01–800 mm.

In the *Caatinga* Forest, only sample 12 showed a high number of globular granulate, a typical diagnostic morphotype for woody plants. We identified globular granulate producing plants in the surroundings of sample 12, but the production is different in each species, for example, it can be rare in *Aspidorperma pyriforme* Mart. & Zucc. (Apocynaceae), occasional in *Cordia oncocalyx* Allemão (Boraginaceae), and frequent in *Handroanthus impetiginosus* (Mart. ex DC.) Mattos (Bignoniaceae), *Anadenanthera colubrina* (Vell.) Brenan (Fabaceae), and *Mimosa tenuiflora* (Ricardo et al., 2018). This particular site is approximately 1 km away from the Aiuaba Ecological Station (6°35'55.48"S; 40° 7'16.77"O), a preserved area with relevant natural characteristics, created and protected by the Federal Government. Samples 9, 10 and 11 showed mainly saddle, followed by bilobate types. They were produced by Poaceae and could be related to degradation or anthropic pressure in more closed environments, when grasses, instead of woody plants, arise (Ledru et al., 2020).

Therefore, the discrepant production of phytolith types among plants from the *Caatinga* can lead to inaccurate interpretations of assemblages by super or under-representing some of them. Studies on *Caatinga* plants (Coe et al., 2017; Ricardo et al., 2018) showed that in some families, such as Fabaceae, the phytolith production could vary according to the woody species; e.g., *Libidibia ferrea* (Mart. ex Tul.) L.P. Queiroz showed a very low production of globular granulate, *Anadenanthera colubrina* showed very high silicification of globular granulate, and *Cenostigma bracteosum* showed no silicification structures. So, in the *Caatinga* Forest, the type and abundance of woody species can affect the production of the globular granulate and its concentration in soil surfaces. Also, the high degradation level in *Caatinga* Forest can affect the record of the phytolith type, because the replacement of the original vegetation by grasses can produce grass silica short cells.

Some elongate phytoliths, such as elongate psilate, have no taxonomic value, as it is produced in the epidermis of all grasses (Bremond, 2003). On the other hand, cuneiform bulliform phytoliths appear in the literature as water stress indicators (Bremond et al., 2005).

5.2. Phytolith from the cores

The analyses in the two cores from the Open Shrubby *Caatinga* (Acarau Mirim and Araras reservoirs) revealed a predominance of the globular echinate morphotype. This morphotype can be associated with the riparian forest in the edge of the reservoirs, bearing a high number of *Copernicia prunifera* species (Arecaceae). These results were similar to phytolith assemblages from the cores in Lake Gbali, Central Africa (Aleman et al., 2014). The globular echinate morphotype has dominated (40%), though Arecaceae plants constituted only 5% of the riparian forest and were not part of the savanna matrix (Aleman et al., 2014). Palm trees produce abundant phytoliths and are expected to be over-represented in assemblages (Pearsall, 2009; Piperno, 2006).

In the Acarau Mirim core, we found a high frequency of globular echinate and a low frequency of globular granulate at the first record in 1965, which could be related to the open environment with the presence of the Arecaceae family and few woody plants. That scenario changed gradually until 1978. In 1983, the phytoliths revealed again evidence of an open environment, which could be related to the severe drought of 1982–83. According to pollen studies at the same core, the vegetation became more open between 1980 and 1988 (Ledru et al., 2020).

The highest number of globular echinate occurred in 1991, whereas globular granulate peaked in 1996. A satellite image acquired in 1991 (Ledru et al., 2020) and the significant rise in tree pollen taxa between 1990 and 1997, at the same studied core (Ledru et al., 2020), indicated the return of a natural vegetation cover and a reduction in the extent of bare soil. That recovery was associated with the abandonment of cultivated land due to law changes (National Institute for Colonization and Agrarian Reform INCRA Law 97,844 July 19, 1989). Hence, the pollen analyses corroborated our phytolith record for the same reservoir.

