DIATOM-BASED PALEOENVIRONMENTAL RESEARCH: GLOBAL TRENDS, REGIONAL DISPARITIES AND THE EVOLVING ROLE OF SOUTH AMERICA

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ABSTRACT

The use of diatoms in paleoenvironmental research is of the utmost importance for reconstructing past ecosystems because it provides crucial insights into the adaptability and resilience of these systems under ongoing climate change and increased human impacts. Maintaining a comprehensive dataset distribution is crucial to ensure the validity and relevance of these reconstructions on a global scale. This scientometric study aimed to analyze trends in diatom-based paleoenvironmental research on a global scale with an emphasis on South America. This study aimed to investigate disparities in the geographical distribution of diatom-based paleoenvironmental studies, collaboration networks in the field, and regions in which this research is lacking. The Scopus search criteria excluded certain types of publications, such as conference articles and notes. The search focused on articles, reviews, books and chapters of books using specific keywords aligned with the objectives of this study. Using the Scopus database, we identified 7,091 publications (1979-2023) that employed diatoms as a primary proxy for paleoenvironmental reconstruction. The results show significant changes in this field recent decades. The analysis highlights a marked upsurge in publication output during the 1980s and a substantial increase in publications after 2000. This upward trend in scientific documentation reflects the growing interest in and recognition of the importance of this field in the context of palaeoecology and environmental sciences. After 2011, the results revealed a shift in thematic focus from historical and geological reconstruction to ecological, anthropogenic, and climatic interactions. Key researchers, including Smol JP, Leng MJ, and Birks HJB, have been at the forefront of international collaborations. Since the 2000s, South American studies have focused primarily on lakes, climate change effects, and volcanic activity. In this region, researchers such as Maidana N.I., Urrutia, R., and García-Rodriguez, F. emphasized the significance of regional ecosystems and their paleoenvironmental history in the global context of the field. Despite its high biodiversity, South America contributed only 6.7% of the global research output, placing it 19th globally. Socioeconomic factors and other obstacles faced by researchers in the region could explain the observed disparity in scientific output in South America compared to other regions. To unlock South America's vast potential for diatom-based paleoenvironmental research, which boasts the highest global biodiversity yet remains underrepresented in the field, stakeholders must implement equitable partnerships, increase funding and improve their academic infrastructure and opportunities. These strategies are crucial for advancing the global paleoenvironmental understanding, informing future conservation and environmental policies in South America, and promoting scientific progress on a global scale.

Keywords: Bacillariophyceae; Diatom-based proxy; Paleoenvironmental analysis; Paleolimnology; South American diatom studies.

RESUMO

INVESTIGAÇÃO PALEOAMBIENTAL BASEADA EM DIATOMÁCEAS: TENDÊNCIAS GLOBAIS, DISPARIDADES REGIONAIS E A EVOLUÇÃO DO PAPEL DA AMÉRICA DO SUL. O uso de diatomáceas em estudos paleoambientais é de extrema

importância para a reconstituição de ecossistemas passados, pois fornece informações essenciais sobre a adaptabilidade e a resiliência desses sistemas, sobretudo em um contexto de crescentes impactos antrópicos e de mudanças climáticas em curso. Para garantir a validade e a relevância dessas reconstituições em escala global, é crucial manter uma distribuição geográfica equitativa dos estudos. Com o intuito de mapear o progresso científico das pesquisas paleoambientais que empregam diatomáceas como indicadores, este estudo cientométrico foi delineado para investigar as tendências e padrões em âmbito global, com enfoque particular nos desenvolvimentos pertinentes à América do Sul. Os objetivos do estudo se estenderam para incluir um exame detalhado das disparidades na distribuição geográfica dos estudos, avaliar o avanço das temáticas de pesquisa priorizadas ao longo do tempo, analisar as redes de colaboração científica e identificar regiões onde a carência de pesquisas nesse campo é mais pronunciada. Os critérios de busca excluíram certos tipos de publicações, como artigos de conferências e notas, e focaram em artigos, revisões, livros e capítulos de livros usando palavras-chave específicas e alinhadas aos objetivos. Utilizando o banco de dados Scopus, identificamos 7.091 publicações entre 1979 e 2023 que empregaram diatomáceas como principal indicador para reconstituição paleoambiental. Os resultados revelaram mudanças significativas nas últimas décadas. Houve um notório incremento na produção científica iniciado na década de 1980, seguido por um segundo aumento expressivo na quantidade de estudos publicados após 2000. Essa tendência ascendente reflete um interesse crescente e a reconhecida importância deste campo de estudo no contexto da paleoecologia e das ciências ambientais. Após 2011, observou-se uma transição no foco temático dos estudos, migrando de uma predominância em reconstituições históricas ambientais e geológicas para estudos que focaram em interações ecológicas, antropogênicas e variáveis climáticas. Esta mudança reflete uma resposta acadêmica às urgências impostas pelas alterações globais contemporâneas e à necessidade de compreender como os ecossistemas responderam às perturbações antrópicas e climáticas no passado, um entendimento crucial para antever e mitigar impactos futuros. Pesquisadores-chave, incluindo Smol JP, Leng MJ e Birks HJB destacaram-se em colaborações internacionais. Desde 2000, os estudos sul-americanos concentraram-se principalmente nos impactos climáticos e das atividades vulcânicas a partir da análise de registros lacustres. Pesquisadores sul-americanos como Maidana NI, Urrutia R e García-Rodriguez F. enfatizaram a importância dos ecossistemas regionais e de sua história paleoambiental no cenário científico mundial. Apesar de sua elevada biodiversidade, a América do Sul contribuiu com apenas 6,7% da produção científica global na área, ocupando a 19º posição. A disparidade na produção científica observada na América do Sul comparada a outras regiões pode ser atribuída a fatores socioeconômicos e outros obstáculos enfrentados pelos pesquisadores da região. Parcerias equitativas, ampliação dos investimentos, melhorias na infraestrutura acadêmica e oportunidades aos pesquisadores locais devem ser implementadas para desbloquear o vasto potencial de pesquisa paleoambiental baseada em diatomáceas na América do Sul, que possui a maior biodiversidade global e está atualmente sub-representada na área. Essas estratégias são fundamentais para avançar o entendimento paleoambiental global, informar futuras ações conservacionistas e políticas ambientais na América do Sul, além de promover o progresso científico em escala global.

Palavras-chave: Bacillariophyceae; Diatomáceas como indicadores paleoambientais; Análise paleoambiental; Paleolimnologia; Estudos sul-americanos sobre diatomáceas.

1 INTRODUCTION

Sedimentary diatoms play a crucial role in the investigation of past environmental conditions, including ecological, limnological, and climate-induced transformations (BATTARBEE et al. 2002, SMOL 2022). These microorganisms, which are known for their sensitivity to environmental fluctuations, serve as valuable paleoenvironmental indicators and provide profound insights

into ancient aquatic ecosystems by uniquely responding to specific ecological conditions through changes in their abundance, presence or absence, and morphology (BATTARBEE et al. 2002, SMOL 2022). Consequently, they have made significant contributions to the elucidation of critical past environmental changes including climate oscillations (FONTANA et al. 2019, RODRÍGUEZ-ZORRO et al. 2022, ALMARAZ-RUIZ et al. 2023, BALASUBRAMANIAM et al. 2023, SAROS et al. 2023), limnological/ecological changes (WENGRAT et al. 2019, NASCIMENTO et al. 2021), hydrological regimes (RIBEIRO et al. 2010, FAYÓ et al. 2018, HAN et al. 2023), alterations in land-use practices (TRÁBERT et al. 2020, GARDOKI et al. 2023), and the historical deposition of pollutants and eutrophication (BENNION et al. 2004, COSTA-BÖDDEKER et al. 2012, FONTANA et al. 2014, SIMMATIS et al. 2022, CHEN et al. 2022, GREGERSEN et al. 2023).

