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MICROBIOLOGY

177 years of diatom studies in Brazil: knowledge, gaps, and perspectives

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Abstract: The actual status of the progress and the main aspects of diatom studies in Brazil remain unknown. This paper describes a survey of published studies addressing material of Brazilian origin in non-marine aquatic environments. Our objectives are to (1) summarize and categorize diatom research topics, (2) to describe how related studies evolved and developed over time, as well as respective journals, (3) to identify the most studied regions and environments, and (4) to indicate the main institutions and works addressing diatom research and related interactions. We conducted a systematic review selecting 478 studies. Since the early studies, the approach on diatom floristic exclusively was the most frequent, even though, ecological studies have been increasing since the 2000s. However, these concentrate in the southern and southeastern. It was only in the last decades that other Brazilian regions became the setting of more extensive samplings, thus reflecting on the interactions between authors and institutions from the collection sites. However, the actual biodiversity scenario of diatoms in Brazil still seems to be underestimated, which may influence further conservation measures. Finally, we indicate some suggestions aimed at filling the sampling gaps presented/highlighted in this study.

Key words: aquatic biodiversity, Brazil, ecology, scientometry, taxonomy.

INTRODUCTION

Over the past decade, Brazil has made important advances to reconcile biodiversity conservation and economic development, thus emerging as a strong player in the international conservation debate (Loyola 2014, Overbeck et al. 2015). Despite the substantial knowledge gaps and sampling bias, methods have been developed to model the influence of these issues on biodiversity conservation analyses and point out regions that require further investigation, essential inventory planning actions (Sousa-Baena et al. 2014, Oliveira et al. 2016, 2017), in addition to directing funding and research to address such issues (Stendera et al. 2012). Indeed, it is common in tropical countries that the biodiversity collection is deeply flawed, which is also true in the Brazilian case (Oliveira et al. 2016). Moreover, the heterogeneous nature of knowledge on taxa, habitats, and biomes imposes the need of surveys on diversity and distribution of freshwater species (Brandon et al. 2005) - a relevant, yet highly threatened biodiversity component (Dudgeon et al. 2006). Although their potential as sensitive indicators of environmental conditions is well known, microorganisms hardly figure in any method aimed at assessing the nature of intrinsic conservation values, mainly due to taxonomic difficulties and lack of knowledge on species ecology and distribution (Coesel 2001). Many of their species can be endemic and some seem to be restricted to a small geographic area, hindering even more to further analyze their conservation status (Mann & Droop 1996). In the case of diatoms, even in well-documented regional compilations, essential information related to their conservation biology is often missing (e.g., Van Dam et al. 1994, Coesel 2001, Vanormelingen et al. 2008, Novais et al. 2014).

Diatoms are unicellular and belong to a group of photosynthetic eukaryotic microalgae well known for their siliceous cell walls, featuring different shapes and a myriad of types of pores and structures that allow exchanges with the nutrient sources and movement on substrates (Mann 1999, Kooistra & Medlin 1996, Kociolek 2010). These structures are used to differentiate species and group taxonomy and systematics (Round et al. 1990). They are widely distributed through most aquatic ecosystems and humid surfaces, like mosses, bromeliads, pounds, rocks, and soils (Maltsev et al. 2021, Soininen 2007). Among the various genera and species complexes, the estimated number of extant species of diatoms varies between 30,000 and 100,000 (Mann & Vanormelingen 2013).

Diatoms are one of the most important freshwater algae group in the scope of ecosystem functioning (Masouras et al. 2021) due to their contribution to nutrient cycling, such as phosphorus, nitrogen, silica, and carbon (Allen et al. 2006), as well as for representing over 25% of the primary productivity on earth, in addition to their crucial role in the food chain of aquatic ecosystems (Kociolek 2010). Because of their well-known ecological tolerances and well-preserved taxonomic features in long-lasting samples, diatoms are important tools for water quality biomonitoring programs (Soininen 2007, Kociolek 2010), paleolimnology reconstruction of ecological and nutrient references conditions (Bennion et al. 2011), and climate changes patterns (Spiridonov et al. 2021). These approaches demonstrate the role of diatoms in hydric resource management by identifying potential areas for ecological preservation, energy power generation, irrigation, and human consumption (Masouras et al. 2021, Wengrat et al. 2019, Passy 2008).

Historically, the early Brazilian sampling procedures encompassed freshwater, marine, and humus attached to Gramineae, in Tefé Lake, Amazonas state, Barra Beach, in Rio de Janeiro, and Santo Antônio do Monte, in the state of Minas Gerais, respectively, between 1829 and 1841. Naturalist explorers Eduard Friederich Poeppig and Karls Sigsmund Kunth were responsible for the collections. The samples were sent to Ehrenberg and the respective paper was published in 1843. The collection is currently stored at the Museum für Naturkunde, in Germany. In turn, Hermes Moreira-Filho was the first Brazilian diatomist and carried out his studies on diatoms back in 1959. He introduces periphytic diatoms flora in *Sargassum* (Moreira-Filho 1959) and thereafter publishes studies on diatoms in mollusk stomach content (Moreira-Filho 1960), estuarine planktonic diatom (Moreira-Filho 1961, Moreira-Filho & Kutner 1962), diatoms in *sambaquis* (Moreira-Filho & Mômoli 1962), and a new genus of an estuarine diatom (Moreira-Filho 1968). Over time, other Brazilian authors have published many other works on the subjects of flora (e.g., Morais et al. 2019, Silva-Lehmkuhl et al. 2020), new species (e.g., Tusset et al. 2018, Costa et al. 2019, Bertolli et al. 2019, Lehmkuhl et al. 2019, Morais et al. 2020, Zorzal-Almeida et al. 2020, Marquardt et al. 2021a, b), ecology (e.g., Marquardt et al. 2017, Zorzal-Almeida et al. 2018, Medeiros et al. 2020), bioindicators (e.g., Lobo et al. 2015), and paleolimnological approach (e.g., Fontana et al. 2014, Wengrat et al. 2019). However, the evolution and current status of diatom research in Brazil have not yet been addressed.