In the Araras reservoir, the samples were considered sterile between 1993 and 1972 because they did not show the minimum GSSC number (200 morphotypes). Hence, the information about most layers was unreadable. The sediment size of samples may be favorable to the accumulation of phytoliths (finer particles, such as silt and clay), or may, when coarse (sandy), allow their percolation to deeper layers (Coe et al., 2017). However, the main sediment size in this core is fine-grained, from top to bottom (0–60 cm) (Ledru et al., 2020). In the readable layers, from 1962 until 1970, there was an increasing frequency of globular granulate and globular echinate, and a decreasing frequency of GSSC. According to pollen studies in the Araras core (Ledru et al., 2020), the main changes in the vegetation between 1963 and 1971 were reforestation with the expansion of *Caatinga* tree species, mainly *Mimosa caesalpinii-fofia*, *M. tenuiflora* and *Astronium urundeuva*, and an abrupt decrease in herb taxa.

So, pollen studies (Ledru et al., 2020), in this same core, confirm the phytolith assemblage in Araras and Acaraú-Mirim reservoirs. In general, the pollen and phytolith data sets give a remarkably complementary picture of environmental change, despite the disparate range of taxa identifiable by each technique and the different taphonomy of each microfossil assemblage (Kealhofer and Penny, 1998).

6. Final considerations

The present study analyzed the phytolith assemblage from a semi-arid region in Ceará, northeastern Brazil, in three different vegetation covers from the Crystalline *Caatinga*: Open Shrubby *Caatinga*, Dense Shrubby *Caatinga*, and *Caatinga* Forest.

The phytolith morphotypes showed good conservation, so we could qualify and quantify them and the presence and variation of the Poaceae (subfamily Panicoideae and Chloridoideae), Arecaceae and Cyperaceae families.

In soil samples, the saddle was the most common morphotype. It is related to warm and dry conditions and dominated most samples. However, we noticed exceptions. In the Open Shrubby *Caatinga*, there was a dominance of the *globular echinate* morphotype, produced by palms, which can be related to the riparian forest with Carnauba surrounding the collection area. In the Dense Shrubby *Caatinga*, the dominance of the bilobate morphotype could be associated with warm and humid environments. Finally, in the *Caatinga* Forest, only one sample, collected in an area with natural vegetation protected by Brazilian laws, showed the predominance of the *globular granulate* morphotype, which is related to woody plants. Therefore, there is evidence that the original flora is well recorded through phytolith assemblages in Ceará, corresponding to actual vegetation.

In core samples from the two reservoirs in the Open Shrubby *Caatinga*, we could record the main changes in the vegetation structure, based on grass silica short cells and woody plant morphotype records. The variation in open or more closed vegetation cover could be related to natural phenomena (e.g., droughts) or anthropic pressure (e.g., abandonment of cultivated land due to a new law). The phytoliths present in the sediments of water reservoirs could be related to land use.