Given the increasing significance of this field and its profound implications for understanding environmental history, adopting a global perspective in diatom-based paleoenvironmental research is of utmost importance. As research in this domain continues to advance, it is essential to evaluate global patterns and regional contributions comprehensively. An imbalance in the distribution of studies across certain regions compared to others can lead to diminished informativeness of proxy-based data. Given the paramount importance of proxy-based research and diatom-based paleoenvironmental studies efforts must be made to enhance and further develop these areas of inquiry. These studies can potentially reveal past ecosystem responses to various impacts, including their frequency and intensity (BENITO et al. 2022, GREGERSEN et al. 2023). Consequently, analysis of historical observational data provides valuable insights into contemporary and future environmental challenges. This information aids evidence-based decision making and complements conservation efforts, particularly when long-term monitoring data are unavailable (BENNION et al. 2004, BENNION & SIMPSON 2011, LIU et al. 2022). A comprehensive global examination of diatom-based paleoenvironmental research and future directions is essential, particularly in the context of ongoing climate change and associated environmental risks to freshwater ecosystems (DOUVILLE et al. 2022, ZHANG et al. 2023).

South America has emerged as a focal point of this research field for several reasons. First, the continent boasts a wealth of aquatic ecosystems, ranging from pristine lakes to intricately dammed and impacted rivers (FEARNSIDE 2006, ABELL et al. 2008, JUNK 2013), offering diverse historical dynamics and potentially unanswered scientific questions. Second, the complex and unique climatic conditions in South America underscore the importance of this region. The continent spans a remarkable spectrum of climate zones, from the humid tropical rainforests of the Amazon Basin to arid savannas, Patagonia deserts, and high-altitude Andes (NOGUÉS-PAEGLE & MO 1997, FOLLAND et al. 2001, CARVALHO et al. 2004, MARENGO 2004, MARENGO et al. 2004, GARREAUD et al. 2009, MA et al. 2011, ARIZMENDI et al. 2022). This climatically diverse region presents an exceptional opportunity to investigate how diatoms adapt to and interact with various environmental conditions over time. By examining the responses of diatom communities to varying climates and ecosystems, valuable information regarding the complex interplay between microorganisms, lakes, humans, and their surrounding ecosystems can be obtained. Additionally, varied levels of natural and anthropogenic disturbances in South America have critical implications for environmental conservation and management policies within the region (SALAZAR et al. 2007, SALAZAR 2016, WU et al. 2017, NAGY et al. 2019, ZALLES et al. 2021). Incorporation paleoecological data into contemporary conservation strategies is crucial, as it allows for a historical perspective on ecosystem changes, enabling policymakers to develop informed and proactive measures, instead of relying on simple solutions.

Analysis of South American lacustrine sedimentary archives using diatoms has enabled researchers to make significant contributions to answering global scientific questions regarding the environmental conditions of aquatic ecosystems. This approach resulted in significant advancements in the field, as exemplified by a diatom-based paleoenvironmental study in Chile (Lago Pichilaguna), which has provided a comprehensive understanding of long-term climatic fluctuations and their intersections with human interventions (SEPÚLVEDA-ZÚÑIGA et al. 2022). This study highlights the profound impact of historical human disturbance on aquatic and terrestrial ecosystems, exceeding their natural resilience and variability over the last millennium. Another example is the Lake Esponja, Northern Chilean Patagonia study, which employed multi-proxy analyses, including

diatoms (FAGEL et al. 2023). The results of this study revealed changes in volcanic supply, productivity, and detrital inputs, with diatom shifts indicating basin closure approximately 2,000 years ago, possibly due to tectonic activity related to the Mañihuales fault. Similarly, diatoms from Lago Cipreses, southeastern Patagonia, detailed the historical variability of the Southern Westerly Winds (SWW), a dominant wind system in the Southern Hemisphere that is crucial to regional climate oscillations (VILLACÍS et al. 2023). The diatoms in this study revealed distinct periods marked by an increased influence of Southwesterly Wind (SWW) on the regional climate interspersed with intervals of reduced wind impact.

Several studies have been conducted in certain territories, such as Chile, Argentina, and Peru. However, research on this topic in the Amazon region is limited. One of the few investigations carried out in the region was at Itupanema Beach in the State of Pará. This study employed diatoms to identify modifications in hydrodynamics, which included a period of sea-level regression and a dry season linked to the Little Ice Age (LIA), as well as a period of decreased precipitation in eastern Amazonia that persisted from 1300 to 1850 CE (RIBEIRO et al. 2010). In a recent investigation, a lake situated along the border between Brazil and Venezuela in western Amazonia, known as Lake Pata, exhibited a stable limnological profile over the past millennia. This stability was observed despite fluctuations in precipitation, which displayed the most significant variation during the Little Ice Age (LIA) (NASCIMENTO et al. 2021). The impact of the Little Ice Age (LIA) on Lake Pata was relatively moderate compared with other regional records, implying that this pristine lake may act as a reference system and respond differently to non-pristine lakes in the Amazon. Nevertheless, additional regional records are needed to facilitate comparative analyses and to advance our understanding of these observations.

Studies employing diatoms to infer past environmental changes in artificial lakes (reservoirs) in South America are rare. This scarcity of studies is surprising, considering the widespread practice of transforming larger rivers into lacustrine-dammed systems across the continent, serving purposes ranging from human water supply to hydropower generation (ZHANG & GU 2023). The dataset of georeferenced dams in South America showed 1,010 entries of dams with a combined reservoir volume of 1,017 km^3 (PAREDES-BELTRAN et al. 2021). In Brazil, 3,459 dams contribute to more than 80% of the water expansion in South America. Other Andean countries (Bolivia and Chile) also have many dams, more than 600 of which are located in the Peruvian Andes and are mainly used for irrigation and hydropower generation (ZHANG & GU 2023). Artificial lakes, crucial for human activities, are particularly vulnerable to eutrophication. Examples of studies primarily focused on Brazilian reservoirs highlight the threat of eutrophication and other anthropogenic impacts, signaling the need for further research. For example, WENGRAT et al. (2019) used diatoms from five Brazilian reservoirs with ages ranging from 50 to 90 years. This study provides information on the baseline conditions and degree of ecological change, aiding the management of regional reservoirs vulnerable to anthropogenic pressure (WENGRAT et al. 2019). Similarly, paleolimnological studies focusing on southeastern region of Brazil revealed anthropogenic impacts on two urban reservoirs. These studies concluded that cultural eutrophication began in the mid-1970s and intensified during the 1990s (COSTA-BÖDDEKER et al. 2012, FONTANA et al. 2014). The drastic modification of natural aquatic systems, coupled with the impacts of human activities and climate change, underscores the urgent need to comprehensively understand these environments and their adaptive dynamics. However, discrepancies between diatom-based paleoenvironmental studies, particularly in regions lacking sedimentary records, can hinder the usefulness of these reconstructions in both regional and global contexts. A multifaceted approach that incorporates both detailed local palaeoenvironmental studies and a comprehensive global perspective is necessary to address this gap.

Scientometric studies offer valuable means of gaining empirical insights into trends, geographical disparities, collaborative networks, thematic emphasis, and scientific gaps within a particular research domain. Such studies are instrumental in informing evidence-based decision making and identifying future directions in the field (CHEN & SONG 2019, WU et al. 2023). The performance of a scientometric analysis of diatom-based paleoenvironmental research can serve as a reference for historical and collaborative networks that have influenced the research field, and for identifying emerging areas of inquiry. By examining the scientometric themes in diatom-based paleoenvironmental research, key contributors, critical funding mechanisms, and geographic contours can be identified. This approach can

reveal nuanced patterns and insights that may need to be explored, ultimately providing a more comprehensive understanding of the field.