Scientometrics employs quantitative and statistical methods to map trends in the scientific literature and generate information and discussions on a specific topic (Spinak 1998), in addition to filling gaps and guiding further investigations (e.g., Carneiro et al. 2008, Schneck 2013, Wang et al. 2015, Zhang et al. 2019). We propose a scientometric analysis to identify, quantify, and describe patterns in diatom research (spatial and temporal) during the period of 1843–2020 in Brazil. Our goals are (1) to summarize and categorize diatom research topics, (2) to describe how the related studies evolve and developed over time, as well as respective journals, (3) to identify the most studied regions and environments, and (4) to indicate the main institutions and works addressing diatom research and related interactions. Our results bring insights that can benefit the understanding of the future scenario and studies gaps on diatom and Brazilian freshwater ecosystem conservation.

MATERIALS AND METHODS

We searched for diatom studies in Brazil published until 2020 on three electronic databases: ISI Web of Knowledge (https://www.webofknowledge.com), Scopus (www.scopus.com), and Scielo (https://scielo.org). For the two first databases, we searched based on the following terms: Diatom* AND Bacillariophy* AND Brazil*; Diatom* AND Phytoplank* AND Brazil*; Periphy* AND Diatom* AND Brazil*; Phytoplank* AND Bacillariophy* AND Brazil*; Periphy* AND Bacillariophy* AND Brazil*; Perifít* AND diatomácea* AND Brasil*; fitoplanc* AND diatomácea* AND Brasil*. For Scielo, we used the following terms: Diatom AND Brazil; Diatomáceas AND Brazil; Perifítica AND diatomáceas AND Brasil; Diatomáceas AND perifíton and Brasil; Diatomáceas AND Bacillariophyceae AND Brasil; Diatomáceas AND Bacillariophyta AND Brasil; Diatoms AND Bacillariophyta AND Brazil; Bacillariophyceae AND phytoplankton AND Brazil. Papers that had first been published online until 2020 were included, even if the published volume indicated 2021 (one case in this study).

Additionally, we included publications identified from other sources, such as bibliographic references in papers on electronic databases and authors' abstracts in the manuscripts. We disregarded papers that assessed only marine species/environments (only estuaries presenting freshwater samples were included in our study), as well as those without analyses of samples collected in Brazil. Also, we did not consider diatom species described in books or other publications not included in our search on the database. We only included books that addressed exclusively Brazilian diatom samples (one case in this study).

We gathered the following information from the selected articles:

1) Keywords
2) Journal name and year of publication
3) Language
4) Sampling sites (state/region, and coordinates)
5) Study approach (see description below)
6) Environment of study (rivers/streams, lakes/lagoons, reservoirs, wetlands, estuary, and others)
7) Sampled biological community/compartment (see description below)
8) Taxonomic novelty (number of new genera, new species, and new varieties described in the paper)
9) Authors
10) Authors' affiliation institutions

We classified the paper according to the approach used in each publication, which could cover more than one category, as in:

1) Animal diet: studies involving the removal of diatoms from stomachalcontent or used to feed another organism.
2) Ecological: studies investigating the factors that drive communities or their patterns in space-time, as well as species autecology.
3) Monitoring: studies assessing environmental quality using diatom community as marker.
4) Palaeoecology: reconstruction of ancient environment using diatoms as a proxy.
5) Physiology: studies assessing physiological aspects at the individual level (photosynthesis, lipid production, teratology etc.).
6) Species description (diatom flora): showing descriptions of local populations of species already known. It must contain illustrations.
7) Species list: a simple list of the species found, without illustrations (although with description).
8) Taxonomic: population-based description of new species or other taxonomic level, with illustrations. It could be either new combinations or taxonomic reviews.
9) Others: studies that do not fit any of the descriptions above.

We also recorded the origin of the diatom material according to the biological community or compartment: 1) phytoplankton, 2) periphyton (including epiphyton, epipelon, epipsammon, epizootic, among others), 3) surface sediment, 4) stomachal content, and 5) other origin that do not fit any of the descriptions. It is worth mentioning that a single study can be attributed to different origins.

We also determined the Cooperation Index, which indicates the level of interaction among authors considering the number of their respective publications. The index was calculated as the number of partnerships divided by the number of publications of each author or each institution. We also calculated the transitivity from network analysis, which is the probability of two researchers who share a common partner author writing a manuscript together (Csárdi et al. 2016). All analyses were performed on the R Program (R Core Team 2020) and the packages *igraph* (Csárdi & Nepusz 2006), *tidyr* (Wickham 2020), and *wordcloud* (Fellows 2018). Wordcloud was elaborated using keywords with more than five citations to avoid a crowded image.

