

# The Enduring Legacy: A Scientometric Analysis of Foraminiferal Research Over Two Centuries

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**ABSTRACT:** Foraminifera have emerged as essential tools for understanding Earth's history and monitoring the health of marine ecosystems. This scientometric analysis offers a comprehensive overview of the enduring legacy and evolving landscape of foraminiferal research over more than two centuries. By leveraging data from three extensive bibliographic databases, we collated a dataset of over 58,000 publications spanning from 1824 to 2023. Our analysis reveals an exponential growth in foraminiferal research, with an annual growth rate of 3.35%. The dataset shows a strong increase in citation impact, with the 1990s and 2000s emerging as the "golden era" of foraminiferal studies, characterized by groundbreaking publications and a surge in citations. Keyword co-occurrence analysis identified five major research domains: ecology and environment, paleoceanography and paleoclimatology, stratigraphy and sedimentology, biostratigraphy and evolution, and environmental biomonitoring. The United States, Europe, and China emerge as major contributors to foraminiferal research, with China showing a rapid rise in recent years. Collaboration network analysis highlights the formation of research communities around key themes, authors, and institutions. Thematic landscape analysis identifies core research areas, such as benthic foraminifera, biostratigraphy, and evolution, while also revealing emerging trends in molecular genetics, geochemical analysis, and bioindicator applications. This study emphasizes the need for method standardization, data accessibility, and alignment with societal challenges to harness the full potential of foraminiferal research. This scientometric analysis provides a roadmap for navigating the challenges and opportunities ahead, building upon the rich history and achievements of foraminiferal research while embracing new perspectives, technologies, and collaborations. By fostering a diverse, inclusive, and globally connected research community, we can recognize the full potential of foraminifera as a powerful tool for understanding Earth's complex systems and informing sustainable solutions for our planet's future. The enduring legacy of foraminiferal research serves as a testament to the scientific curiosity, ingenuity, and dedication of generations of researchers who have significantly contributed to our understanding of these fascinating organisms and their role in shaping the world we inhabit.

**Keywords:** Foraminifera, Scientometrics, Big Data Analytics, Bibliometrics, Research Trends, Data Visualization, Network Analysis, Interdisciplinary Research.

## INTRODUCTION

### *Foraminifera in a nutshell*

Foraminifera are single-celled eukaryotes that have captivated scientists for over two centuries with their diversity of form, ubiquity in marine sediments, and sensitivity to environmental change (Culver 1987; Alve 1995; Hallock et al. 2003; Amao et al. 2019). Since their discovery and scientific description in the early 19th century, foraminifera have emerged as invaluable tools across an array of geological, biological and environmental disciplines. Several thousand species exist today (Murray 2007), that are the products of a long-lasting evolutionary history since their first appearance in Precambrian marine sediments (Culver 1994; Pawlowski et al. 2003). Their cells are enclosed in a test (i.e., shell) composed of varied materials from sand grains to calcium carbonate. Test composition, structure, size, shape, texture, color, and complexity all vary enormously across genera and species. Foraminifera generate intricate branching pseudopodia that allow motility and facilitate ingestion of food sources like algae, bacteria, and organic detritus (Culver 1987). With a wide range of sizes spanning from less than a millimeter to more than 10 cm, foraminifera can be found throughout the marine realm, from shallow intertidal areas to the deepest

parts of ocean and at various depths within the water column (Murray 1991). Their abundant fossil record and fundamental role as ecological indicators have uniquely positioned them to transform fields as far-ranging as biostratigraphy, paleoclimatology, paleoceanography, marine pollution monitoring, and conservation paleobiology (Boersma 1998). Based on the mode of life, foraminifera can be divided into two principal groups: benthic forms living within or on sediments and planktonic ones that float in the upper water column (Gooday et al. 2021). The bottom-dwelling forms have existed since late Precambrian time, whereas the planktonics first evolved in the Mesozoic. Their rich fossil record coupled with short lifespans and generation times on the order of weeks to months make foraminifera exceptionally valuable biostratigraphic markers (Bandy 1964; Bolli 1966; Blow 1969; Berggren 1977; Van Morkhoven et al. 1986; Sliter 1989; Berggren et al. 1995; Serra-Kiel et al. 1998; Hallock et al. 2003; Kaminski et al. 2005; Amao et al. 2022). Their abundance in sediment samples can reach tens of thousands per square meter, and in tropical environments, their diversity may exceed 60 to 70 species in a sample of just 300 individuals (Culver 1987).

### **Origin and evolution of foraminifera**

Foraminifera first appeared in the late Proterozoic and underwent significant diversification during the Phanerozoic, giving rise to tens of thousands of species, with approximately 3000 - 4000 extant species known today (Murray 2007). Their evolutionary history is punctuated by radiations and extinctions that have had profound impacts on both biological and geological systems. Current understanding of foraminiferal evolution is primarily based on agglutinated and calcareous multilocular species that experienced a major radiation during the Carboniferous period. In contrast, the evolutionary history of noncalcareous unilocular foraminifera remains largely obscure due to the poor preservation potential of their thecate (organic-walled) or agglutinated tests, resulting in a sparse fossil record (Lipps and Rozanov 1996). Even more limited is the geological information available for "naked" species, which lack tests altogether, despite their potential crucial role in the early evolution of foraminifera (Holzmann et al. 2021).

In the past, foraminifera were classified within the phylum Rhizopoda (von Siebold) and associated with various groups such as Lobosea (Carpenter), Entamoebidea (Cavalier-Smith), Filosea (Leidy), and Xenophyophorea (Schulze) (Pawlowski et al. 2003). However, recent DNA studies suggest that they originated from a heterokaryotic flagellated marine protist, likely during the later Proterozoic (Wray 1994; Wray et al. 1995; Pawlowski et al. 2003). The earliest fossil evidence of agglutinated foraminifera is found in Cryogenian (Sturtian) to Ediacaran deposits (Plotnikova 1991; Bosak et al. 2011; Malik et al. 2024), coinciding with the appearance of the first soft-bodied metazoan fossils. However, the poor preservation of early unilocular foraminiferal tests and the challenges in identifying them have hindered our understanding of early foraminiferal evolution.

Moreover, the precise origin of foraminifera and their phylogenetic relationships with other eukaryotes remain uncertain. Many researchers attribute the early unilocular forms, also known as vase-shaped microfossils, to testate amoebae (e.g., Porter et al. 2003). Phylogenetic analyses based on ribosomal RNA gene sequences have yielded conflicting results regarding the evolutionary position of foraminifera (Wray 1994; Pawlowski et al. 1996). These studies indicate that foraminifera diverged early in the eukaryotic evolutionary tree, after the amitochondrial Archezoa but before the Euglenozoa and other mitochondria-bearing phyla, making them one of the earliest eukaryotic lineages to possess mitochondria (Pawlowski et al. 2003). The fossil record reveals the presence of two-chambered agglutinated foraminifera by the mid-Cambrian (Culver 1994), while the oldest known multichambered hormosinids date back to the middle Ordovician (Gutschick 1986). Recently, the discovery of the oldest multichambered lituolids in lower Silurian deposits of Saudi Arabia (Kaminski and Perdana 2020) has pushed back the known evolution of this stem group by more than 40 million years.

### **The Early Days of Foraminiferal Research**

The protozoan nature of foraminifera was first recognized by the French naturalist Felix Dujardin when he correctly identified the pseudopoda of a living miliolid in 1835. Although drawings resembling foraminifera appeared in publications as early as the 16<sup>th</sup> century, d'Orbigny (1826) ushered them into formal scientific study by devising the initial taxonomic classification based on test morphology (Murray 2006). In the late

19<sup>th</sup> century, global dredging expeditions like the famous HMS Challenger voyage yielded bathyal and abyssal foraminiferal specimens, revealing their ubiquity across the depths of the sea. The richly illustrated plates and species descriptions in the resulting Challenger report of Brady (1884) remain a seminal taxonomic contribution (Boersma 1998; Murray 2006). In this early period, research focused largely on morphological documentation rather than ecological or evolutionary dynamics.

The utility of microfossils as tools for the petroleum industry was first demonstrated by Józef Grzybowski in 1898 in the oil fields of eastern Galicia (see Kaminski et al. 1993). After World War I, the emerging petroleum industry recognized the immense value of foraminifera for biostratigraphic dating and paleoenvironmental reconstruction, greatly accelerating applied micropaleontological research (Cushman 1928; Berry 1999). The American naturalist Joseph Cushman revolutionized foraminiferal taxonomy in the early 20<sup>th</sup> century by traveling widely to study type specimens and reference collections in the world's major natural history museums. The establishment of the Cushman Laboratory for Foraminiferal Research in the 1920s marked a turning point toward more comprehensive biostratigraphic, paleoenvironmental, and phylogenetic analyses (Murray 2006). Cushman developed a far more detailed and complex new taxonomic classification compared with Brady's 10-family scheme (Cushman 1928; 1948). Initially viewed as too complex by his contemporaries, Cushman's novel system gradually gained acceptance after the 1928 publication of his taxonomic monograph "Foraminifera, Their Classification and Economic Use". Under Cushman's leadership, the laboratory trained a generation of specialists, amassed extensive taxonomic collections, and generated prolific publications spanning foraminiferal biology across geological timescales. The taxonomic framework developed by Cushman and his students provided the fundamental baseline for all subsequent foraminiferal research.

One monumental two-volume monograph by Loeblich and Tappan (1987) included all known genera and higher taxa of the time with complete diagnoses and synonymy. This morphology-based scheme adhering strictly to nomenclatural rules has served as an indispensable foundation for classification stability across all fields of foraminiferal research (Mikhalevich 2013; 2021). The taxonomic hierarchies and phylogenies established by Cushman and his students remain largely valid today, though taxonomy and evolutionary histories have immensely grown since his death in 1949. Sadly, no single person or research group today is keeping track of all the validly described genera, and as time moves on it appears increasingly unlikely that we will ever see an update to the book by Loeblich and Tappan (1987).