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Credit author statement

Francisco Rony Gomes Barroso: Conceptualization, Writing - original draft, Writing - review and editing. **Vaneicia dos Santos Gomes:** Methodology, Writing - original draft, Writing - review and editing. **Carlos Eduardo Carvalho:** Formal analysis, Writing - original draft, Writing - review and editing. **Marie-Pierre Ledru:** Formal analysis, Resources, Writing - original draft, Writing - review and editing. **Charly Favier:** Formal analysis, Writing - original draft, Writing - review and editing. **Francisca Soares Araújo:** Project administration, Investigation, Conceptualization, Supervision, Writing - original draft, Writing - review and editing. **Laurent Bremond:** Conceptualization, Data curation, Formal analysis, Supervision, Writing - original draft, Writing - review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Ab'Saber N., A., 1974. O domínio morfoclimático semi-árido das *Caatingas* brasileiras. *Geomorfologia* 43, 1–39.
- Ab'Saber, A.N., 2003. Os domínios de natureza no Brasil: potencialidades paisagísticas. Ateliê Editorial, São Paulo, p. 159.
- Aleman, J.C., Blarquez, O., Bentaleb, I., Bonté, P., Brossier, B., Carcaillet, C., Gond, V., Gourlet-Fleury, S., Kpolita, A., Lefèvre, I., 2013. Tracking land-cover changes with sedimentary charcoal in the Afrotropics. *Holocene* 23, 1853–1862.
- Aleman, J.C., Cnall-Subitani, S., Favier, C., Bremond, L., 2014. Influence of the local environment on lacustrine sedimentary phytolith records. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 414, 273–283.
- Alexandre, A., Meunier, J.D., Lezine, A.M., Vincens, A., Schwartz, D., 1997. Phytoliths: indicators of grassland dynamics during the late Holocene in intertropical Africa. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 136, 213–219.
- Andrade-Lima, D., 1981. The *Caatingas* dominium. *Rev. Bras. Botânica* 4, 149–153.
- Antongiovanni, M., Venticinque, E.M., Matsumoto, M., Fonseca, C.R., 2020. Chronic anthropogenic disturbance on *Caatinga* dry forest fragments. *J. Appl. Ecol.* 1–11, 00.
- Barboni, D., Bonnefille, R., Alexandre, A., Meunier, J.D., 1999. Phytoliths as palaeoenvironmental indicators, west side middle awash valley, Ethiopia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 152, 87–100.
- Bennett, K.D., 2005. Documentation for Psimpoll 4.25 and Pscomb 1.03: C Programs for Plotting Pollen Diagrams and Analysing Pollen Data. Department of Earth Sciences, University of Uppsala, Uppsala. Available at: <http://www.chrono.qub.ac.uk/psimpoll/psimpoll.html>.
- Bremond, L., 2003. Calibration des fonctions de transfert entre assemblages phytolithiques, structure des végétations et variables bioclimatiques actuelles, pour l'intégration de la dynamique des biomes herbacés dans les modèles de végétation. Ph.D. thesis. Université de Droit, d'Économie et des Sciences D'Aix-Marseille.