RESULTS

Screening of the published studies/bibliographies

We compiled 758 papers from three databases and additional sources (Figure 1) that had been published until 2020. According to our eligibility criteria, we excluded 279 records that assessed only marine diatoms or did not include any sampling in Brazil, thus generating an analysis containing 479 studies (Table available in https://github.com/stefanozorzal/braziliandiatoms.git). Scopus was the electronic database that returned the highest number of publications (479).

We recorded 836 different keywords (plural words were converted into singular) in the analyzed publications. Diatom (127), taxonomy (66), Brazil (47), periphyton (42), and phytoplankton (41) were the five most cited keywords. Other words related mainly to the type of environment, region, or study approach were commonly used (Figure 2).

The number of diatom publications has increased over time, especially since the

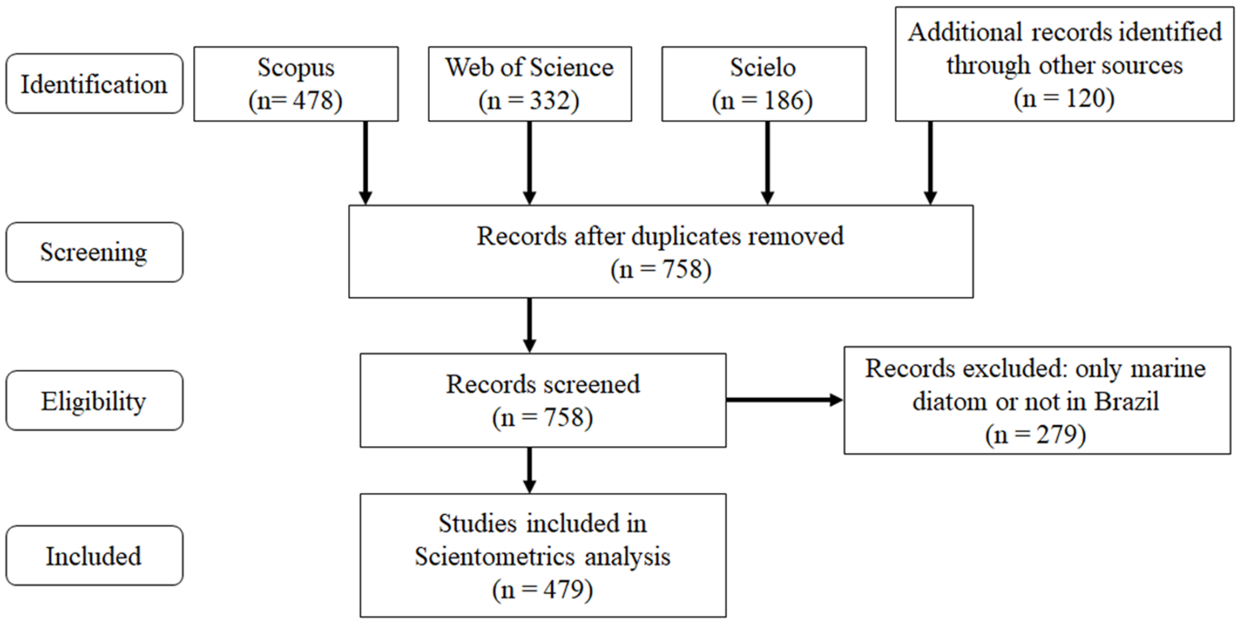

Figure 1. Systematic review flowchart.

2000s (Figure 3a). Only in the last decade, 257 manuscripts were published, representing more than a half of the recorded studies. About 58% of the publications (279) were published in Brazilian journals. In the earlier decades (1970s to 2000s), the manuscripts were mostly published in Brazilian journals. However, in the last decade, Brazilian journals published the same number of manuscripts about diatoms than non-Brazilian journals. By dividing figures from the journals, we found 79 non-Brazilian journals and 51 Brazilian journals, three of them (Acta Botanica Brasilica, Brazilian Journal of Biology, and Iheringia) encompassed the largest numbers of publications (Figure 3b). English was the main language in the manuscripts (65.5%), with emphasis to the last decade, comprising about 45% of the manuscripts.

Types of Diatom studies in Brazilian regions

More than 40% of the publications addressed diatoms from the South region and one-quarter of the publications investigated diatoms from the Southeast (Figure 3c). Studies carried out exclusively in the states of Paraná (PR), São Paulo (SP), or Rio Grande do Sul (RS) account for more than 53% of the publications. A few publications were collected over a large area, considering the extension of the Brazilian territory (Figure 4).

Studies addressing only diatom floristic (diatom flora description, species list, new species description etc.) were the most frequent throughout all decades (Figure 5a). Purely ecological studies (community ecology, monitoring, paleoecology etc.), however, were overlooked in the early years having gained numbers only from the 2000s. Even if we considered studies with both approaches (ecological and floristic), it would show the same tendency for purely ecological studies. Interestingly, most studies represent efforts to understand how diatom communities are controlled by environmental factors or finding species ecological preference (Figure 5b). In this context, we found studies related to floristics, such as flora description, species list, and taxonomic (e.g., new species or new combinations), and it is worth emphasizing the

Figure 2. Wordcloud of the keywords with more than five citations.

low number of monitoring studies since diatoms are largely used as bioindicators worldwide (Lobo et al. 2016, Reid et al. 1995). Lotic environments were the focus of most studies, with twice as many publications for lakes/lagoons or reservoirs (Figure 5c). In turn, most studies in the scope of diatom communities/compartment (Figure 5d) focused on phytoplankton, followed by periphyton in second place.