### **Foraminifera Enter the Modern Era**

The advent of advanced geophysical technologies like reflection seismology as well as growing global oil exploration sparked a renaissance in foraminiferal micropaleontology from the 1950s onward. Energy companies valued foraminifera for rapid and accurate dating of drilled core samples, thereby revolutionizing biostratigraphic practice (Berry 1999). Government mapping agencies also relied extensively on foraminiferal biostratigraphy for dating sedimentary sequences during geologic survey efforts. Quantification of past ocean temperatures using foraminiferal test geochemistry emerged as another groundbreaking development in this period. The recognition that the

oxygen isotopic ratio fixed in calcium carbonate shells records the temperature conditions at time of formation provided scientists with a robust paleothermometer unlocking deep-time climate shifts (Emiliani 1966). This discovery, alongside growing interest in reconstructing marine paleoenvironments more broadly, spurred extensive ocean drilling projects to recover long sediment cores for foraminiferal analysis. Deep Sea Drilling Project (e.g., DSDP, ODP, IODP etc.) samples offered unprecedented insights into evolutionary turnover events, regional habitat shifts, and global climate cycles on million-year timescales (Hay 1973; Zobel 1975).

From niche oil exploration tools, foraminifera ascended by the late 20<sup>th</sup> century into indispensable proxies for nearly every realm of marine science from biosphere history to pollution biomonitoring. Their sensitivity to subtle environmental cues combined with unparalleled fossil abundance established foraminifera as the most extensively utilized marine microfossil group, reflected in an ever-expanding publication output exceeding early specialists' imagination. Keeping track of the growing body of foraminiferal literature is a daunting task. In pre-internet days, Joseph Cushman kept track of the foraminiferal publications in his quarterly "Recent Literature" column in his journal "Contributions from the Cushman Laboratory for Foraminiferal Research". Cushman's successor was his former student and collaborator Ruth Todd, who continued writing the "Recent Literature" column in the *Journal of Foraminiferal Research* until her death in 1985. Ruth had retired to Martha's Vineyard in Massachusetts, and she would be occasionally seen in the reading room of the MBL Library in Woods Hole compiling literature for her column.

The "Recent Literature" column was then continued by Doris Low and Sue Richardson until the summer of 1991. However, this column simply compiled "articles that have come to hand" – it was not a systematic search of the literature. In 1993 one of us (MAK) began conducting a more systematic search of the literature and compiling a running bibliography of publications dealing with foraminifera. At the time, the UCL library subscribed to the Institute for Scientific Information database of publications, and it was possible to search for the term "Foraminifer" in titles of journal articles published each year. This search usually found about a hundred journal titles for a given year. Unfortunately, at the time, the majority of paleontological and micropaleontological journals were not listed in the ISI database, which necessitated systematically browsing the current journals housed in the Geology reading room of the UCL Science Library. Moreover, book chapters and geological survey reports were completely missed by the ISI database, and none of the Eastern European journals were listed. Therefore, the journal search continued in the library of the Polish Geological Society in Kraków. The resulting yearly lists of foraminiferal publications became known as "FORAM-REFs", and this bibliography of journal articles, book chapters and survey reports beginning with the year 1980 are now freely accessible on the website of the Grzybowski Foundation (<http://www.gf.tmsoc.org/foram-refs.html>).

### **Importance of Foraminifera**

Foraminifera offer immense value across earth and environmental sciences through their unparalleled utility in solving geological problems. Their tiny tests enable researchers to estimate paleotemperatures via isotope analyses (e.g., Duplessy 1978; Berger 1979) and infer paleodepth environments from fossil assemblage compositions (e.g., Grimsdale 1955; Douglas 1979; Hayward and Buzas 1979). Investigating biogeographic distributions facili-

tates reconstructions of ancient ocean current movements (e.g., Schnitker 1980; Miller and Lohmann 1982), while biostratigraphic zonations have been used to identify tectonic plate shifts over time (e.g., Monger and Ross 1971; Behr and Becker 2018). Numerous planktonic and benthic biostratigraphical schemes already exist for various periods (Sliter 1989; Hallock et al. 1991; Berggren et al. 1995; Wade et al. 2011).

Beyond driving innovation in traditional geology, foraminiferal research has enabled the integration across environmental and biological sciences. Genetic studies using foraminifera critically confirmed the evolutionary linkage between single-celled eukaryotes and multicellular organisms (Pawlowski et al. 2003). Further genetic analyses have revealed foraminifera as ancient symbiotic engines powering marine nutrient cycling through intracellular bacteria and algae. Moreover, researchers have identified foraminifera as sensitive bioindicators, with species reflecting pollution levels and community shifts indicating climate change stressors (Alve 1991; 1995; Martins et al. 2014; 2016). Modern interdisciplinary efforts have been established to unite various specialists through collaborative foraminiferal research (Schönfeld 2012; Schönfeld et al. 2012; Greco et al. 2024).

Other specialized but diverse applications include isotope paleoclimatology, sequence stratigraphy, phylogeography, biomonitoring, ecology, and climate impact forecasting (Boersma 1998). Specific examples comprise high-resolution correlation (e.g., Berggren et al. 1985; Berggren et al. 1995; Dowsett et al. 2023), paleoclimate reconstructions (e.g., Zachos et al. 2007), tracking past ocean circulation changes (e.g., Sexton et al. 2006), sequence stratigraphic studies (Leckie and Olson 2003), assessing anthropogenic pollution impacts (e.g., Yanko et al. 1994; 1998), quantifying biotic resilience (e.g., Weinmann et al. 2013), and forecasting climate-driven range shifts (e.g., Mouanga and Langer 2014; Titelboim et al. 2019).

### **Current and Future Directions**

Modern trends include increased laboratory experiments (mesocosm) simulating projected climate change impacts (Nigam et al. 2009; Kurtarkar et al. 2017; Frontalini et al. 2018a), high-resolution 3D X-ray microtomography visualizing complex morphologies (Speijer et al. 2008; Caromel et al. 2017; Gooday et al. 2018; Zarkogiannis et al. 2020; Belanger 2022; Choquel et al. 2023), DNA barcoding cryptic species complexes (Darling and Wade 2008; Pawlowski and Holzmann 2014; Morard et al. 2017; Macher et al. 2021), eDNA-foraminiferal based monitoring (Pawlowski et al. 2014; Frontalini et al. 2020; Al-Enezi et al. 2022), ultrastructure studies (e.g., LeKieffre et al. 2018; Frontalini et al. 2018b; 2019 for reviews), biogeographic and ecological niche modeling (Weinmann et al. 2013; Schmidt et al. 2015), invasive/alien taxa (e.g., Stulpinaite et al. 2020), assessing deep-sea morphological biodiversity (Gooday et al. 2008; 2018; Nomaki et al. 2021), genetic relationships of higher taxa (Pawlowski 2000). Technological improvements enabling high-resolution imaging, advanced genetic sequencing, and fine-scale geochemical profiling provide promising new avenues for foraminiferal research entering its third century. Three-dimensional pore structure modelling, comparative transcriptomics, and microsensor monitoring now permit more intricate views into foraminiferal morphology, physiology and calcification dynamics across spatial gradients and evolutionary timescales (Bernhard et al. 2006; 2015; Frontalini et al. 2019). Meanwhile, anthropogenic accelerated climate change and other human disturbances has generated an imperative for applying foraminifera



as rapid marine ecosystem threat assessors.

### **Scientometric network analysis**

Scientometric approach offers a powerful lens for examining the historical development and current landscape of research fields (Börner et al. 2003; Leydesdorff and Rafols 2009). By leveraging quantitative analysis of bibliographic data, these investigations unveil patterns of knowledge production, dissemination, and collaboration that shape the structure and dynamics of scientific domains (Glänzel 2001; Small 1973). Scientometric tools enable us to map the intellectual landscape of a field, tracing the emergence of key concepts, the formation of research clusters, and the impact of seminal contributions (Van Eck and Waltman 2010; Aria and Cuccurullo 2023). In doing so, they provide valuable insights into the evolution of scientific inquiry and help identify promising frontiers for future exploration. For the field of foraminifera research, comprehensive scientometric analysis is both timely and essential. As the applications of foraminifera continue to expand across diverse disciplines, from paleoceanography to ecological monitoring, there is a growing need to synthesize the vast body of knowledge accumulated over two centuries of study.

This paper provides the first comprehensive, quantitative assessment of over 200 years of global scientific contributions on foraminifera, evaluating publication trends and knowledge networks through new data science approaches. By mapping two centuries of academic research, this study synthesizes long-term trends in the evolving specialization and diversification of foraminiferal studies. The visualizations and statistics presented deliver an unprecedented perspective into the growth of this research field and demonstrate the rising prominence of foraminifera as integrators across various disciplines. This quantitative review of the expansive foraminiferal literature identifies key developments that structured the research field over two centuries, while highlighting current frontiers and emerging opportunities as foraminiferal science entering its third century.

## **MATERIALS and METHODS**

### ***Data Collection and Preprocessing***

This scientometric approach employed a comprehensive collection of studies to ensure a robust and representative analysis of the foraminiferal research landscape. Three extensive bibliographic databases, namely Scopus, Web of Science (WOS), and OpenAlex, were systematically mined to retrieve relevant publications spanning over two centuries of research. The choice of these databases was based on their comprehensive coverage, data quality, and complementary nature, ensuring a thorough capture of the global research output on foraminifera. The data collection process involved the use of a well-defined search strategy, incorporating a range of foraminifera-related keywords and phrases, such as "foraminifera\*", "foraminifer\*", "foram\*", "foraminiferid\*", and "foraminiferal". The asterisk (\*) wildcard was employed to capture variations in word endings and plurals, maximizing the inclusivity of the search results. The search was conducted across multiple fields, including titles, abstracts, and keywords, to cover a comprehensive retrieval of relevant publications.

The search results were carefully filtered to include only peer-reviewed articles, conference proceedings, and book chapters, excluding non-peer-reviewed sources such as editorials, letters, and commentaries. This approach enabled the focus on original research contributions and maintained the quality and credibility

of the analyzed data. The publication year range was set from the earliest available date in each database up to 2023, capturing the complete historical span of foraminiferal research. The initial search yielded a total of 31,932 publications from Scopus (1826-2023), 17,463 from Web of Science (1902-2023), and 32,000 from OpenAlex (1826-2023). The data were exported in a standardized format (e.g., BibTeX) to facilitate further processing and analysis. A rigorous data cleaning and preprocessing procedure was then applied to guarantee data consistency and integrity. The preprocessing steps included the removal of duplicate records, the standardization of author names and affiliations, and the harmonization of keywords and subject category schemes across the databases. This process involved a combination of automated scripts and manual verification to ensure the accuracy and reliability of the final dataset. The resulting de-duplicated and pre-processed dataset contained a total of over 58,000 unique publications, forming the basis for the subsequent scientometric analyses.