- Bremont, L., Alexandre, A., Hély, C., Guiot, J., 2005. A phytolith index as a proxy of tree cover density in tropical areas: calibration with Leaf Area Index along a forest-savanna transect in southeastern Cameroon. *Global Planet. Change* 45, 277–293.
- Bremont, L., Alexandre, A., Peyron, O., Guiot, J., 2008. Definition of grassland biomes from phytoliths in West Africa. *J. Biogeogr.* 35, 2039–2048.
- Cabrera, A.L., Willink, A., 1973. *Biogeografia de America Latina*, 2th ed. OEA, Washington, p. 122p.
- Campos, J.N.B., 2014. Secas e políticas públicas no semiárido: ideias, pensadores e períodos. *Estud. Avançados* 28, 65–88.
- Coe, H.H.G., Chueng, K.F., Gomes, J.G., 2012. Reconstituições da vegetação e inferências de paleoclimas através da utilização dos indicadores fitólitos e isótopos de carbono – exemplos de estudos no Brasil. *Revista Geonorte* 1, 248–261.
- Coe, H.H.G., Ricardo, S.D.F., Sousa, L.O.F., Dias, R.R., 2017. Caracterização de fitólitos de plantas e assembleias modernas de solo da *Caatinga* como referência para reconstituições paleoambientais. *Quat. Environ. Geosci.* 8, 9–21.
- Dias, R.R., Coe, H.H.G., Ricardo, S.D.F., Vasconcelos, A.M.C., Sousa, L.F., 2019. Reconstituição paleoambiental de dunas vegetadas na *Caatinga*, em Aracati, Ceará, através de biomíneralizações de sílica. *Rev. GeoUECE* 8, 193–208.
- Fernandes, A.G., 1998. *Fitogeografia Brasileira*. Multigraf, Fortaleza, p. 340p.
- Figueiredo, M.A., 1997. A cobertura vegetal do Ceará (Unidades Fitoeológicas). Atlas Do Ceará. Governo Do Estado Do Ceará, IPLANCE, Fortaleza, p. 65.
- Fredlund, G.G., Tieszen, L.T., 1994. Modern phytolith assemblages from the north American great plains. *J. Biogeogr.* 21, 321–335.
- FUNCEME, 1994. Fundação Cearense de Meteorologia e Recursos Hídricos. Mapa de Vegetação (escala 1:1.000.000). SEPLAN. Projeto Áridas: Grupo de Trabalho 1, Recursos Naturais e Meio Ambiente. Fortaleza-CE.
- Gosh, R., Naskar, M., Bera, S., 2011. Phytolith assemblages of grasses from the Sunderbans, India and their implications for the reconstruction of deltaic environments. *Palaeogeogr. Palaeoclimatol. Palaeocol.* 30, 93–102.
- IBGE [Instituto Brasileiro de Geografia e Estatística], 2004. Mapa de biomas do Brasil: primeira aproximação. IBGE, Rio de Janeiro.
- IPCC, 2011. Intergovernmental panel on climate change. Palaeoclimate proxy indicators. Disponível em: <http://ipcc.ch/ipccreports/tar/wg1/068.html>. (Accessed 28 June 2011).
- IPECE, 2015. Instituto de Pesquisa e Estratégia Econômica do Ceará. Fortaleza-CE.
- IPLANCE, 1995. Atlas Do Ceará. Governo do Estado do Ceará, Fortaleza, p. 64.
- Judd, W.S., Campbell, C.S., Kellogg, E.A., Stevens, P.F., Donoghue, M.J., 2009. *Sistemática vegetal: um enfoque filogenético*, 3th ed. Artmed, Porto Alegre, p. 603.
- Kealhofer, L., Penny, D., 1998. A combined pollen and phytolith record for fourteen thousand years of vegetation change in northeastern Thailand. *Rev. Palaeobot. Palynol.* 103, 83–93.
- Kondo, R., Childs, C., Atkinson, I., 1994. Opal Phytoliths of New Zealand. Manaaki Whenua Press, Canterbury, p. 85.
- Ledru, M.-P., Jeske-Pieruschka, V., Bremont, L., Develle, A.-L., Sabatier, P., Martins, E.S.P.R., Freitas Filho, M.R., Fontenele, D.P., Arnaud, F., Favier, C., Barroso, F.R.G., Araújo, F.S., 2020. When archives are missing, deciphering the effects of public policies and climate variability on the Brazilian semi-arid region using sediment core studies. *Sci. Total Environ.* 723, 137989.
- Luz, L.D., Kalinowski, E.C.Z., Parolin, M., Souza-Filho, E.E., 2015. Estágio Atual do Conhecimento sobre Fitólitos no Brasil. *Terrae Didática* 11, 52–64.
- Madella, M., Alexandre, A., Ball, T., 2005. International code for phytolith nomenclature 1.0. *Ann. Bot.* 96, 253–260.
- Mesquita, N.S., Sousa, M.C., Caracristi, I., Diniz, S.F., 2016. Análise Socioambiental Do Médio Curso Do Rio Acaraú – CE. *Revista de Geociências do Nordeste*, pp. 443–451.
- Moro, M.F., Lughadha, E.N., Araújo, F.S., Martins, F.R., 2016. A phytogeographical metaanalysis of the semi-arid *Caatinga* Domain in Brazil. *Bot. Rev.* 82, 91–148.