A total of 66 papers described four new genera, 127 new species, and four new varieties in Brazil, out of which 64% were described in the last decade. Furthermore, the 1970s and 1980s presented a gap of new taxa description (Figure 6).

Research network

Ludwig TAV was the author with the highest number of publications (71 publications), followed by Torgan LC (60 publications) (Table I), both of them also had the greatest variety of partnerships (Figure S1 – Supplementary Material). In fact, we found a positive correlation between the number of publications and number of partnerships (Pearson $r = 0.90$; $p < 0.01$). However, the Cooperation Index did not follow such correlation. Despite their 11 publications, Bartozek ECR and Marquardt GC were the authors with the highest Cooperation Index, thus indicating that the diversity of interaction seems to be author-dependent. Eigenvector centrality indicates the connection between authors who are connected to other authors, and so on. The authors with the highest eigenvector centrality also had the highest number of publications. The exception was Torgan LC, probably due to her partnerships whose publications involved a restricted group of authors, or just one or few publications. In general, the authors network showed a higher transitivity (0.39), which is the probability of two researchers who share a common partner writing a manuscript together. Such findings demonstrate the dynamics of the authors' connection (Figure S1).

In the scope of institutions, the Federal University of Paraná (UFPR) presented the highest number of publications, followed by Fundação Zoobotânica (Fund ZooBot) and Instituto de Botânica/São Paulo (IBt-SP) (Table II). We also recorded a large number of different partnerships in these institutions (Figure S2) and a positive correlation between the number of publications and number of partners (Pearson $r = 0.84$; $p < 0.01$), similarly to authors. Regarding the Cooperation Index, the lowest values were found for UFPR and Fund ZooBot when considering the institution as a partner. It can be related to publications with authors from the same institution (researchers and graduate or postgraduate students). In contrast, the Federal University of Rio de Janeiro (UFRJ) and Federal University of Goiás (UFG) showed a high Cooperation Index value, despite the lower number of publications. It is worth highlighting the case of the Public Research Centre Gabriel Lippmann (PRC Gab Lipp) and Luxembourg

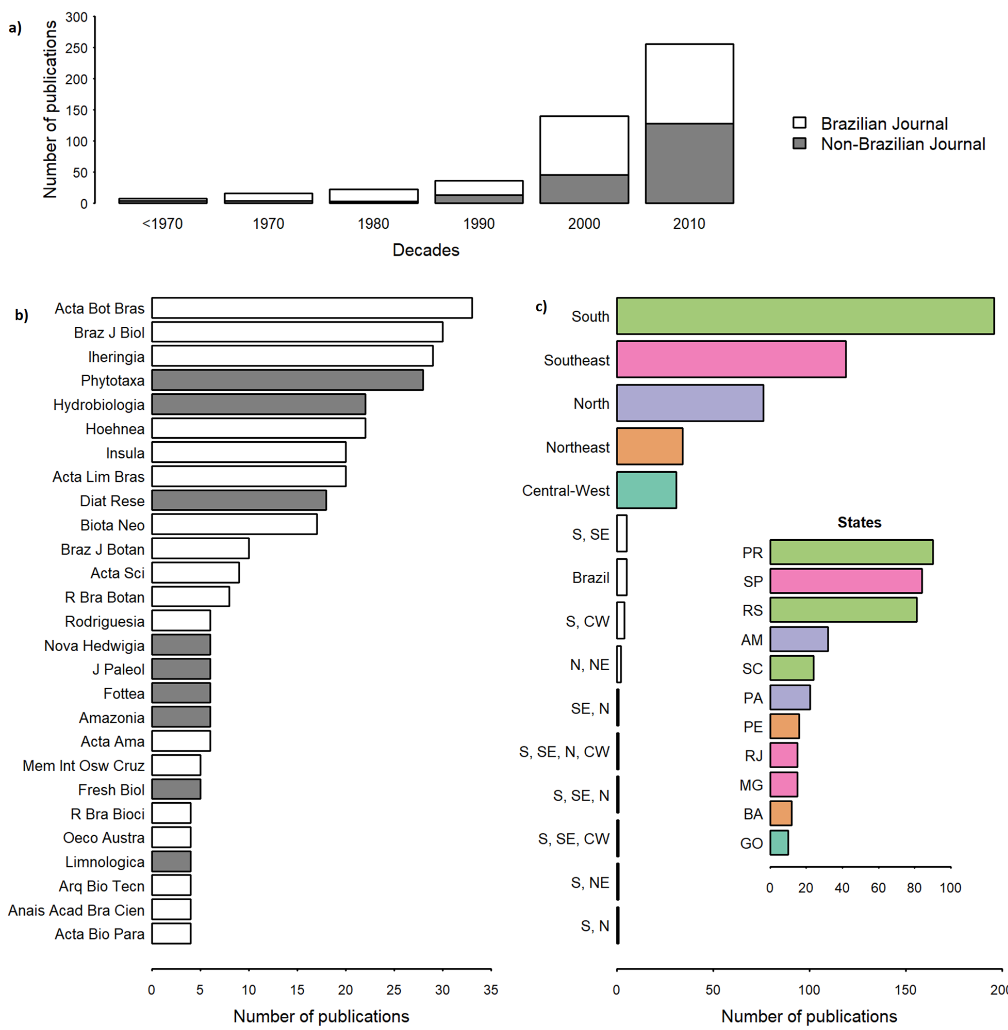

Figure 3. a) Publications over decades. b) Publications per journal (showing journal with 4 or more publications). c) Number of publications per sampling sites region: inset graph shows the number of publications in the Brazilian States (with 10 or more publications). Colors in the inset graph indicate the regional location of the state.