This study aimed to perform a comprehensive scientometric analysis of global diatom-based paleoenvironmental studies, with a particular focus on South American contributions. This study aimed to (1) examine temporal trends and identify significant growth periods, key research themes, and shifts in research focus; (2) evaluate the geographic distribution of research activities and identify prominent regions where research is comparatively limited; (3) identify central researchers, countries, and funding sources that have significantly influenced the field; and (4) identify prevailing research topics, emerging trends, scientific gaps, and potential future directions in diatom-based paleoenvironmental research.

2 MATERIAL AND METHODS

To investigate the temporal patterns and geographical distribution of diatom-based paleoenvironmental research in South America, we used a multimethod approach, including scientometric, bibliometric, modeling, and descriptive analyses.

2.1 Data Collection and Data Processing

On July 10, 2023, we conducted a systematic literature survey using the Scopus database to investigate relevant research publications aligned with the main objectives of this study. The survey was divided into three stages. In the first stage, we employed a combination of the keywords "Paleolimnology" and "Diatoms" to identify articles in paleolimnology, where diatoms were utilized as limnological proxies. In the second stage, we utilized the keywords "Paleoecology" and "Diatoms" to identify research articles focusing on paleoecological studies involving diatoms. Finally, in the third stage, we employed the keywords "Paleoclimatology" and "Diatoms" to identify articles in the field of paleoclimatology where diatoms were used as climate proxy indicators. This three-stage survey approach was implemented to capture the diverse applications of diatoms as proxies in various paleo-subfields.

A keyword-based filtering process was implemented to assess the relevance of each publication to the objectives of this study. We did not limit our search to any specific publication year to obtain a comprehensive representation of relevant literature. Compilation was prioritized to include research articles, book chapters, books, and reviews. Conference articles, notes, editorials, editorial opinions, and letters were excluded to maintain rigor and relevance of the dataset.

Publications were evaluated based on the prominence of primary keywords within their titles, abstracts, and designated keyword sections. Those that failed to adequately emphasize pertinent keywords were excluded. A detailed review of a randomly chosen subset comprising 20% of the initial publications was conducted to evaluate the precision of the proposed keyword-based filtering approach. Utilizing the accuracy rate from this subset as a benchmark, we projected the likely count of nonaligned articles within the entire dataset and adjusted our selections to reflect this.

The final dataset was structured into a matrix that included relevant details, such as the authors, publication year, citation count, journal name, abstract, key discoveries, affiliations of the authors, and other relevant data. This matrix sets the stage for the subsequent in-depth analysis, which includes reading abstracts to refine the selection of studies aligned with the objectives of this study.

Global indicators, such as the Human Development Index (HDI) and Gross Domestic Product (GDP), were extracted from the United Nations Development Programme–Human Development (UNDP; https://hdr.undp.org/data-center) and World Bank data (https://data.worldbank.org). These indicators, integrated into our analysis and discussion, provided valuable insights into the socioeconomic dimensions of the regions and countries under investigation.

2.2 Ethical considerations in data collection and analysis

We strictly adhered to ethical standards during the data acquisition from the Scopus database. Permission was duly secured and the confidentiality of the authors and associated stakeholders was maintained. We transparently detailed our methodologies and sources and provided due credit to the Scopus Database.

2.3 Descriptive, scientometric, and modeling analysis

The dataset was imported into VOSviewer, a widely used tool for scientometric analysis (https://www.vosviewer.com/) to identify research themes and their interrelationships. The resulting

clusters are mapped to outline the global research landscape. The regional distribution of publications in the dataset was visualized using the Matplotlib library in Python (HUNTER 2007). As the dataset did not provide geographic information (latitude and longitude), we employed geocoding tools and services, such as the GeoPy Python library, to assign geographic coordinates to each entry (https://github.com/geopy/geopy).

Collaboration network analysis was applied to discern the relationships and collaborations between authors, countries, and institutions within diatom-based paleoenvironmental research. This analysis was conducted using the NetworkX library in Phyton (HAGBERG et al. 2008). We identified the principal hubs within the collaboration network through centrality measurements, namely, degree, betweenness, and eigenvector centrality.

To identify the most common research areas or topics, we analyzed the term frequencies and generated a list of the ten most frequently explored topics. To understand how these research topics have evolved, we analyzed their occurrence in relation to the publication year, allowing us to track their evolving research emphases. Vectorization techniques for the combined text of titles and abstracts in the dataset were used to identify common frequently occurring terms. A filtration mechanism was applied to identify key terms representing prominent research areas or topics, which were then organized into a matrix for further examination.

Titles and abstracts were subjected to Natural Language Processing (NLP) methodologies for preprocessing, including tokenization and lowercasing (BIRD et al. 2009). Techniques in topic modeling, specifically Latent Dirichlet Allocation (LDA), have been applied to filter significant research domains from vectorized text (BLEI et al. 2003). We used the PyScopus library (https://github.com/scopus-api/pyScopus), that provides access to the Scopus database. To apply LDA, we turned to Gensim, a library adept in topic modeling and document similarity computations (ŘEHŮŘEK & SOJKA 2010). Data manipulation and visualization were conducted using libraries, such as Pandas and Matplotlib (HUNTER 2007, MCKINNEY 2010).

To investigate abrupt surges in keyword popularity within a designated period, we used an algorithm developed in Python using Pandas and Matplotlib libraries (HUNTER 2007, MCKINNEY 2010). A significant increase in keyword frequency often signifies emerging trends or shifts in the focus of the dataset. This approach aimed to identify scientific voids (intervals with minimal or absent bursts) and areas of oversaturation (keywords exhibiting consistent bursts) in the domain. One potential limitation of these analyses is that they rely solely on obtainable data, which may not include only some relevant research, and the outcomes are vulnerable to the model's parameters, particularly in the modeling and burst detection stages. These complexities could affect the robustness of our findings. However, these analyses have a significant potential for detecting influential themes, mapping research landscapes, and identifying emerging trends. They provide valuable insights into research strategies, funding allocation, and policy development. The ability to detect gaps and oversaturation offers a nuanced understanding of the research ecosystem, guiding researchers towards underexplored areas and optimizing resource allocation for maximum impact. Furthermore, these analyses can foster interdisciplinary collaboration by revealing the potential partners and key contributors within a research network.

3 RESULTS AND DISCUSSION

3.1 Temporal trends and geographic distribution in Diatom-based paleoenvironmental research: South American focus

Using the Scopus database, 14,200 studies published between 1979 and 2023 were identified. After adhering to our inclusion criteria, 7,074 publications were analyzed using a bibliometric approach. Table 1 presents an overview of scientometric results.

The late 1970s marked the inception of a gradual rise in research output that persisted until

TABLE 1 – Scientometry of diatom-based paleoenvironmental research between worldwide and South American contributions. The results were extracted from the Scopus database on July 10, 2023.

Scientometric data	*Total (Global)*	*Total (South America)*
Documents	7,074	474
Year range of publications	1979 to 2023	1995 to 2023
Authors	6,809	469
Journals	874	144
Articles	6,411	453
Reviews	328	9
Book of chapters	251	0
Books	82	0
Most active years	2013-2014	2013
Most common ecosystem	Lake	Lake

the early 2000s. This trend has been emerging since 2000, with 2021 and 2022 marking the highest number of publications. This uptick reflects a reinvigorated global interest in this area, as illustrated in figure 1a. Regarding the involvement of South America in diatom-based paleoenvironmental research, distinct nuances are evident compared to the global trajectory. Although studies in this region are sporadic and date back to the early 2000s, a consistent growth trend has been observed in recent years. The interval between 2010 and 2013 and in recent years has demonstrated an accelerated increase in contributions from South America, reflecting the intensification of diatom-based research in the region (Figure 1b).