### ***Scientometric Analysis***

The scientometric analysis employed a range of quantitative and qualitative techniques to uncover patterns, trends, and insights within the foraminiferal research landscape. The analysis was conducted using the R programming language (version 4.3.1: R Core Team 2023) and various specialized packages, such as bibliometrix (version 4.1.4: Aria and Cuccurullo 2017; 2023), igraph (version 1.3.4: Csárdi et al. 2024), and ggplot2 (version 3.4.1: Wickham et al. 2021), which provided a robust and flexible framework for data manipulation, visualization, and interpretation. VOSviewer software (version 1.6.16: Van Eck and Waltman 2010) was used with Bibliometrix to visualize and explore networks.

In addition, other used packages include magrittr (version 2.0.3; Bache and Wickham 2020), rio (version 1.0.1; Chan et al. 2023), stringi (version 1.8.3; Gagolewski et al. 2023), ggpubr (version 0.6.0; Kassambara 2023), report (version 0.5.8; Makowski et al. 2023), tibble (version 3.2.1; Müller and Wickham 2023), prettydoc (version 0.4.1; Qiu 2021), pacman (version 0.5.1 Rinker and Kurkiewicz 2019), forcats (version 1.0.0; Wickham 2021), tidyverse (version 2.0.0; Wickham 2022), readxl (version 1.4.3; Wickham and Bryan 2022), dplyr (version 1.1.4; Wickham et al. 2023), purrr (version 1.0.2; Wickham and Henry 2023), readr (version 2.1.5; Wickham et al. 2024) and tidyr (version 1.3.0; Wickham et al. 2023b).

### ***Descriptive Analysis***

The descriptive analysis focused on characterizing the basic features and trends of the foraminiferal research output. Key metrics calculated included the annual publication count, average citations per year, total citations per publication, and the distribution of publications across authors, countries, and research categories. These metrics provided an overview of the growth, impact, and diversity of foraminiferal research over time. Visualization techniques, such as line plots, bar plots, and network charts, were used to present the temporal evolution of publication and citation trends, the geographic distribution of research output, and the relative contribution of different research categories and subdisciplines. These visualizations facilitated the identification of key patterns, trends, and milestones in the development of foraminiferal research.

### ***Network Analysis***

Network analysis techniques were applied to uncover the com-

plex relationships and structures within the foraminiferal research landscape. The analysis focused on three main types of networks: keyword co-occurrence, author collaboration, and institutional collaboration networks. The keyword co-occurrence network was constructed based on the frequency of co-occurrence of keywords within the publication dataset. Each keyword was represented as a node, and the edges between nodes represented the strength of their co-occurrence relationship. The network was analyzed using various centrality measures, such as degree, betweenness, and eigenvector centrality, to identify the most important and influential keywords within the research landscape. Community detection algorithms, such as the Louvain method (Blondel et al. 2008), were applied to identify clusters or communities of closely related keywords, representing distinct research themes or subdomains within the field of foraminiferal studies. The resulting keyword clusters were visualized using network maps, with node sizes reflecting the frequency of occurrence and edge weights representing the strength of co-occurrence relationships. Author and institutional collaboration networks were constructed based on co-authorship relationships within the publication dataset. Each author or institution was represented as a node, and the edges between nodes represented the collaborative ties between them. These networks were analyzed using centrality measures and community detection algorithms to identify key authors, institutions, and collaborative communities within the research landscape. The collaboration networks were visualized using force-directed layouts, with node sizes reflecting the productivity or influence of authors and institutions, and edge weights representing the strength of collaborative ties. The analysis of these networks provided insights into the structure and dynamics of scientific collaboration, the formation of research communities, and the role of key actors in shaping the field of foraminiferal studies.

### **Thematic Analysis**

Thematic analysis techniques were employed to identify and characterize the major research themes, trends, and frontiers within the field of foraminiferal studies. The analysis was based on the co-occurrence of keywords, subject categories, and citation patterns within the publication dataset. A thematic map was constructed to visualize the intellectual structure and research frontiers of the field. The map was based on a two-dimensional representation of research themes, with the x-axis representing the centrality or importance of themes and the y-axis representing the density or development of themes. The themes were classified into four quadrants: motor themes (high centrality, high density), basic themes (low centrality, high density), emerging or declining themes (low centrality, low density), and highly developed and isolated themes (high centrality, low density). The thematic analysis also involved the identification of the most frequently occurring and highly cited keywords, subject categories, and publications within each research theme. This analysis provided insights into the core concepts, methods, and landmark studies that have shaped the development of each research theme over time.

### **Science Mapping**

Science mapping techniques were used to visualize the intellectual landscape and evolution of foraminiferal research over time. The analysis was based on the co-citation and bibliographic coupling of publications, authors, and journals within the dataset. Co-citation networks were constructed based on the frequency with which pairs of publications, authors, or journals were cited together within the dataset. These networks were analyzed using centrality measures and community detection algorithms to identify the most influential publications, authors, and journals

within the research landscape, as well as the formation of distinct intellectual communities or schools of thought.

Bibliographic coupling networks were constructed based on the similarity of reference lists between pairs of publications, authors, or journals. These networks were used to identify clusters of closely related research, representing the intellectual structure and evolution of the field over time. The resulting co-citation and bibliographic coupling networks were visualized using science maps, with nodes representing publications, authors, or journals, and edges representing the strength of their similarity or relatedness. The maps were color-coded to represent distinct research themes, intellectual communities, or time periods, providing a visual representation of the intellectual landscape and its evolution over time.

### **Limitations and Future Directions**

While this scientometric study provides a comprehensive and data-driven analysis of the foraminiferal research landscape, it is important to acknowledge its limitations and potential avenues for future research. First, the study relies on bibliographic data from three major databases (Scopus, Web of Science, and OpenAlex), which, despite their extensive coverage, do not capture all publications, particularly theses in university archives, defunct journals, geological survey publications, and those in non-indexed or regional journals. Future studies could explore the inclusion of additional data sources, such as specialized databases or gray literature, to provide an even more comprehensive view of the research landscape. Second, the study focuses primarily on the analysis of bibliographic metadata, such as keywords, citations, and collaboration patterns, which may not fully capture the nuances and context of the research content itself. Future studies could employ advanced text mining and natural language processing techniques to analyze the full text of publications, providing deeper insights into the thematic structure and conceptual evolution of the field. Third, the study provides a macro-level analysis of the research, focusing on broad patterns and trends over time. Future studies could delve into more specific aspects of foraminiferal research, such as the development of particular methodologies, the impact of landmark studies, or the dynamics of specific research communities or geographic regions. Despite these limitations, this scientometric study offers a robust and comprehensive analysis of the foraminiferal research landscape, providing valuable insights into its intellectual structure, collaborative patterns, and emerging frontiers.

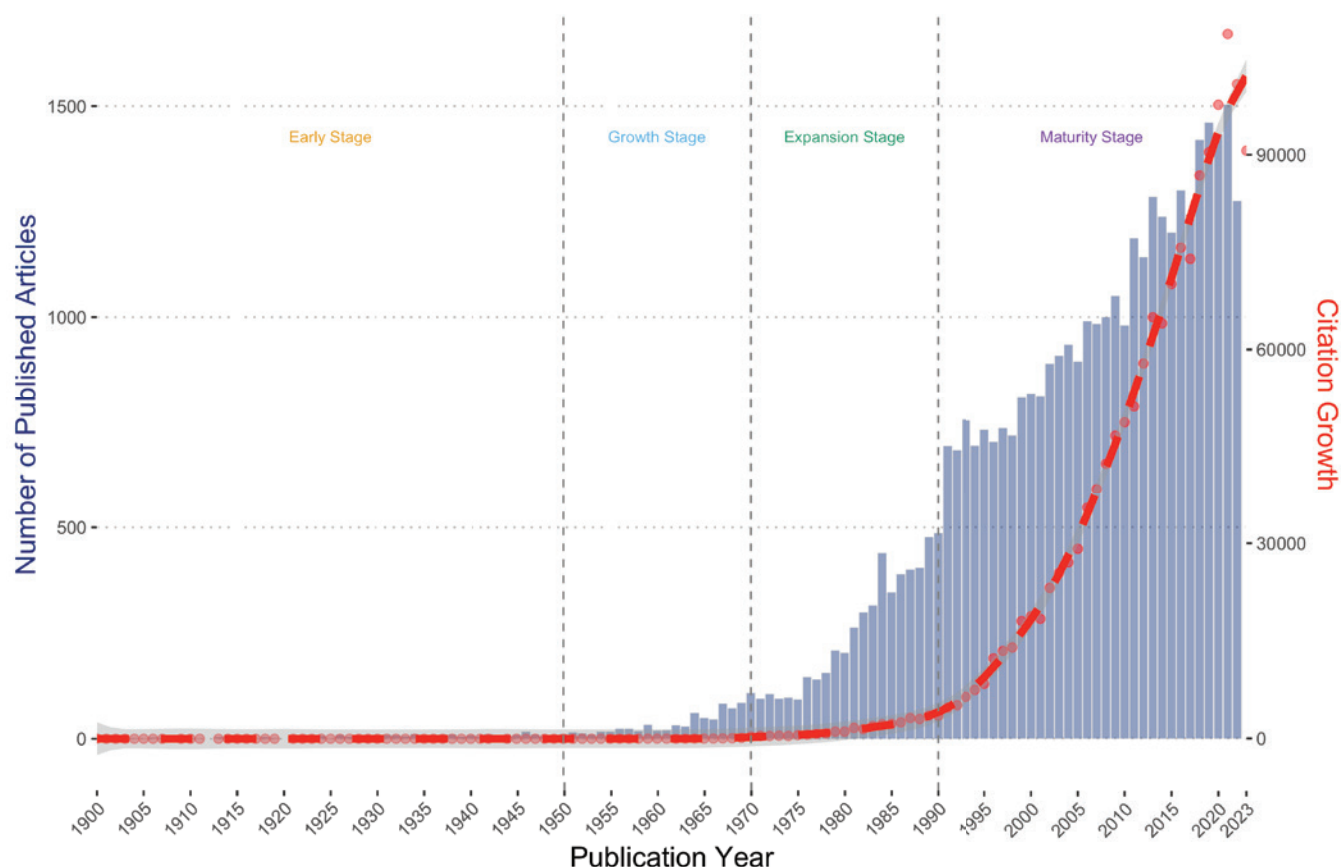
## **RESULTS**

### **Publication Trends and Research Output Overview of the Dataset**

The scientometric analysis of foraminiferal research draws upon a comprehensive dataset spanning from 1824 to 2023, encompassing more than 58,000 documents from a wide array of sources (Supplementary Material 1:1-8). This extensive coverage enables a robust assessment of the field's evolution and dynamics over the past two centuries. The annual growth rate of 3.35% indicates a sustained increase in scholarly interest and productivity, reflecting the ongoing relevance and vitality of foraminiferal studies.