Institute of Science and Technology (LIST) for their international status among the top ten institutions based on the number of publications and high cooperation index. However, it is important to point out that the PRC Gab Lipp has been part of the LIST since 2014. In our study, we decided to keep the original names of the institutions found in previous publications. Finally, the eigenvector centrality shows that IBt-SP and UFPR seem to be the more strategic and central institutions in the scope of diatom studies in Brazil. Despite large, the transitivity value for institutions network (0.26) was lower than for the authors' network.

Sampling effort distribution

Early diatom sampling campaigns (before 1970s) focused on the Amazon region, Pernambuco State (Northeast region), and South and Southeast regions (Figure 7). Between the 1970s and 2000s, efforts increased toward collecting in these regions along with the Central-west region and other states of Northeast. In the 2010s, Brazil experienced a rising trend of samplings efforts in all states. However, the South and Southeast regions encompass the largest number of sampling sites, especially the states of São Paulo, Paraná, and Rio Grande do Sul, with 450, 376, and 271 sampling sites, respectively. We

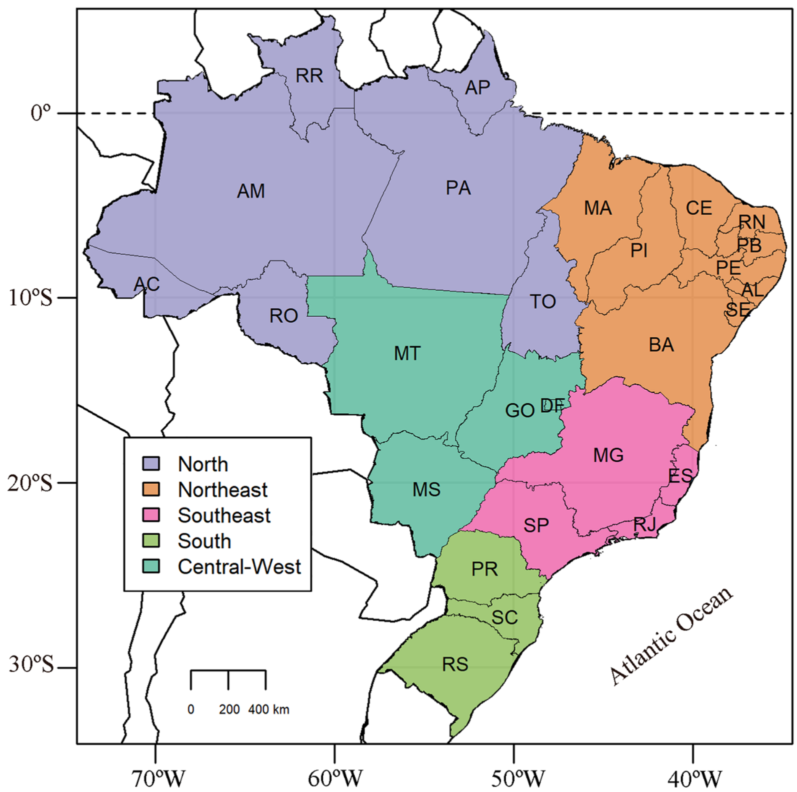

Figure 4. Brazilian States distribution per region: North (AC – Acre, AM – Amazonas, RR – Roraima, RO – Rondônia, AP – Amapá, PA – Pará), Northeast (MA – Maranhão, PI – Piauí, CE – Ceará, RN – Rio Grande do Norte, PB – Paraíba, PE – Pernambuco, AL – Alagoas, SE – Sergipe, BA – Bahia), Central-West (MT – Mato Grosso, MS – Mato Grosso do Sul, GO - Goiás, DF – Distrito Federal), Southeast (MG – Minas Gerais, ES – Espírito Santo, RJ – Rio de Janeiro, SP – São Paulo), South (PR – Paraná, SC – Santa Catarina, RS – Rio Grande do Sul).