Figure 1c shows the countries that led publications on diatom-based paleoenvironmental studies. The United States had the highest number (1,812), followed by the United Kingdom, Germany, Canada, and China, with 1,503, 1,138, 1,049, and 882 publications, respectively. Despite the ecological wealth of South America and its rich biodiversity, diverse aquatic ecosystems, and climate, research in this region is currently underrepresented globally. Furthermore, South American authors accounted for only 6,9% of publications (Table 1).

The cumulative contribution of South America to global publications was 6,7%, with the initial submission dating back to 1995 by SYLVESTRE et al. (1996), or 15 years after the first publication from other regions (Table 1, Figure 1a, b). This study, conducted in Bolivia, focused on fluctuations in water levels during the Late Glacial period, using diatoms as indicators (SYLVESTRE et al. 1996). The most recent contribution identified in our dataset is related to the evaluation of the paleolimnological responses of Ecuadorian Páramo lakes to regional climate change and local human impacts during the last millennium (LUETHJE et al. 2023).

Within South America, Argentina demonstrated a notable presence with 117 publications, whereas Brazil and Chile closely followed with 114 and 95 publications, respectively. Other countries, such as Peru, Uruguay, Bolivia, Venezuela, and Colombia, made minor contributions, with limited presence in the dataset (Figure 1d). Table 1 summarizes the other observed discrepancies.

In a global context, the significance of South American diatom-based paleoenvironmental research is not merely captured by the publication volume. Given its rich environmental history, varied climate, and diverse aquatic ecosystems (SALAZAR et al. 2007, GARREAUD et al. 2009, ZALLES et al. 2021), South America stands as a sentinel of invaluable information that can potentially redefine our current understanding of paleoenvironmental transitions, the global influence of climate change, human legacies, and other unanswered global questions. Since 2000, there has been a notable trend of rising research productivity in the region, consistent with the international pattern (Figure 1c, d), underscoring its growing proficiency in diatom-based studies and highlighting its central role in the global picture in the field.

The significant disparity between North and South America in terms of global research visibility in the field raises several important questions that require further investigation. What are the root causes for South America's limited visibility in this domain? How have historical, political, and economic factors influenced this region's research development and trajectory? A comprehensive analysis of these factors is necessary to gain a deeper understanding of the challenges faced by South American researchers.

Figure 2 illustrates the correlation between the continent's average mean Human Development Index (HDI) values and their research output. As depicted in figure 2a, the continents with the highest HDI values also had high research output, as shown in figure 2b. The correlation coefficient obtained between the HDI and the number of publications was approximately 0.6608, indicating a moderate positive correlation, as depicted in figure 2c. This trend is also apparent when Gross Domestic Product (GDP) is used as an indicator (Figure 2d). This observed trend may be attributed to heightened investment in scientific research and a more structured scientific environment in territories with higher HDI and GDP and their associated advantages.

Several studies in diverse research areas have observed positive correlations between elevated human development indices, political stability, and heightened scientific research production (GÖK et al. 2016, CONFRARIA 2019, BLOCH 2020 NABOUT et al. 2021, MORALES-MARROQUÍN et al. 2022, SEIBERT & BARROS NETO 2023). Specifically, MORALES-MARROQUÍN et al. (2022) analyzed the relationship between scientific production on biodiversity and HDI in northern countries in Central America, regions

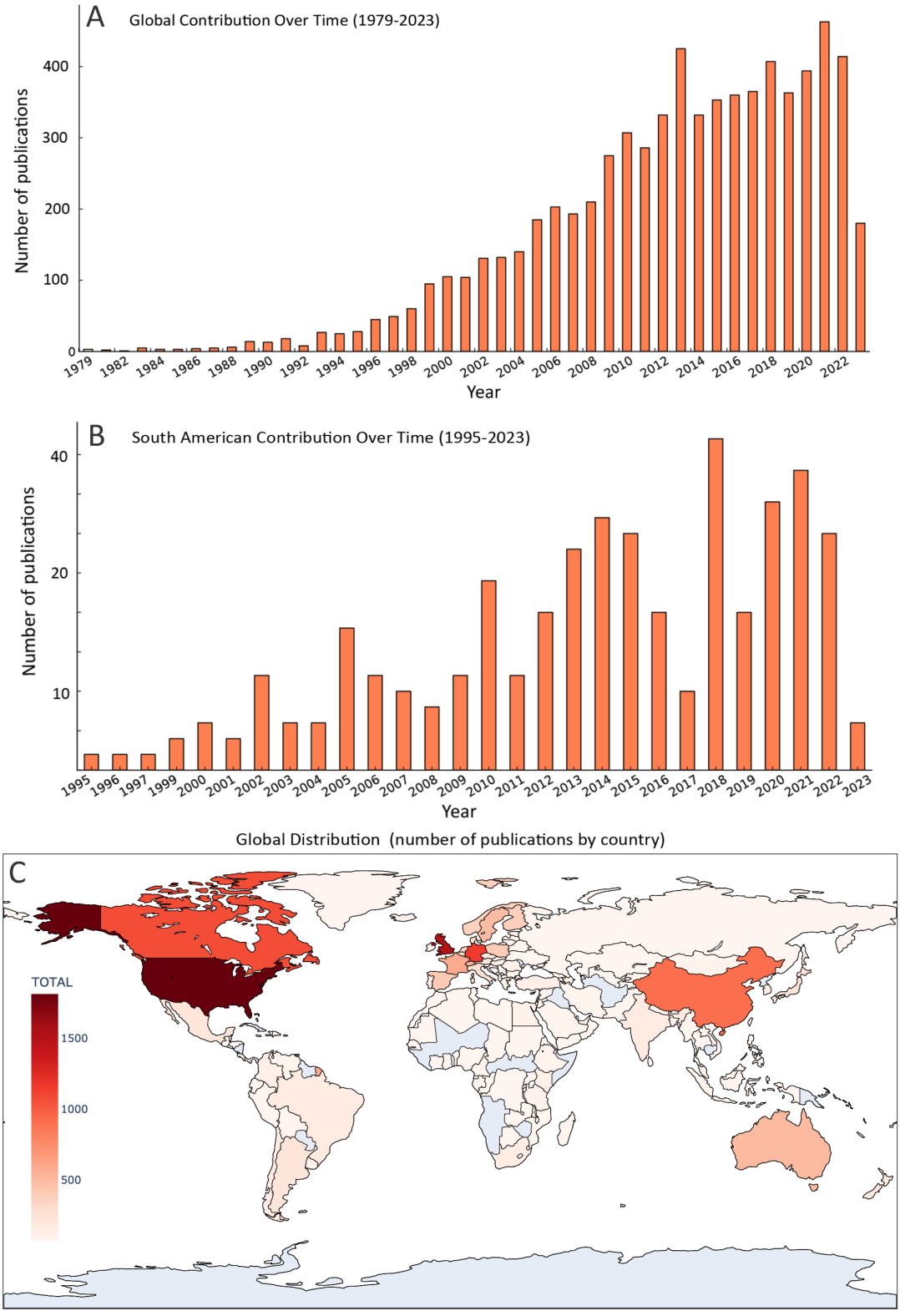

FIGURE 1 – Temporal trends, geographic distribution, and South American context in diatom-based paleoenvironmental research. A) Temporal distribution of publications worldwide (1979-2023). B) Temporal distribution of publications with an emphasis on South America. C) Global map showing geographic disparities in diatom-based paleoenvironmental publications.