### **Temporal Distribution of Publications**

Examining the temporal distribution of publications (text-fig. 1) unveils distinct phases in the development of foraminiferal research. The early 20<sup>th</sup> century (1900-1949) was characterized by a gradual increase in the number of studies, with an average of five publications per year. This period laid the foundation for the



TEXT-FIGURE 1

Temporal trends in foraminiferal research: annual publication number and citation growth (1900–2023).

field, with pioneering studies establishing the taxonomic and ecological framework for subsequent research (Cushman 1928; Grimsdale 1951).

The post-World War II period (1950–1969) saw a marked acceleration in research activity, with annual publications rising to an average of 41. This growth can be ascribed to the increasing recognition of foraminifera as valuable tools in biostratigraphy, paleoceanography, and oil exploration (Berggren 1969; Bolli et al. 1989). The trend intensified during the 1970s and 1980s, with yearly output reaching 108 and 209 publications, respectively. This period marked significant cultural changes in academic publishing, with many new journals emerging in the mid to late 1980s that provided additional publication venues for foraminiferal research. The period also witnessed the advent of advanced analytical techniques, such as scanning electron microscopy and stable isotope analysis, which revolutionized the study of foraminiferal morphology, ecology, and geochemistry (Emiliani 1955; Shackleton 1967; Haq et al. 1977).

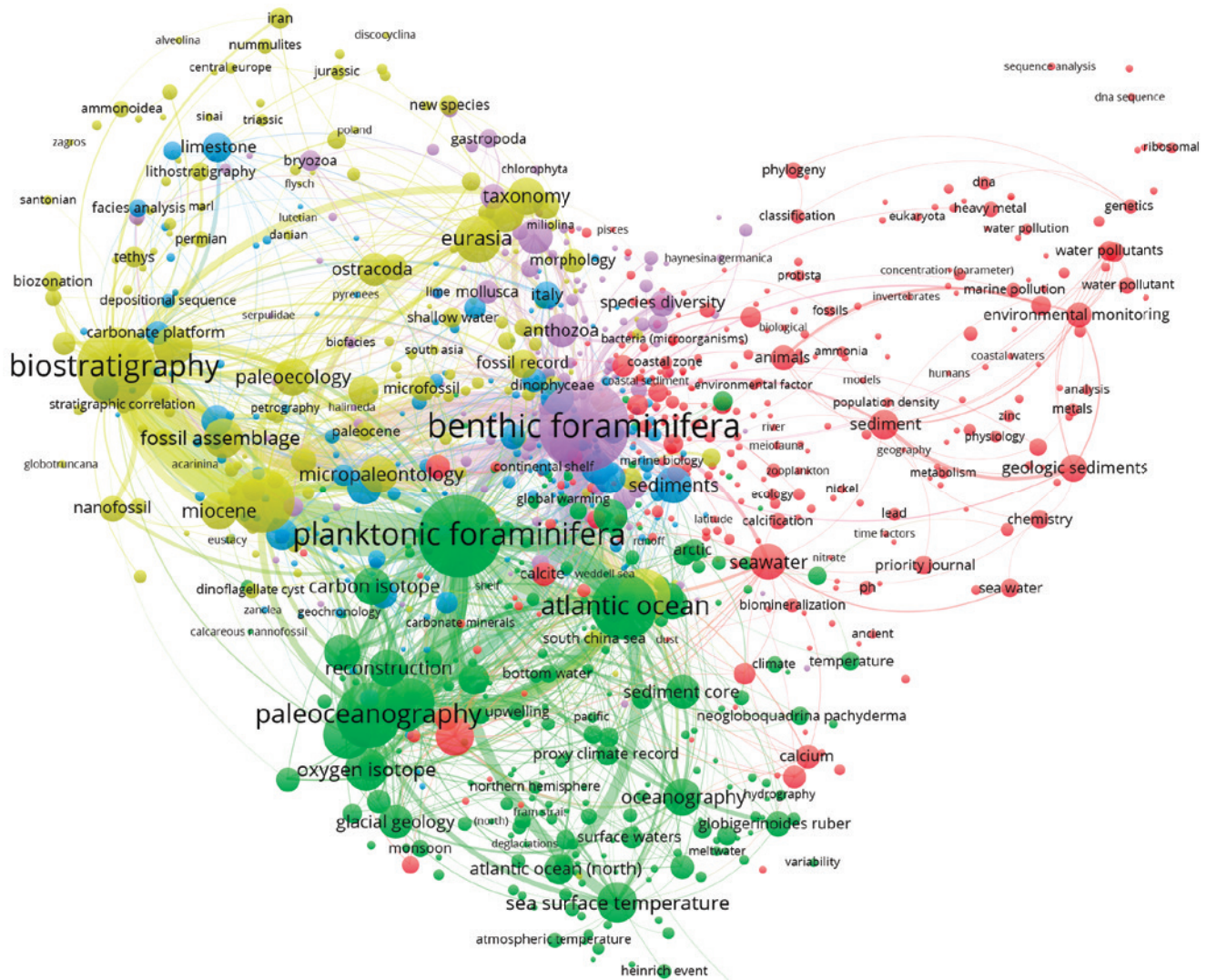
The 1990s emerge as a watershed decade, marking a dramatic surge in foraminiferal research. The average annual publication count reached 436, a more than twofold increase from the previous decade. This "golden era" of foraminiferal studies can be attributed to several factors, including the proliferation of ocean drilling programs, the development of high-resolution paleoceanographic proxies, and the increasing recognition of

foraminifera as bioindicators of environmental change. While the 2010s and early 2020s show a slight deceleration in growth rate, the annual publication output remains highly substantial, averaging well above 1000 studies per year. This sustained productivity underscores the relevance and vibrancy of foraminiferal research in addressing a wide range of scientific questions, from paleoclimate reconstruction to biodiversity assessment over the Phanerozoic.

#### ***Citation Impact and Influential Publications***

Analyzing the citation patterns across time (text-fig. 1) provides further insights into the impact and evolution of foraminiferal studies. The early decades of the 20th century show minimal citation activity, reflecting the nascent stage of the field. However, from the 1950s onward, a clear upward trajectory emerges, mirroring the growth in publication output. The 1990s stand out as a pivotal period, not only in terms of publication volume but also in terms of citation impact. The decade garnered a total of 70,412 citations, a more than sevenfold increase compared to the 1980s. This surge in citations can be attributed to the publication of several seminal papers that significantly advanced the field, such as the estimation of sea-level and deep water temperature variation from foraminiferal isotopic records (Chappell and Shackleton 1986; Miller et al. 1987; Shackleton et al. 1990) and, in part, because of ease of finding references, the definition of benthic foraminiferal microhabitats (Hallock and Hansen 1979; Corliss 1985), and the documentation of Cenozoic cosmo-





TEXT-FIGURE 2

Network visualization of the top 1000 keywords in foraminiferal research, revealing five major clusters representing key research themes and their interconnections. Node size is proportional to the total link strength, and edge thickness represents the frequency of keyword co-occurrence.

politan deep-water benthic foraminifera (Van Morkhoven et al. 1986; Kaminski and Gradstein 2005) as well as their application in paleoceanography (Duplessy 1978; Boyle and Keigwin 1987). The highest cited papers in 1990s include the development of the conceptual model, TROX, explaining benthic foraminiferal microhabitats (Jorissen et al. 1995), the investigation of key paleoclimatic events (Miller et al. 1991), the calibration of oxygen isotopes on planktonic foraminifera as paleothermometer (Spero et al. 1997; Bemis et al. 1998), the definition of biostratigraphical scheme for the Paleocene and Eocene based on larger benthic foraminifera (Serra-Kiel et al. 1998), the development of the Mg/Ca paleothermometer (Nürnberg et al. 1996) as well as the investigation of phylogeny of the kingdom Protozoa (Cavalier-Smith 1993). This period also saw the expansion of the application of benthic foraminifera as bioindicators of oxygen availability (Gupta and Machain-Castillo 1993; Kaiho 1994), other factors influencing their distribution (Van der Zwaan et al. 1999) as well as pollution (Alve 1995).

The trend of increasing citation impact accelerated further in the 2000s, with the dataset registering a staggering 280,807 citations. This period witnessed the publication of highly influential papers on topics such as the use of benthic foraminifera in sea-level and deep-water temperature variations (Waelbroeck et al. 2002), the ecology and application of benthic foraminifera (Murray 2006), the impact of ocean acidification (Fabry et al. 2008), the application of boron-isotope ratios on planktonic foraminiferal shells to estimate the pH of surface seawaters and to reconstruct atmospheric CO<sub>2</sub> concentrations (Pearson and Palmer 2000), the revision of tropical to subtropical planktonic foraminiferal zonation for the Paleogene (Hallock et al. 1991; Berggren and Pearson 2005) as well as their application for Mesozoic and Cenozoic paleoclimatic variations (Lea et al. 2000; Lear et al. 2000).