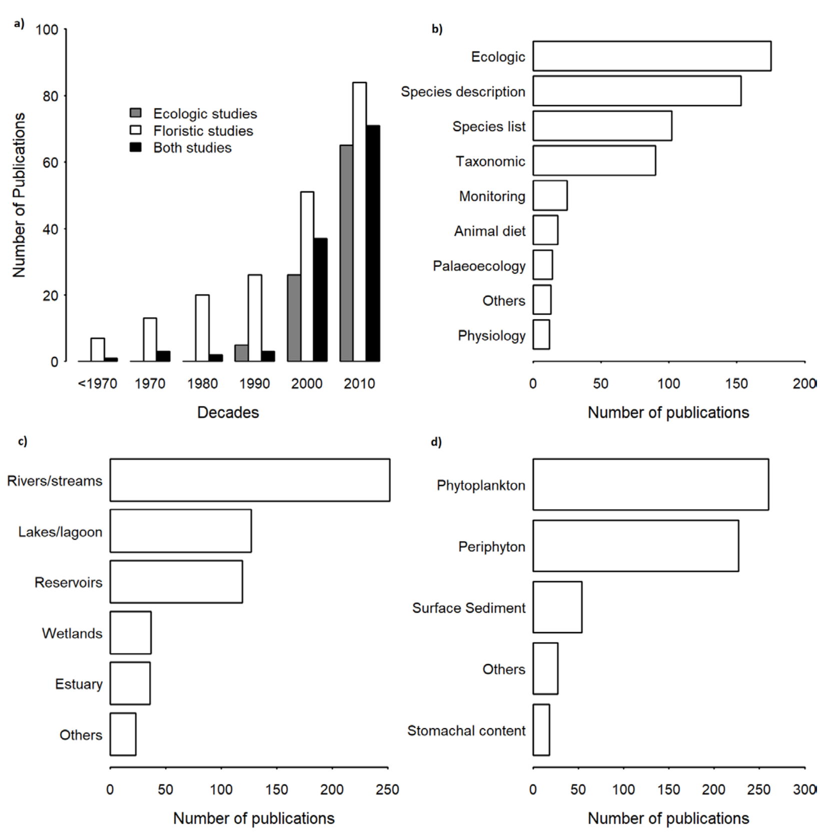

Figure 5. a) Number of publications about Diatom Ecology and Florist over the decades. Ecologic studies also considered monitoring and paleoecology approaches. Floristic studies considered taxonomic, floristic description, and floristic list. **b)** Number of publications according to the study approach. Others (less than 10 publications): Archeology, Biological Control, Biomineralization, Genetic, Methodology, Revision, Speleothems, Stomachal content. **c)** Number of publications according to the environment. Others (less than 10 publications): Bromelia, Diatomite, Doline, Inlet, Mangroove, Ponds, River Delta, *Sambaqui*, Speleothems, Subaerial, Temporary environmental, *Vereda*, or not available. **d)** Number of publications according to communities/compartiment. Others (less than 10 publications): Core sediment, Diatomite, Moss, Phytotelma, Speleothems, or not available.

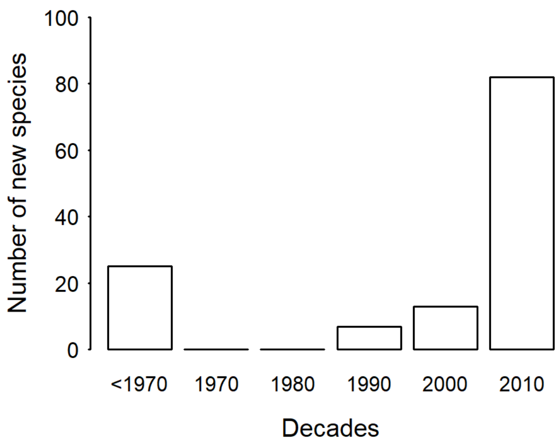

Figure 6. **Number of new species over decades.**

recorded 1836 samplings considering campaigns in space and time.

DISCUSSION

Research on Brazilian continental diatoms has grown at an accelerated rate over the past twenty years. It has been related to species distribution, ecology of communities, and description of new species. The publication rate over the years in Brazil is similar to those found in research in emerging countries, such as China (Zhang et al. 2019). According to our study, most of the works published based on diatom samplings in Brazil address flora description or attempts to understand diatom ecology in their various aspects. These studies do not seem to follow the global trend. In a global scale review, Zhang et al. (2019) found that "hot" topics are related to diatom distribution on a large spatiotemporal scale and the use of molecular techniques, a scenario where basic studies have been droping. Our analyses assessed studies on the distribution of diatoms on a small scale (mostly), few use genetic tools, while the vast majority fit into basic studies. From our point of view, basic studies are still very relevant to understand the diversity and distribution of diatoms in Brazil due to its continental dimension (8.51 million km², the fifth largest in the world; IBGE 2020) and the spatially skewed distribution of the sampling. Another argument in favor of baseline studies is the significant increase in descriptions of new species over the last decade, indicating a potential for further findings.

The factors above-mentioned have guided the research design to obtain results that can be published on international journals. This interest probably derives from (1) an attempt to disseminate the work performed internationally by publishing on journals with better visibility, and (2) the need to comply with the requirements of scientific production of postgraduate programs, as well as competition in research funds processes. Considering these factors, Brazilian journals may no longer be attractive because of their insufficient visibility to support the real need of Brazilian researchers. The Brazilian journals that most published papers on diatoms do not have any impact factor at all or have a relatively low one (Acta Botanica Brasilica – 1,048 / 2019; Brazilian Journal of Biology – 1,260 / 2019). As the classification of journals in Brazil is based on the 'Qualis' criteria, created by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES – Barradas Barata 2016), a researcher's productivity may decrease when publications are concentrated only on Brazilian journals, leading to the disqualification of graduate programs or a low classification in processes for obtaining research funds from development agencies. We observed an increase in the publication of works that integrate both ecological and floristic studies. Strictly floristic diatom works have usually been published on magazines with a local extension (e.g., Hoehnea), in addition, in our experience, they are increasingly restrictive in accepting this type of publication. The studies analyzed seem to have adopted the strategy of merging species description and autecological or community

Table I. Number of publications and number of different partner authors for authors with more than ten publications. Bold values are the five highest in each column.