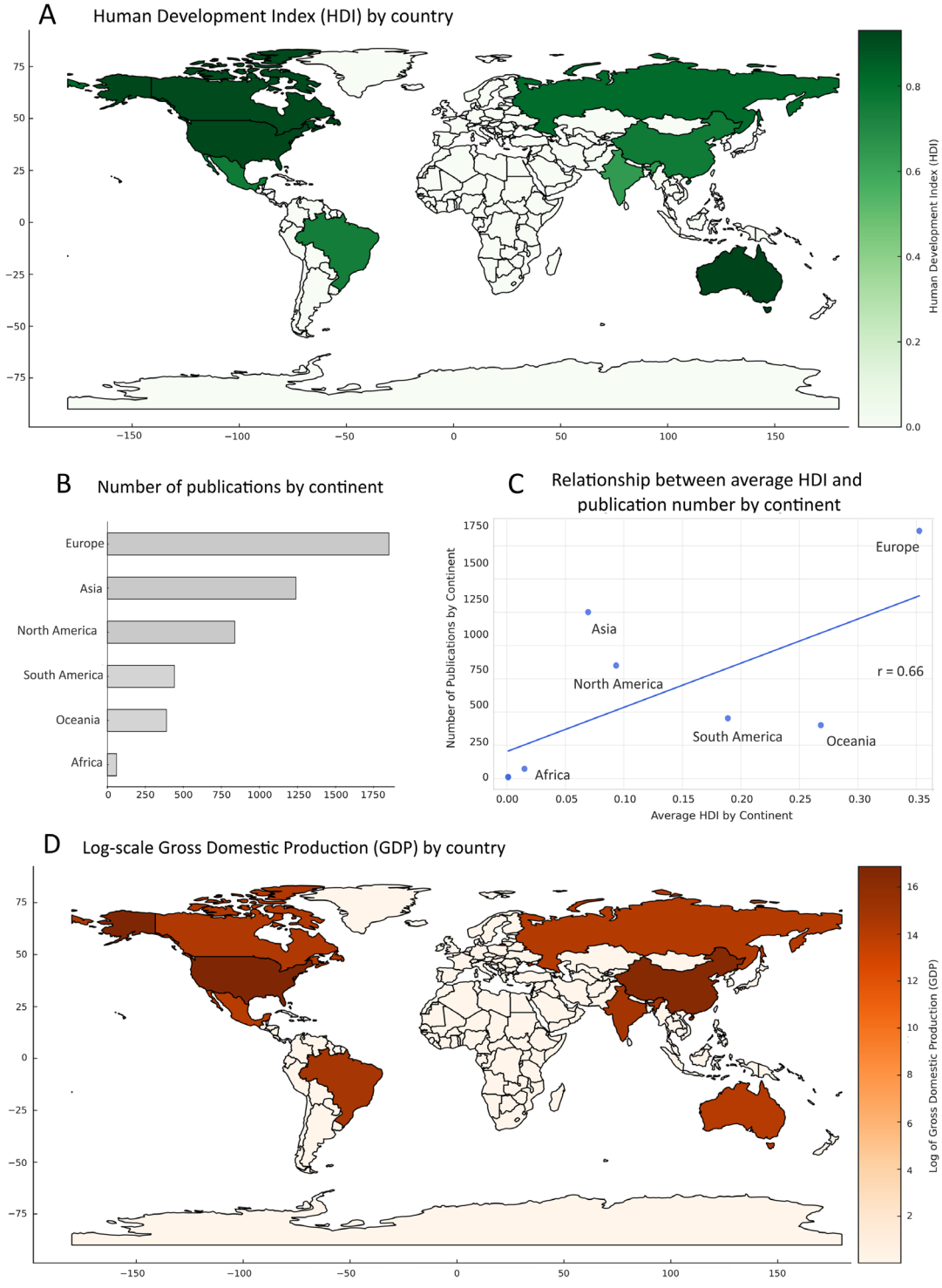

FIGURE 2 – Relationship between Human Development Index (HDI) and diatom-based paleoenvironmental research publications. A) Average HDI values by continent from a global perspective, with darker green shading indicating higher average HDI values. B) The total number of publications by continent, with Europe, Asia, and North America continuing to emerge as leading contributors, whereas South America and Africa exhibited fewer publications in the field. C) Regression correlation analysis between average HDI by continent and number of publications by continent. D) Log-scale gross domestic production (GDP) by country, showing a pattern similar to the HDI data. The GDP and HDI data were updated to 2022.

marked by low indices. Through a scientometric analysis spanning 1980-2020, the authors revealed notable discrepancies in the scientific production of these nations, emphasizing their link to several aspects, including democratic stability (MORALES-MARROQUÍN et al. 2022). In parallel, (GÖK et al. 2016) evaluated the influence of research funding on scientific outputs and found that funding levels were strongly associated with citation counts and high-impact citations, suggesting a positive impact of adequate funding on research outputs.

Several factors could have contributed to the underrepresentation of South American research output observed in this study. Historically, poorer countries in the region have fewer research funds and national scientific agendas often prioritize disciplines that contribute to economic development over ecological research (SPEZIALE et al. 2012, CHANKSELIANI 2023). More resources are needed for interdisciplinary fields such as Paleolimnology and Paleoecology. Additionally, diatom research requires specialized training in taxonomy and specific equipment (light and electronic microscopes), which may not be accessible to all institutions. Limited funding also hampers the ability of researchers to acquire the necessary equipment and collaborate equally with their international partners (DE LIMA et al. 2021, CASTELBLANCO-MARTÍNEZ et al. 2023).

Constrained research contributions from South America may also be attributed to the limited positions of researchers and professors at local universities and institutes (RAMÍREZ & GUTIÉRREZ-FONSECA 2020, ANTÓN-SANCHO et al. 2022), especially in the fields of Paleolimnology and Paleoecology. This contributes to the under-representation of the local expertise in the region. The limited available positions for researchers and professors in South America, along with scarce research funding, have a direct impact on scientific production (DE LIMA et al. 2021).

The imbalanced flow of funding from developed countries to low- and middle-income countries within the global science system (ZHOU et al. 2023) may play a crucial role. Although research funds from developed countries are often perceived as aid, they should be recognized as investments necessary to comprehensively understand global phenomena and promote equal global solutions (DUQUE 2023). However, the distribution of research funding is not equitable, with a considerable proportion flowing into North American and European countries (CHANKSELIANI 2023).

3.2 Collaboration networks in Diatom-based paleoenvironmental research

Globally, a select group of authors distinguishes themselves based on their prolific contributions to the field. Researchers such as Smol JP., Leng MJ., and Birks HJB have emerged as the highest contributors, with their works serving as foundational references to the advancement of diatom-based paleoenvironmental research (Figure 3a). Despite facing unique challenges in South America, researchers such as Maidana NI, Urrutia R and García-Rodriguez F have made significant contributions (Figure 3b). Their insights into the continent's distinctive aquatic ecosystems and historical shifts are of immense value. Through collaborations both within the continent and abroad, these researchers are bridging knowledge gaps, thereby weaving South American discoveries into the broader context of global diatom-based paleoenvironmental studies. Collaboration between established global experts and rising regional academics promises holistic and forward-thinking advancements in this field.

The National Science Foundation (NSF, U.S.), the Natural National Science Foundation of China (NNSFC, China), and the Natural Environment Research Council (NERC-E.U.) provided financial support for the majority of publications in the dataset (Fig. 3c). The significance of government support in promoting scientific advancement in North America and Europe, as well as in selecting regions in Asia, particularly China, cannot be overstated. In South America, Ministerio de Educación and Fondo para Investigación Científica y Tecnológica are the most prolific funders, underscoring their indispensable role in advancing diatom-based paleoenvironmental research within the region (Figure 3d). Despite disparities in global funding structures, these South American institutions have demonstrated a commitment to promote scientific advances in the field (Figure 3d).