- Moro, M.F., Macedo, M.B., Moura-Fé, M.M., Castro, A.S.F., Costa, R.C., 2015. Vegetação, unidades fitoeológicas e diversidade paisagística do estado do Ceará. *Rodriguesia* 66, 717–743.
- Mulholland C., S., 1989. Phytolith shape frequencies in North Dakota grasses: a comparison to general patterns. *J. Archaeol. Sci.* 16, 489–511.
- Mulholland, S.C., Rapp, G., 1992. A morphological classification of grass silica-bodies. In: Rapp, G., Mulholland, S.C. (Eds.), *Phytoliths Systematics: Emerging Issues: Advances in Archaeological and Museum Science*. Springer, Boston, pp. 69–89.
- Neumann, K., Schoch, W., Détienne, P., Schweingruber, F.H., Richter, H.G., 2001. Woods of the Sahara and the Sahel. Paul Haupt, Bern, p. 465p.
- Neumann, V.H., Aragao, M.A.N.F., Valença, L.M.M., Leal, J.P., 2008. Ambientes lacustres. In: Silva, A.J.C.L.P., Aragão, M.A.N.F., Magalhães, A.J.C., Org (Eds.), *Ambientes de sedimentação silicilástica do Brasil*, 1th ed. Becca/BALL edições Ltda, São Paulo, pp. 133–169.
- Pearsall, D.M., 2009. *Paleoethnobotany: A Handbook of Procedures*, 2th ed. Left Coast Press, San Diego, p. 725.
- Piperno, D., 2006. *Phytoliths: a Comprehensive Guide for Archaeologists and Palaeoecologists*. Altamira Press, Oxford, p. 238.
- Piperno, D.R., Pearsall, D.M., 1998. *The Silica Bodies of Tropical American Grasses: Morphology, Taxonomy, and Implications for Grass Systematics and Fossil Phytolith Identification*. Smithsonian Institution Press, Washington, p. 44.
- Piperno, D.R., 1988. *Phytolith Analysis: an Archaeological and Geological Perspective*. Academic Press, San Diego, p. 280.
- Piperno, D.R., 1991. The status of phytolith analyses in the American tropics. *J. World PreHistory* 5, 155–191.
- Pompeu-Sobrinho, P., 1937. Povoamento Do Nordeste Brasileiro. *Revista do Instituto do Ceará*, pp. 107–162.
- Rasbold, G.G., Parolin, M., Caxambu, M.G., 2016. Reconstrução paleoambiental de um depósito sedimentar por análises multiproxy, turvo, Estado do Paraná, Brasil. *Rev. Bras. Palaontol.* 19, 315–324.
- Ricardo, S.D.F., Coe, H.H.G., Dias, R.R., Sousa, L.O.F., Gomes, E., 2018. Reference collection of plant phytoliths from the *Caatinga* biome, Northeast Brazil. *Flora* 249, 1–8.
- Rovner, L., 1971. Potential of opal phytolith for use in paleoecological reconstruction. *Quat. Res.* 1, 343–359.
- Runge, F., 1999. The opal phytolith inventory of soils in central Africa—quantities, shapes, classification, and spectra. *Rev. Palaeobot. Palynol.* 107, 23–53.
- Sampaio, E.V.S.B., 1995. Overview of the Brazilian *Caatinga*. In: Bullock, S.H., Mooney, H.A., Medina, F. (Eds.), *Seasonally Dry Tropical Forests*. Cambridge University Press, Cambridge, pp. 35–63.
- Santos, C.P., Coe, H.H.G., Borrelli, N., Silva, A.L.C., Sousa, L.O.F., Ramos, Y.B.M., Silvestre, C.P., Seixas, A.P., 2015. Opal phytolith and isotopic studies of "Restinga" communities of Maricá. *Braz. J. Oceanogr.* 63, 255–270.
- Scott, A.C., Damblon, F., 2010. Charcoal: taphonomy and significance in geology, botany and archaeology. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 291, 1–10.
- Scurfield, G., Anderson, C.A., Segnit, E.R., 1974. Silica in woody stems. *Aust. J. Bot.* 22, 211–229.
- Souza, M.J.N., Oliveira, V.P.V., 2006. Os enclaves úmidos e sub-úmidos do semi-arido do nordeste brasileiro. *Mercator - Rev. Geogr. UFC* 5, 85–102.
- Souza, M.J.N., Oliveira, J.G.B., Lins, R.C., Jatobá, L., 1992. Condições geo-ambientais do semi-árido brasileiro. *Ciência & Trópico Recife* 20, 173–198.
- Suguio, K., 1999. Recent progress in Quaternary geology of Brazil. *Episodes* 22, 2217–2220.
- Twiss, P.C., Suess, E., Smith, R.M., 1969. Morphological classification of grass phytolith. *Soil Sci. Soc. Am. Proc.* 33, 109–115.
- Veloso, H.P., Rangel Filho, A.L.R., Lima, J.C.A., 1991. Classificação da vegetação brasileira, adaptada a um sistema universal. IBGE, Rio de Janeiro, p. 124.
- Zanella, M.E., 2007. As características climáticas e os recursos hídricos do Ceará. In: Silva, J.B., Cavalcante, T.C., Dantas, E.W.C. (Eds.), *Ceará: um novo olhar geográfico*, 2th ed. Demócrito Rocha, Fortaleza, p. 480.