The 2010s represent the apex of citation activity, accumulating an impressive 657,991 citations. This figure underscores the far-reaching influence and visibility of foraminiferal research in the modern scientific era. Notable contributions during this period

include the revision of Cenozoic tropical planktonic foraminiferal zonations with their calibration to the geomagnetic polarity and astronomical time scale (Wade et al. 2011), the application of foraminifera in assessing the impacts of the Paleocene-Eocene Thermal Maximum (McInerney and Wing 2011), the development of a sampling protocol for foraminiferal biomonitoring (Schönfeld et al. 2012), the supraordinal classification of foraminifera (Pawlowski et al. 2013), their application in Mesozoic and Cenozoic paleoclimatic variations and for paleoenvironmental reconstructions (e.g., Friedrich et al. 2012; Rohling et al. 2014), the introduction of eDNA metabarcoding for diversity estimates and pollution monitoring (Pawlowski et al. 2014; Pawlowski and Holzmann 2014; Pochon et al. 2015; Cordier et al. 2017).

The early 2020s have already amassed 255,148 citations, highlighting the continued prominence and impact of the field. Recent papers have focused on topics such as the effects of microplastic on foraminifera (Bouchet et al. 2023), the application of eDNA in foraminiferal biomonitoring (Frontalini et al. 2020), the investigation of past and future decline of tropical pelagic biodiversity (Yasuhara et al. 2020), determining the diversity and depth distribution of shallow-water benthic foraminifera on tropical islands (Parker and Gischler, 2025; Goeting et al., 2025) the response of planktonic foraminifera to climate change (Roy et al. 2015; Narayan et al. 2022; de Garidel-Thoron et al. 2022) and the application of machine learning techniques in foraminiferal taxonomy and ecology (Mitra et al. 2019; Rostami et al. 2021; 2023).

### ***Keyword Analysis and Research Themes***

#### ***Keyword Co-occurrence Network***

The keyword co-occurrence network (text-figs. 2 and 3) offers a comprehensive map of the intellectual structure and thematic diversity of foraminiferal research. The network, consisting of 1000 nodes and 45,991 edges, exhibits a complex and interconnected topology, with nodes representing individual keywords and edges signifying their co-occurrence relationships. The network's scale-free structure, characterized by a power-law distribution of node degrees, suggests the presence of a few highly connected "hub" keywords that play a central role in organizing the research landscape (Barabási and Albert 1999). These hub keywords, such as "benthic foraminifera," "planktonic foraminifera," and "paleoceanography," serve as integrative concepts, bridging multiple subdomains and research themes. The network's modularity, as revealed by the presence of densely connected clusters, indicates the existence of distinct research communities or specializations within the broader field of foraminiferal studies (Newman 2006). These clusters represent the major research domains that have emerged over time, reflecting the evolving interests and priorities of the scientific community.

#### ***Major Research Domains***

Cluster analysis of the keyword co-occurrence network reveals five major research domains: (1) ecological and environmental aspects, (2) paleoceanography and paleoclimatology, (3) sedimentological and stratigraphic applications, (4) biostratigraphy and evolutionary history, and (5) environmental monitoring and bioindicator potential. The largest cluster (purple) focuses on the ecological and environmental dimensions of foraminiferal research. Central nodes such as "benthic foraminifera," "algae," "species diversity," and "coral reef" highlight the significance of foraminifera in understanding marine ecosystem dynamics and interactions. This cluster encompasses studies on foraminiferal

ecology, biodiversity, and biogeography, as well as their applications in monitoring environmental health and change (Hallock et al. 2003; Kelmo and Hallock 2013).

The second largest cluster (green) revolves around paleoceanography and paleoclimatology. Key nodes such as "planktonic foraminifera," "paleoceanography," "paleoclimate," and "oxygen isotope" underscore the pivotal role of foraminifera as proxies for reconstructing past ocean conditions and climatic variability. This cluster includes research on the use of foraminiferal geochemistry, assemblage composition, and morphology to infer past changes in temperature, salinity, productivity, and circulation patterns (Kucera 2007; Ravelo and Hillaire-Marcel 2007; Katz et al. 2010).

The third cluster (blue) emphasizes the sedimentological and stratigraphic applications of foraminiferal research. Nodes such as "sediments," "stratigraphy," and "carbonate platform" reflect the utility of foraminifera in deciphering depositional environments and constructing stratigraphic frameworks. This cluster encompasses studies on the distribution and preservation of foraminifera in sedimentary sequences, as well as their use in sequence stratigraphy, basin analysis, and reservoir characterization (Flügel 2012; Schiebel and Hemleben 2017; Boudaughier-Fadel 2018).

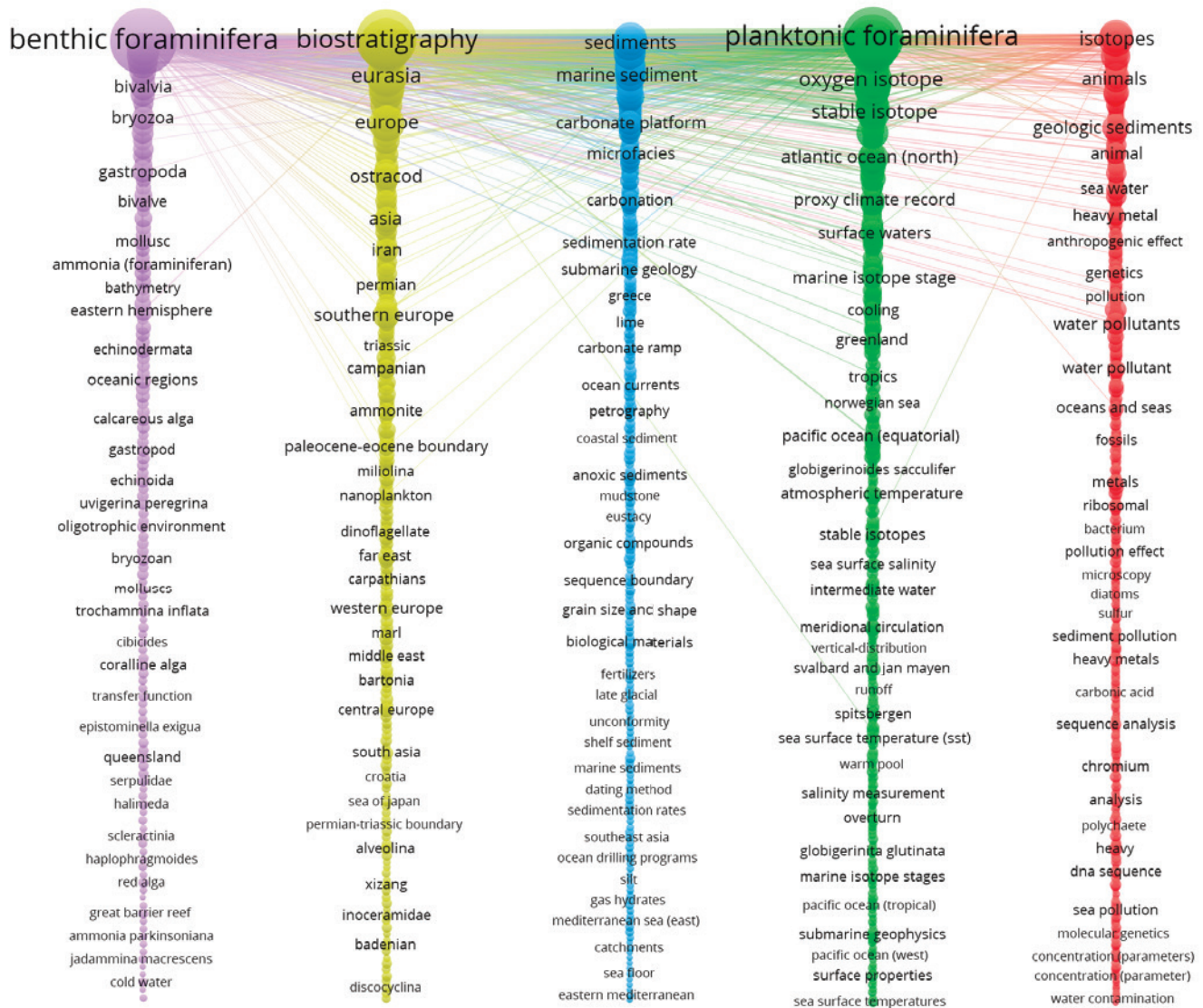
The fourth cluster (yellow) centers on biostratigraphy and evolutionary aspects (text-figs. 2 and 3). Nodes like "biostratigraphy," "cretaceous," and "biozonation" illustrate the importance of foraminifera as biostratigraphic markers and their significance in unraveling evolutionary patterns and paleoenvironmental changes. This cluster includes research on the development and refinement of foraminiferal biozonation schemes, as well as studies on the evolutionary history, diversification, and extinction events of foraminiferal lineages (Gradstein et al. 2012; K BouDagher-Fadel 2015; Papazzoni et al. 2017).

The fifth cluster (red) focuses on the environmental monitoring and bioindicator applications of foraminifera. Nodes such as "environmental monitoring," "pollution," and "heavy metal" highlight the growing recognition of foraminifera as sensitive indicators of anthropogenic stressors and ecological health. This cluster encompasses studies on the response of foraminifera to various environmental perturbations, such as eutrophication, hypoxia, ocean acidification, and contamination by pollutants (Alve et al. 2009; Schönfeld 2012).

#### ***Interdisciplinary Connections and Emerging Themes***

The interconnectivity between clusters underscores the multidisciplinary nature of foraminiferal research. Nodes such as "stable isotope" and "geochemistry" serve as bridging concepts, linking paleoceanographic, ecological, and sedimentological domains. These cross-cutting themes highlight the integrative potential of foraminiferal studies in addressing complex Earth system questions, such as the coupling between climate, ocean circulation, and biogeochemical cycles (Kucera et al. 2005; Ravelo and Hillaire-Marcel 2007; Katz et al. 2010). The network also reveals the prominence of specific foraminiferal taxa, such as "*Globigerinoides ruber*," "*Neogloboquadrina pachyderma*," and "*Ammonia beccarii*," in different research contexts. These taxa serve as model organisms, providing insights into the ecology, biology, and geochemistry of foraminifera across a range of spatial and temporal scales (Kucera 2007; Darling and Wade 2008; Holzmann and Pawlowski 2017).