Despite noteworthy South American contributions, European and North American scientists' pronounced leadership also raises concerns about scientific "neocolonialism" and "helicopter science," especially given the external leadership in South American publications. While

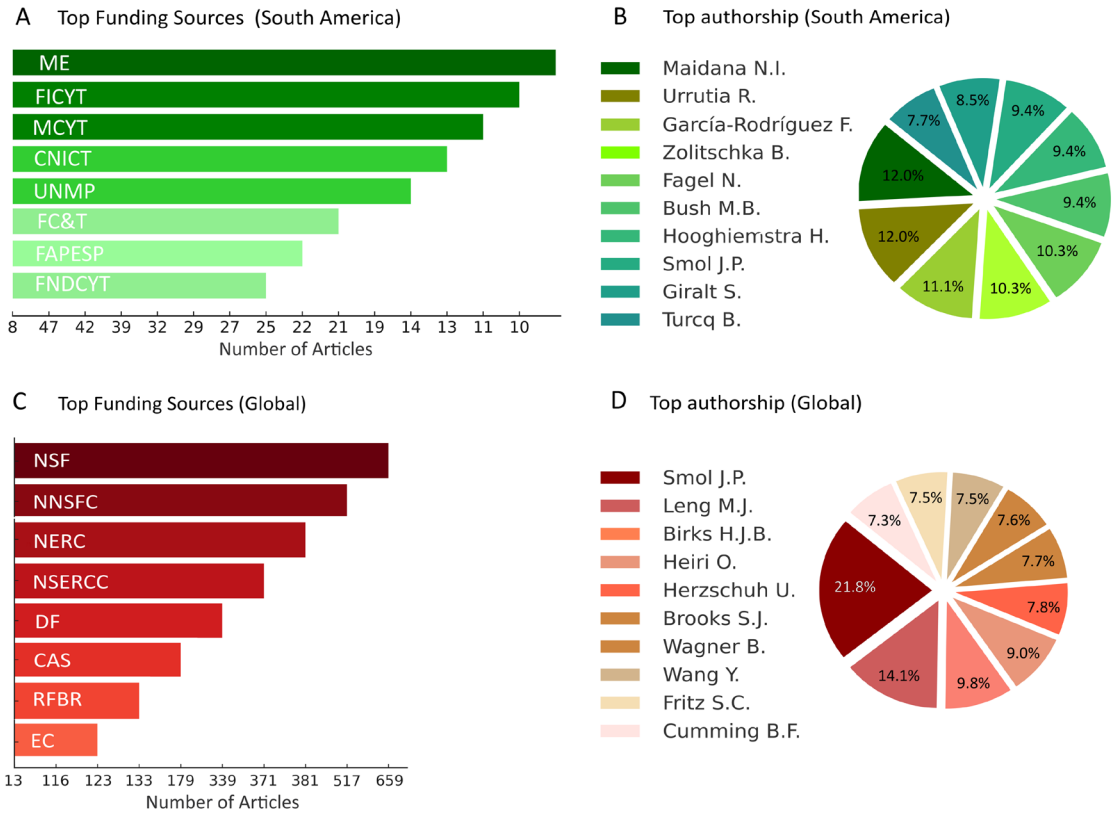

FIGURE 3 – A) Top funding sources for South American diatom-based paleoenvironmental studies. B) Top authorship in South America. C) Top Funding sources worldwide. D) Top Authorships worldwide. Funding sources (NSF = National Science Foundation; NNSFC = Natural National Science Foundation of China; NERC = Natural Environment Research Council; NSERC = Natural Sciences and Engineering Research Council of Canada; DF = Deutsche Forschungsgemeinschaft; CAS = Chinese Academy of Sciences; RFBR = Russian Foundation for Basic Research; EC = European Commission; ME= Ministerio de Educacíon; FICYT = Fondo para la Investigación Científica y Tecnológica; MCYT = Ministerio de Ciencia y Tecnología; CNICT = Comisión Nacional de Investigación Científica y Tecnológica; UNMP = Universidad Nacional de Mar del Plata; FC&T = Fundação para a Ciência e Tecnologia; FAPESP = Fundação de Amparo à Pesquisa do Estado de São Paulo; FNDCYT = Fondo Nacional de Desarollo Científico y Tecnológico).

European and North American collaborations have significantly advanced our understanding of several scientific questions, leadership inequality remains evident (Figure 3b).

Neocolonialism refers to the use of economic, political, cultural, or other pressure to control or influence other countries, primarily former dependencies (SCHROEDER et al. 2019, DE VOS 2022). It is a continuation of past colonial practices but in a more subtle and indirect form. Helicopter science refers to the practice of researchers from the Global North to conduct research in the Global South without long-term investment or consideration of ground realities (DE VOS 2022). This phenomenon is seen as a manifestation of neocolonialism in science, where disparities between the Global North and Global South lead to neocolonial behaviors, inefficiencies, and setbacks (SCHROEDER et al. 2019, DE VOS 2022). Through this practice, local knowledge, participation, and contributions are not considered or acknowledged, and partnerships are unequal. In some cases, local scientists provide only logistical support and the potential benefits to the studied region are often neglected.

It is crucial to increase funding for South American researchers to address inequalities and neocolonialism in the scientific community. If economic development and scientific equality

successfully reduce disparities in research outputs, we anticipate that more South American scientists will be among the top publishing authors in their areas (i.e., writers who publish the most papers).

Additionally, there has been a recent trend of young South American talent scientists seeking opportunities abroad due to limited local opportunities and, in several cases, supported by international funding such as NSF (U.S.), NSFC (China), and NERC (E.U.). This exacerbates the observed geographic disparities in the publications.

Meaningful and equalitarian international collaborations, instead of helicopter research (or neocolonial research), could also positively affect South American countries (SCHROEDER et al. 2019). Addressing scientific leadership, disparities, and helicopter neocolonial practices in science necessitates concerted efforts to support and empower South American scientists. Although external scientists lead most published studies with international research funding, it is crucial to recognize and appreciate their significant contributions to these fields, including South America.

The 15th International Paleolimnology Association (IAL-IPAL) conference was held in Bariloche, Argentina, in November 2022, exemplifying global scientific efforts in this direction. This important conference in the paleolimnology field received scientists worldwide, and the location chosen for this meeting represents a global recognition of the prowess of South American researchers in the field.

Dr. Nora Maidana, who attended this conference, is a leading scientist on phycological studies in South America. She has been instrumental in laying the contemporary foundation for diatom-based paleolimnological research in Argentina and other regions of South America. Her work seamlessly extends and enriches the historic legacy set forth by Dr. Joaquin Frenguelli, an Argentine geologist and paleontologist who made significant contributions to the study of geology and paleontology in South America (RICCARDI 2017). Maidana et al. published over 100 articles and several books on diatoms in different ecoregions of Argentina, from Patagonia to the Andes (for example, HABERZETTL et al. 2005; FERNÁNDEZ et al. 2013, 2020; MAYR et al. 2019; ZOLITSCHKA et al. 2018; VILLACÍS et al. 2023). She has also been the lead diatomist in many paleolimnological scientific projects throughout Argentina, including the large ICDP drilling project on Laguna Potrok Aike in Patagonia (PASADO), which documented the climatic and volcanic history of Patagonia over the last glacial period. Dr. Maidana made the most significant contribution among the South American scientists, as illustrated in figure 3b.