Author	Publication	Partnership	Cooperation Index	Eigenvector Centrality
Ludwig TAV	**71**	**65**	0.93	**0.94**
Torgan LC	**60**	**62**	1.03	0.56
Tremarin PI	**49**	**55**	1.12	**0.97**
Wetzel CE	**42**	**51**	1.21	**1.00**
Bicudo DC	**41**	**51**	1.24	**0.99**
Ector L	40	50	1.25	**0.99**
Bicudo CEM	26	34	**1.31**	0.79
Rodrigues L	23	18	0.78	0.23
Lobo EA	17	25	**1.47**	0.43
Bueno NC	16	22	**1.38**	0.27
Moreira-Filho H	16	19	1.19	0.20
Souza-Mosimann RM	14	13	0.93	0.07
Bere T	12	1	0.08	0.00
Bartozek ECR	11	22	**2.00**	0.57
Marquardt GC	11	18	**1.64**	0.52
Salomoni SE	11	13	1.18	0.13

studies over the last 20 years among, which may have been an attempt by the authors to meet the demand of international (and also Brazilian) magazines to include ecological data in floras, in addition to improving information on the species found in Brazil. In view of the interest in the internationalization of publications, the English language has been increasingly used in the publications of diatoms works in Brazil. This is a worldwide trend in science that has persisted over a few decades in all areas of knowledge.

In the 1970s and 1980s, publications were still scarce, with most of the works related to floristic surveys. It is interesting to note, however, that no new taxon was registered for Brazil in this period. Despite the low publication rate, more than 20 new taxa (between species and varieties) had been described in previous years. In the first 130 years of research on diatoms in Brazil (from 1843), all new taxa were described by foreign researchers (Ehrenberg and Patrick, Table available in https://github.com/stefanozorzal/braziliandiatoms.git). It was only in 1983 that Torgan (1983) published a new variety of *Eunotia didyma* Grunow ex Zimmermann (1915) based on material from the South of Brazil. This gap can be explained by the lack of Brazilian specialists, who would have easily accessed material and sampling sites. At that time, there were few trained researchers and trainees (biographical consultation of researchers in the Curriculum Vitae of the Lattes Platform of the National Council for Scientific and Technological Development – CNPq). Difficulty in accessing specialized equipment (e.g., scanning electron microscope – SEM) may also have been an important factor in maintaining this gap. The

Table II. Number of publications and number of different partner institutions for the top ten institutions considering the number of publications. Bold values are the five highest in each column.

Institution	Publication	Partnership	Cooperation Index	Eigenvector Centrality
UFPR	**101**	**34**	0.34	**0.95**
Fund ZooBot	**71**	**24**	0.34	**0.72**
IBt-SP	**69**	**40**	**0.58**	**1.00**
UFRGS	**46**	**24**	0.52	**0.73**
UEM	**44**	16	0.36	0.49
LIST	23	**21**	**0.91**	0.64
UNIOESTE	22	8	0.36	0.29
UFRJ	21	**21**	**1.00**	0.33
UFG	20	20	**1.00**	0.61
PRC Gab Lipp	19	**21**	**1.11**	**0.66**

UFPR - Federal University of Paraná; Fund ZooBot - ZooBotânica Foundation; IBt-SP - Botany Institute of São Paulo; UFRGS - Federal University of Rio Grande do Sul; UEM - Estadual University of Maringá; LIST - Luxembourg Institute of Science and Technology; UNIOESTE - Western Paraná State University; UFRJ - Federal University of Rio de Janeiro; UFG - Federal University of Goiás; PRC Gab Lipp - Gabriel Lippmann Institute.

first work by Brazilian researchers using SEM to analyze diatoms was published in 1989, by Callegaro & Salomoni (1989). Finally, the difficulty in accessing the specialized bibliography for comparison with Brazilian material may have discouraged the publication of taxonomic news.

Interactions among authors and research institutions are clearly stronger in the South and Southeast regions of the country (network graphics, Figure S1 and S2), mainly among the states of São Paulo, Paraná, and Rio Grande do Sul. Much of the research published and included in our analyses were carried out in these three states or by researchers from institutions in these states. Consequently, the concentration of studied locations is increasing in the South and in the São Paulo state, where specialists and graduate courses were allocated. It was only in the last decade (2010s) that diatoms from other Brazilian regions started to be further explored. This may have resulted from the migration of newly trained specialists to states with little or no study on the community. The opening of federal universities outside the traditional Brazilian research centers provided many of these researchers with the opportunity to start their scholar trajectory. During the 2000s, Brazil experienced an intense opening of new federal higher education institutions, mainly outside the capitals (Figure S3; http://portal.inep.gov.br/basica-censo-escolar-sinopse-sinopse). It is interesting to note that despite the difficult access and the distance from the main research centers, the Amazon region presents a relevant number of studies, including collections included in the first work on diatoms, written by Ehrenberg, in 1843. However, it should be highlighted that these samplings were carried out by researchers that were not affiliated with local institutions.