TEXT-FIGURE 3

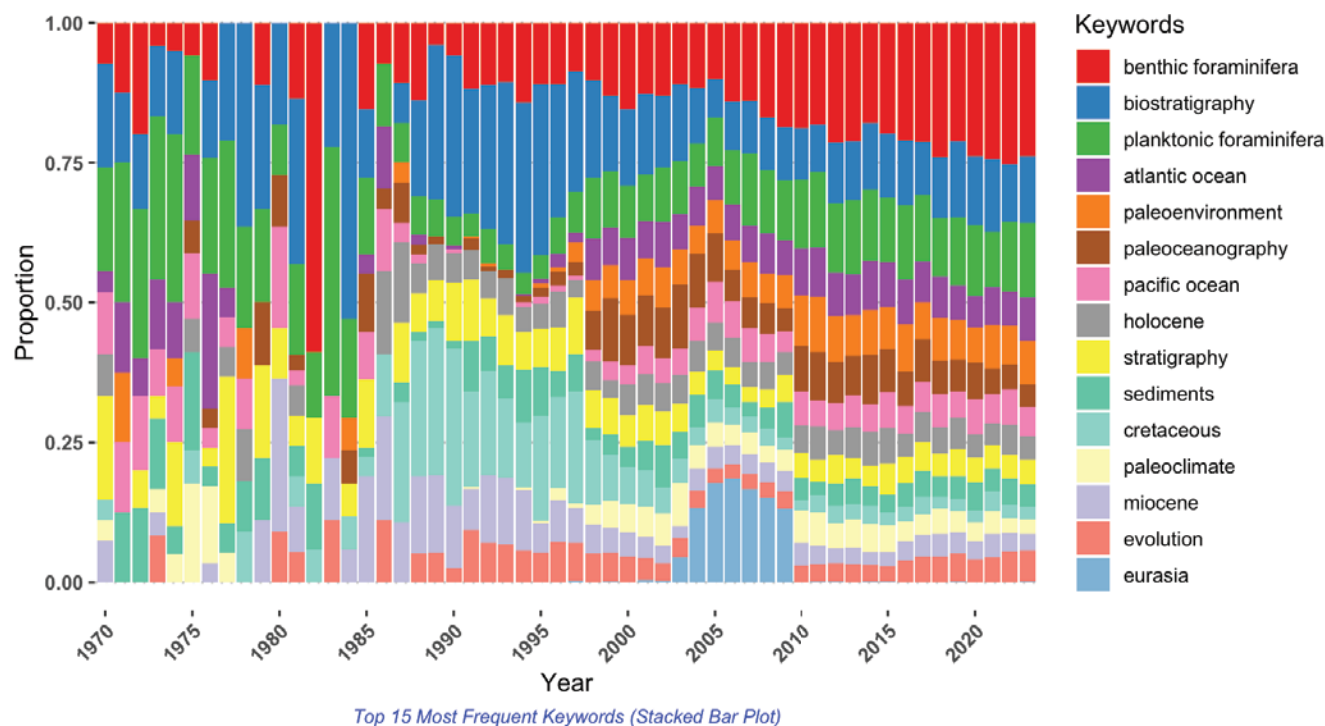
Detailed view of the network structure, highlighting the cross-disciplinary links and the prominence of specific foraminiferal taxa, geographic regions, and research methods major clusters.

Analyzing the temporal distribution of keywords (text-figs. 4-6) provides insights into the evolution of research themes over time. The top 15 keywords (text-fig. 4) showcase the dominance of core concepts such as "foraminifera," "benthic foraminifera," "biostratigraphy," and "paleoceanography." The temporal distribution of publications associated with these keywords (text-fig. 6) reveals a concentration in the 2000s and 2010s, aligning with the overall growth trends in foraminiferal research. Examining the comparative popularity of selected keywords over time (text-fig. 5) highlights the shifting focus of the field. Terms such as "paleoenvironment," "paleoceanography," and "paleoclimate" show a steady increase in usage, reflecting the growing importance of foraminifera in reconstructing past environmental conditions. Similarly, keywords like "ecology," "biodiversity," and "climate change" exhibit an upward trajectory, indicating the increasing relevance of foraminifera in addressing contemporary ecological and environmental challenges. The keyword analysis also reveals the emergence of new research themes

and methodological approaches. For example, the increasing frequency of terms such as "molecular phylogeny," "next-generation sequencing," and "ancient DNA" points to the growing application of molecular techniques in foraminiferal taxonomy, ecology, and evolution (Pawlowski et al. 2014; Darling et al. 2016; Morard et al. 2016). Similarly, the appearance of keywords like "ocean acidification," "anthropogenic impact," and "ecosystem functioning" reflects the expanding scope of foraminiferal studies in assessing the consequences of global change on marine ecosystems (Fujita et al. 2011; Bernhard et al. 2015; Doo et al. 2020).

#### Geographic Distribution and Collaborative Patterns *Leading Countries and Research Output*

Analyzing the geographic distribution of foraminiferal research (text-fig. 7) reveals the dominance of North America and Europe. The United States emerges as the leading contributor, with 4,098



TEXT-FIGURE 4

Frequency distribution of the top 15 keywords in foraminiferal research, highlighting the dominance of core themes.

publications, reflecting its long-standing tradition of micropaleontological research and its extensive network of universities, museums, and research institutions (Lipps 1981). Germany (2,203 publications), France (1,723), and the United Kingdom (1,716) also feature prominently, highlighting the increasingly significant contributions of European researchers to the field. China, a relatively recent entrant, has shown a remarkable growth trajectory, with 1,460 publications, surpassing established contributors such as Italy and Japan. This rapid rise can be attributed to China's increasing investment in scientific research, the expansion of its academic institutions, the large number of Chinese students who study abroad, and the growing international collaboration of Chinese researchers. Other countries, such as Australia, the Netherlands, Canada, and Poland also make notable contributions, reflecting the global extent and diversity of foraminiferal research.

#### Continental and Regional Patterns

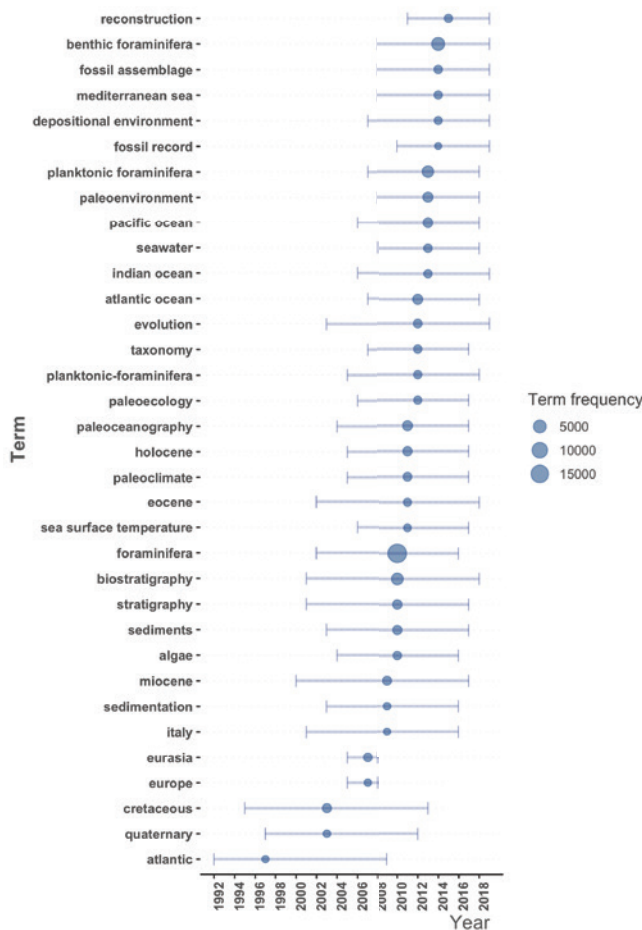
Examining the continental breakdown (text-fig. 7B) underscores the concentration of research output in Europe (11,454 publications) and North America (5,396). This pattern can be attributed to several factors, including the historical development of micropaleontology in these regions, the presence of extensive fossil records, and the availability of research infrastructure and funding. Asia, with 5,276 publications, emerges as a significant player, driven largely by the rapid growth of foraminiferal research in China and the contributions of other countries such as Japan, India, and South Korea. This trend reflects the increasing globalization of scientific research and the growing recognition of the importance of foraminifera in understanding regional stratigraphic, environmental, and paleoclimatic histories.

Notably, South America, Africa, and Oceania exhibit comparatively lower research output, highlighting potential geographic disparities and opportunities for further development. These regions possess rich foraminiferal assemblages and unique paleoenvironmental records that remain relatively understudied compared to other regions. Efforts to enhance research capacity, funding, promote international collaboration, and address regional research priorities could help unlock the full potential of foraminiferal studies in these areas.