Dr. Roberto Urrutia of the University of Concepción (Centro de Ciencias Ambientales, EULA, Chile) and Dr. Felipe Daniel García-Rodríguez of the Universidad de la República de Uruguay (UdelaR) are influential South American researchers in this field. In collaboration with fellow researchers, they have made significant contributions to various areas, including water quality (GARCÍA-RODRÍGUEZ et al. 2022, RODRÍGUEZ-LÓPEZ et al. 2022), climate variability (URRUTIA et al. 2010, CUÑA-RODRÍGUEZ et al. 2020, GARCÍA-RODRÍGUEZ et al. 2021, GARCÍA et al. 2022), biodiversity (VAN DE VYVER et al. 2022), and other topics. This region is actively producing other prominent researchers, who have made remarkable advancements in this field.

The international landscape of diatom research has undergone significant advancement in recent years. Collaboration between South American countries and international organizations presents numerous advantages, including exchanging expertise and resources and disseminating best scientific practices. Several nations and organizations, such as the International Society of Diatom Research (ISDR; https://isdr.org/), have played a crucial role in promoting equity in diatom research, emphasizing the importance of equal research opportunities. Moreover, the ISDR council has recently announced grant schemes for early career researchers (ECRs) who are members of this society. The grant program aimed to support ECRs in undertaking original projects focused on diatoms across all disciplines, thereby facilitating collaboration and networking. One of these grants is related to collaborative networking projects intended to promote collaboration and multidisciplinary research among scientists. In addition to these initiatives, Marie Sklodowska-Curie's actions have also contributed to opportunities for diatomists interested in the paleoenvironmental approach. These include research grants, Global Postdoctoral Fellowships for researchers from outside Europe, staff exchange actions that

fund short-term international and intersectoral exchanges between staff members from academic and non-academic sectors, and other initiatives. Furthermore, other initiatives and opportunities that increase collaborative network research between countries are essential for advancing this field, particularly in underrepresented areas.

3.3 Research topics and scientometric insights

The scientometric map revealed a diverse and dynamic research landscape within the fields of Paleoecology and Paleolimnology, which used diatoms as a proxy and encompassed various subfields and specialized areas of investigation (Figure 4a). The analysis identified four predominant research clusters.

Holocene and palynology cluster (purple), displaying robust connectivity between publications that address "Holocene, Paleoecology, and Palynology." This cluster emphasizes publications on ecological dynamics during the Holocene, mainly using palynological data and diatoms as proxies. Several connections were detected in the cluster. Certain keywords belong to different disciplines. The intersection of these disciplines can lead to innovative, interdisciplinary research.

The paleolimnology and aquatic organisms cluster (yellow) with overlapping keywords such as "Paleolimnology, Bacillariophyta, and Chironomidae," emphasizing the symbiotic relationship between paleolimnology and the study of biotic interactions. The interconnection between these subjects underscores the potential for a deeper exploration of biotic interactions, especially in understanding how diatoms and other organisms respond to environmental changes.

The glacial Geology and Quaternary cluster (blue), highlighting studies centered on "Glacial Geology, Sea Level, and Quaternary," reveal the interest in geological processes linked to glacial epochs and Quaternary sea-level fluctuations. Thus, diatom-based studies have emphasized the importance of using a multi-proxy strategy to understand past global climatic events.

Stratigraphy and Geochemistry cluster (green) is dominated by the keywords "Stratigraphy, Isotopes, and Geochemistry," which emphasize the indispensability of stratigraphic investigations and the use of isotopic and geochemical markers in paleoenvironmental studies. The modern integration of these techniques with diatom studies suggests the importance of a multidisciplinary approach for deciphering paleoenvironments.

The paleolimnology and biodiversity cluster (red), centered on water quality, emphasizes the understanding of diatom composition, biodiversity patterns, and phosphorus dynamics in aquatic ecosystems. This cluster provides promising areas for applied studies, particularly freshwater restoration and conservation.

There has been a notable upsurge in the global interest in diatom-based paleoenvironmental research, spanning various subjects from the 1980s to the 1990s (Figure 4b). During this period, there was considerable excitement and activity in the field. However, after the year 2000, several diatom-based research topics began to diminish. Studies based on floristic surveys of diatoms in lakes and geological deposits, limnological changes, and Holocene climate patterns have received little attention. In contrast, the post-2000 period saw a surge in interest in DNA and silica analyses (Figure 4b). The emerging trend post-2000 in the field of paleolimnology may indicate the implementation of innovative methodologies and cutting-edge approaches rather than a substantial shift in focus. Complementary DNA and silica analyses, such as biogenic silica analyses, have been employed to investigate lacustrine biodiversity and paleolimnological changes (DOMAIZON et al. 2017, WESTOVER et al. 2021). DNA analysis of lake sediments has expanded the scope of inquiry in paleolimnology, allowing the investigation of taxa that do not leave distinct morphological remains in sediments. This field is undergoing rapid development, facilitating more comprehensive examination of a broader range of diatom taxa. However, it is essential to conduct rigorous research to evaluate preservation biases and develop appropriate methods beyond calibration by comparing sedimentary DNA with morphological or geochemical data, as DOMAIZON et al. (2017) emphasized. A comparative study between sediment DNA sequencing and traditional microscopic analysis of diatoms in thermokarst lakes in Siberia has revealed similar results at the genus level. The genetic approach using sediment DNA holds promise for reliable investigation of diatom composition in lake sediments, with potential future applications in paleoecology and environmental monitoring (DULIAS et al. 2016).

Keywords with sudden fluctuations in frequency over time provide valuable insights