Despite the suggested internationalization of publications, it seems to us that, in terms of partnership, it continues to be local. The Luxembourg Institute of Science and Technology (LIST) had the highest number of partnerships in works with Brazilian institutions. However, this

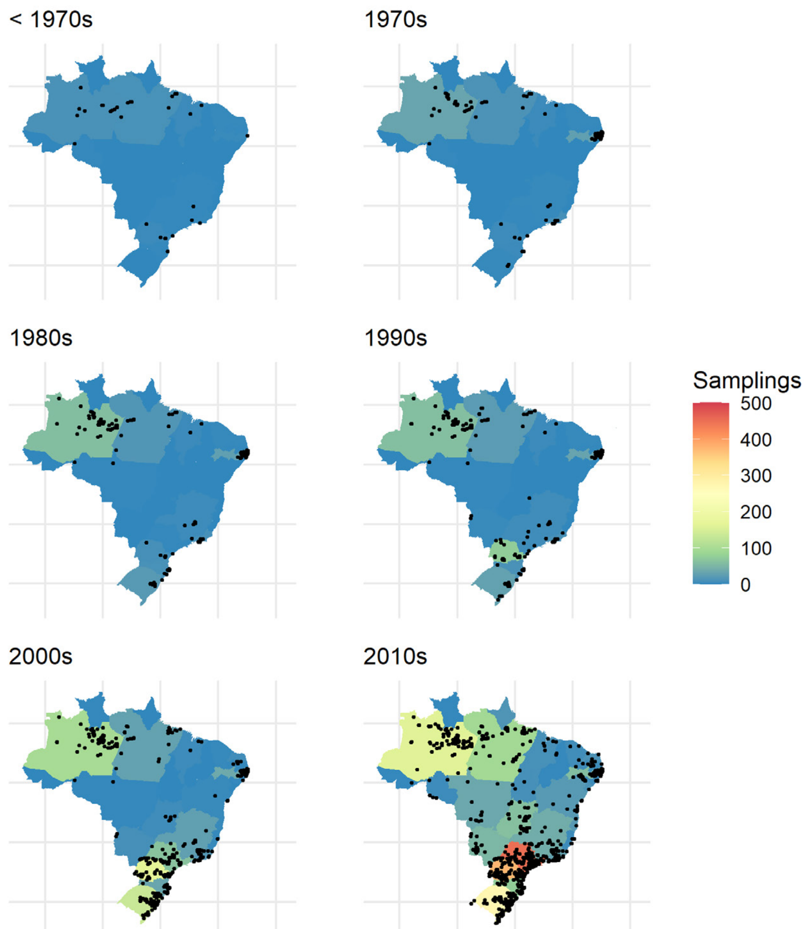

Figure 7. Cumulative distribution of sampling sites in Brazil over the decades (black points) and number of sampling sites per state (color areas).

seems to have resulted from the performance of a researcher trained in Brazil (CE Wetzel). The most consolidated international partnerships in the scope of diatoms studies in Brazil, a greater number of partner institutions was expected. Certainly, strengthening partnerships with at least one foreign institution is a promising start as it opens the door to other partnerships. Considering that the pool of diatom studies emerged in the last two decades, international partnership networks are expected to extend over the coming years.

Aggregate pattern of sampling sites can generate large gaps in the knowledge of diatom biodiversity, as well for other groups (Oliveira et al. 2016). In addition to the location of the specialists, as previously discussed, logistical issues can amplify this pattern. In the case of aquatic environments, such as most of the diatom studies, access to the water body and the more internal areas of these systems, such as the pelagic zone of a lake or the interior of a wetland, makes sampling difficult. The sampling bias found may also be associated with the distribution of investment in biodiversity research in Brazil (e.g., PELDs – Long Term Ecological Research). Magnusson et al. (2016) presented a map with a distribution occurring mainly in the Brazilian coast, especially in the South and Southeast regions, as well as in the Amazon. These are the same places with the highest concentration of collections in diatoms studies, suggesting that the bias found involves the distribution of investments as well.

Brazil is among the countries with the greatest biodiversity in the world (Lewinsohn & Prado 2002). The sampling bias presented in ours (diatoms) and in other works (for other groups; e.g., Oliveira et al. 2016) indicates an underestimation of the Brazilian biodiversity. For example, the aquatic environments of the Savanna Tropical Estacional Semiárida (Caatinga) and Savana Tropical Estacional (Cerrado) biomes (sensu Coutinho 2016) are spatially subsampled in diatom studies in relation to biomes such as Tropical Forest and Atlantic Forest. Even so, Brazil has recorded over 80 new taxa just in the last decade, which reinforces the need to uncover the true biodiversity of Brazilian diatoms.

Considering their ecological importance (Stevenson 2014), improving the knowledge on the biodiversity of diatoms can help managers selecting and managing the increasingly threatened areas of aquatic ecosystem conservation (Reid et al. 2019), as well as monitoring the quality of water for various purposes by sanitation bodies and other environmental agencies. To this end, we suggest potential lines of action to enhance the quality of diatom studies. For researchers located in reference centers (e.g., São Paulo, Rio Grande do Sul, and Paraná), we suggest (1) maintaining the training of specialists with projects for floristic survey in subsampled regions, (2) developing applied research in regions with greater knowledge on diatoms biodiversity, and (3) proposing partnerships with sanitation agencies and environmental organizations to use diatoms as a biotechnological tool. For researchers from other regions, we suggest (1) the development of projects in partnership with reference centers, and (2) research for knowledge of biodiversity in areas with little sampling effort. For development agencies, we indicate (1) launching programs to establish specialists in areas distant from reference centers, (2) promoting biodiversity projects in the subsampled regions, (3) encouraging courses and workshops on diatoms for continued training of human resources in areas without any or with few trained researchers, and (4) stimulating the arrival of visiting researchers in these areas to train specialists. Finally, we emphasize the importance of a more active collaboration network in the context of diatoms study and knowledge to fill the existing gaps and assist in areas that are yet to be studied. We hope that our study can be the first step towards solving the problems discussed.

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