#### International Collaboration and Research Networks

Investigating the collaborative patterns among countries (text-fig. 8) provides insights into the internationalization of foraminiferal research. Switzerland, the Netherlands, and Germany emerge as the most collaborative nations, with over 40% of their publications involving international co-authors. This high level of international engagement can be attributed to several factors, including the presence of leading research institutions, the availability of funding for collaborative projects, and the active participation of researchers in international networks and consortia. In contrast, countries like Poland, India, and Japan show lower levels of international collaboration relative to their domestic output. This pattern may reflect differences in research priorities and funding structures. Efforts to promote international cooperation, facilitate data sharing, and enhance research mobility could help foster a more globally integrated foraminiferal research community. The author collaboration network (text-fig. 9) highlights the prominence of key researchers who serve as central nodes in their respective clusters. These influential authors have made significant contributions to various aspects of foraminiferal research, including taxonomy, paleoceanography, ecology, molecular taxonomy, and

## Trend Topics

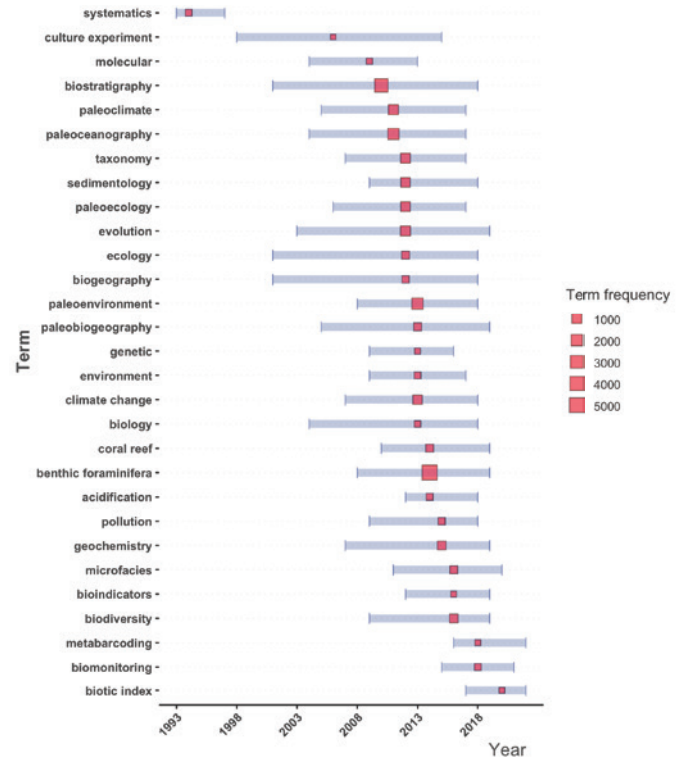


TEXT-FIGURE 5

Comparative popularity of selected foraminiferal research keywords over time, based on publication frequency.

deep-sea ecology. The network topology suggests the formation of research communities around shared themes and geographic foci, reflecting the specialization and regional expertise of different research groups. Similarly, the institution collaboration network (text-fig. 10) unveils the centrality of leading universities and oceanographic research centers in foraminiferal studies. The University of California, University of Bremen, University College London, University of Southampton, and Woods Hole Oceanographic Institution emerge as major hubs, fostering extensive collaborative ties with other institutions worldwide. These institutions have a long-standing tradition of excellence in micropaleontological research, with access to cutting-edge facilities, diverse sample collections, and interdisciplinary expertise. Unfortunately, some of the hubs identified in text-figure 10 are no longer active owing to the retirement of key researchers. The collaboration networks also reveal the presence of regional clusters, such as the European, North American, and Asian groups, which represent important centers of foraminiferal research. These clusters echo the historical development of the field, the availability of funding and infrastructure, and the existence of long-term research programs and initiatives. Strengthening collaborations within and between these regional clusters could help address global research challenges, promote knowledge

## Selected Keywords



TEXT-FIGURE 6

Temporal distribution of keywords associated with publications from the 1980s to 2022, with a density in the 2000s and 2010s.

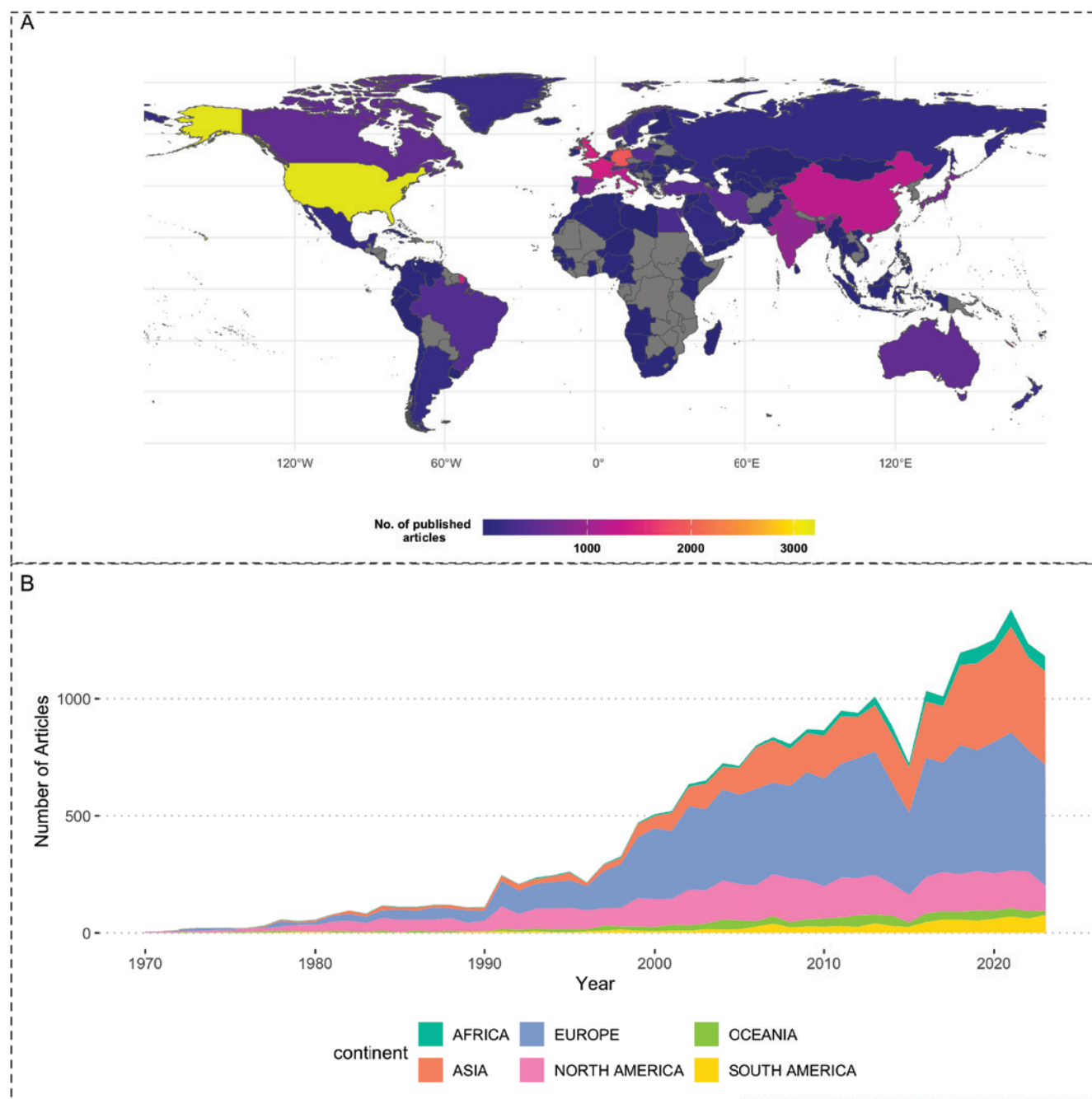
exchange, and enhance the impact and visibility of foraminiferal studies.

## Thematic Map and Main Research Themes

The thematic map (text-fig. 11) provides a comprehensive overview of the intellectual structure and research frontiers within foraminiferal studies through the positioning of research themes along centrality and density dimensions. In the motor themes quadrant (upper-right), characterized by high centrality and density, "benthic foraminifera" and "planktonic foraminifera" emerge as fundamental clusters, closely interconnected with "paleoenvironment" and "paleoceanography" themes. This positioning reflects their critical role in paleoenvironmental reconstructions (Gupta and Gupta 1999; Gooday 2003; Jorissen et al. 2007). The presence of "Atlantic Ocean," "Pacific Ocean," and "paleoclimate" in this quadrant further emphasizes their significant influence in shaping the field's intellectual landscape.

The basic themes quadrant (lower-right), exhibiting high centrality but lower density, is anchored by the "biostratigraphy" cluster, demonstrating its well-established position through connections with "limestone," "Cretaceous," and "carbonate platform" themes. The "evolution" theme, positioned as a motor theme alongside "biodiversity" and "calcium carbonate," highlights the integrated nature of evolutionary studies in foraminifera (Gradstein et al. 2012; Boudaughier-Fadel 2018). In the niche themes quadrant (upper-left), "genetics" and "phylogeny" clusters, together with "DNA" and "classification," represent highly developed but specialized research areas that bridge traditional and molecular ap-





TEXT-FIGURE 7

Geographic distribution of foraminiferal research. (A) Top 25 countries by total publication count. (B) Continental breakdown of research output, led by Europe and North America.

proaches (Darling and Wade 2008; Pawlowski and Holzmann 2014).