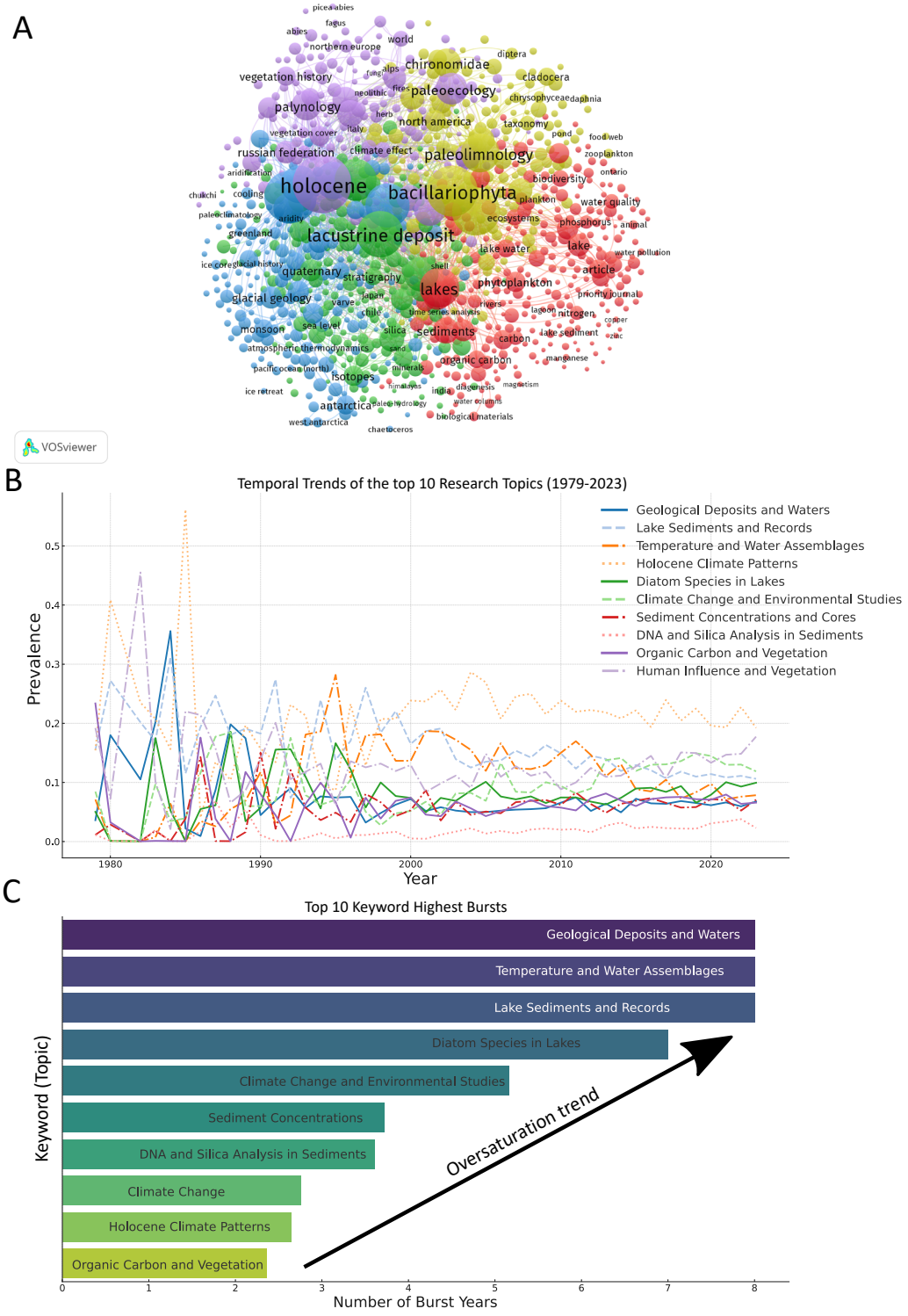

FIGURE 4 – Scientometric analysis of diatom-based paleoenvironmental research (1979-2023). A) VOSviewer map illustrating the primary research topics and their interrelationships with clusters differentiated by size and color. B) Temporal progression of the dominant ten research themes in the field, highlighting the evolving focus over the years. C) Burst analysis showing significant spikes in the frequency of the dataset's top ten topics or keywords. This scientometric approach provides insights into the evolution, focal shifts, and intricate interplay of topics in diatom-based paleoenvironmental research over the analyzed period.

into the current state of research in a particular field (LEYDESDORFF & WELBERS 2011). By analyzing these patterns, researchers can better understand areas that are oversaturated with research and potential future trends. Keywords with high frequencies have received substantial attention, indicating that they may be oversaturated with existing studies (ZHANG et al. 2016). However, niche topics within these areas still need to be explored (MILOJEVIC 2015). Keywords with a sudden surge in frequency indicated emerging research trends. These areas are gaining momentum, but have not yet been fully explored. Researchers can capitalize on these emerging trends by conducting studies in these areas before they become widely recognized. Pioneering research in these areas can lead to scientific discoveries and establishment of researchers as leaders in their fields. Figure 4c shows intriguing insights into the development of paleoenvironmental research. The prominence of topics such as "organic carbon and vegetation" and "Holocene climate patterns" with their lowest burst years is particularly interesting. These areas, which have not been extensively explored, are witnessing a resurgence in global interest. This could be attributed to a variety of factors, including increasing global recognition of the importance of organic carbon in climate models (BEILLOUIN et al. 2022, WANG et al. 2022) and the role of vegetation in understanding past environmental and climatic conditions (HAGEMANS et al. 2022). The Holocene, the most recent geological epoch, offers a window into climate patterns that are most relevant to the current climate scenario. As such, the growing attention towards Holocene climate patterns also suggests a shift in research focus towards understanding more recent climatic changes and their implications.

On the other hand, the sustained interest in floristic surveys, limnological studies on lake sediment records, temperature reconstruction, and geological surveys underscores their foundational importance in the field (Figure 4c). Diatom floristic surveys provide a comprehensive understanding of the diversity and distribution of diatom species, which is crucial for paleoenvironmental reconstruction. Limnological studies of lake sediment records have long been standard in paleoenvironmental research, as shown in figure 4c, offering a continuous and detailed record of past environmental changes. Temperature reconstruction, mainly based on diatom proxies, provides invaluable data for climate modeling and understanding past climate variations and their influence on productivity and lake dynamics. Geological surveys, the bedrock of environmental studies, have consistently been the focal point of research, providing context and baseline data. Although traditional areas of study, such as floristic surveys and limnological studies, continue to be pillars of paleoenvironmental research, there has been a discernible shift towards underexplored areas (lowest burst years). This shift not only reflects the evolving priorities and interests of the research community, but also underscores the dynamic nature of the field, constantly adapting and evolving in response to new challenges and discoveries.

Advancements in diatom-based paleo-environmental research have highlighted the inter-disciplinary and dynamic nature of this field. While traditional domains, such as floristic surveys and limnological studies, remain foundational, there is a clear trend towards exploring new research areas. The changes observed over time are influenced by advancements in methodology and pressing global concerns such as ongoing climate change and its impact on aquatic ecosystems. Researchers must integrate established methods with cutting-edge approaches to address the contemporary environ-mental challenges.

4 CONCLUSION

While South America is characterized by profound ecological diversity, its representation in the diatom-based paleoenvironmental field remains disproportionately low compared to continents such as Europe, North America, and Asia. Argentina, Brazil, and Chile have been identified as the predominant contributors in South America. However, only 6,7% of the global publications in the field are attributed to this region, underscoring the need for an in-depth investigation into the underlying factors contributing to this observed geographic disparity.

This study revealed a moderate positive correlation between the Human Development Index (HDI), the number of publications in diatom-based paleoenvironmental research and a corresponding trend in the Gross Domestic Product (GDP). Regions boasting political stability, a flourishing economy, and advanced human development are more likely to produce higher research output. The scarcity of publications in South America may

be attributed to several factors, including limited funding, economy-focused national priorities, and the need for regional academic positions for specialists in the field. Recognizing that these observations are preliminary and requiring additional research to establish causality is crucial.

Addressing the disproportionate allocation of funding resources towards North America and Europe is crucial for a more balanced approach to facing global challenges. South American institutions, including the Ministerio de Educación and Fondo para Investigación Científica y Tecnológica, maintain their commitment to the field. However, external funding sources such as the NSF (U.S.), NNSFC (China), and NERC (E.U.) have significantly shaped the global research direction in this area. It is crucial to view funding for lower- and middle-income countries as aid and strategic investments to understand global phenomena, such as climate change. The equitable distribution of resources is essential for proposing effective solutions to global challenges, and it is imperative to consider resource allocation more comprehensively.

Researchers such as Smol JP, Leng MJ, and Birks HJB have conducted diatom-based research on a global scale and fostered international collaborations in the field. South American researchers, such as Maidana NI, Urrutia R, and García-Rodriguez F, have amplified the significance of the region's ecosystems on a global scale. Collaborative initiatives are essential to harmonizing South American records.

Scientific leadership in this field has revealed European and North American dominance. This disparity raises concerns regarding scientific neocolonialism or "helicopter science," especially when external researchers lead pivotal leadership in South America. Addressing this inequity involves supporting South American researchers, counteracting the trend of young talent-seeking opportunities abroad, and ensuring equitable international collaborations. A new trend towards meaningful and equalitarian international collaboration worldwide to stop the reinforcement of neocolonial practices is overdue but welcome.

The field of diatom-based paleoenvironmental research is undergoing a significant transformation. While traditional research areas, such as floristic surveys, remain relevant, there is growing interest in topics such as organic carbon and Holocene climate patterns. This dynamic evolution reflects the adaptability and commitment of the research community to address contemporary environmental challenges.

By actively addressing current challenges, fostering equitable and interdisciplinary collaborations, and responding to emerging research topics, we can help address existing disparities and promote advancements in the global diatom-based paleoenvironmental scientific landscape.

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