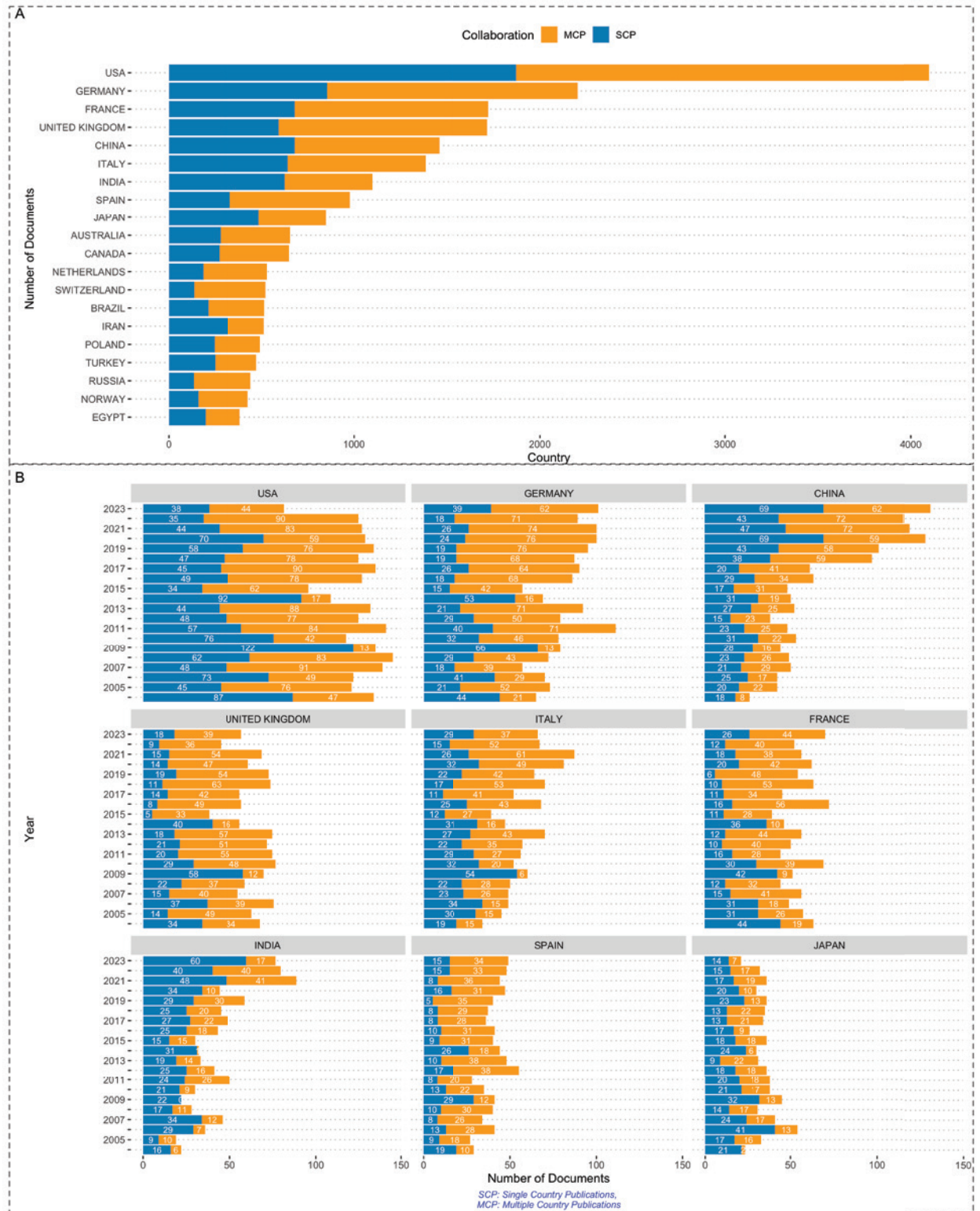
The emerging or declining themes quadrant (lower-left), characterized by low density and centrality, contains themes such as "climate," "ocean circulation," "variability," and "marine environment." Their positioning suggests either nascent research directions or areas of diminishing focus within foraminiferal

studies. The spatial distribution and interconnections between these themes across all quadrants illustrate the dynamic nature of foraminiferal research, highlighting both established core areas and potential future research trajectories.

#### Journal and Research Categories

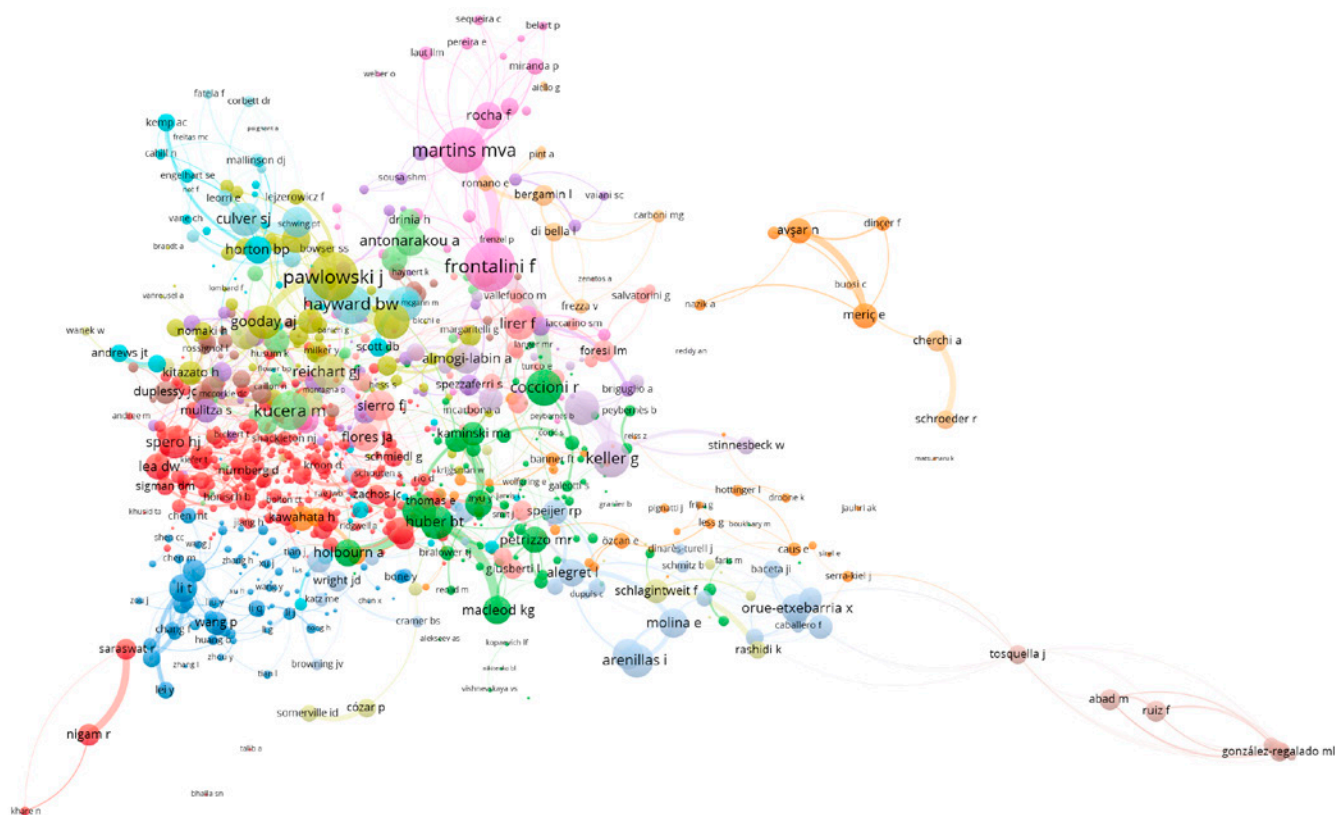
##### Leading Publication Outlets

Examining the distribution of publications across journal sources



TEXT-FIGURE 8

Collaborative trends in foraminiferal research: intra-country (SCP) and inter-country (MCP) collaboration. (A) Proportion of multi-country publications for top 20 countries, highest in Switzerland, Netherlands, and Germany. (B) Publication trends over 20 years for top 9 countries, showing growth in China and Germany.



TEXT-FIGURE 9

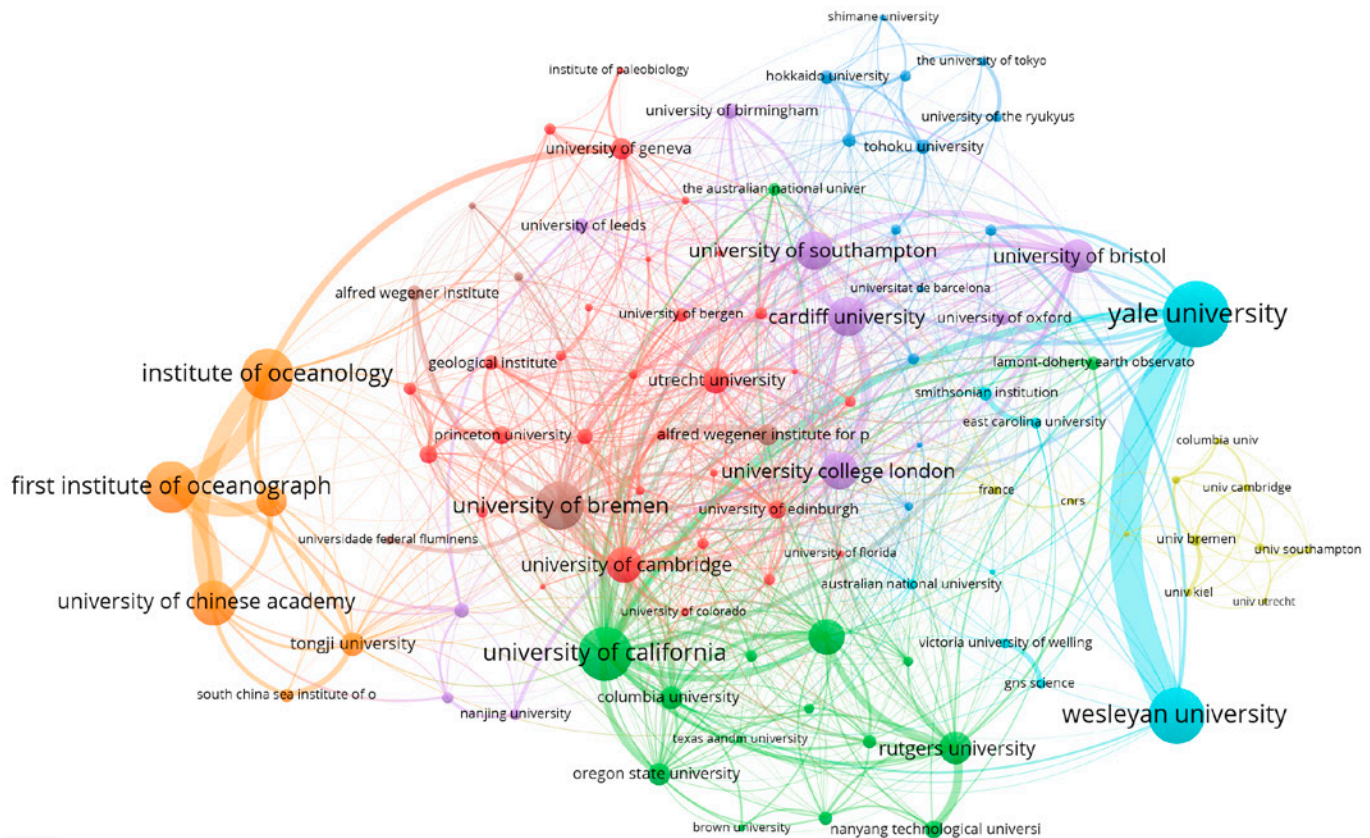
Author collaboration network based on the top 500.

es (text-figs. 12-13) highlights the significance of specialized outlets in disseminating foraminiferal research. The Journal of Foraminiferal Research emerges as the most prolific, with 1,731 publications, reflecting its status as the premier forum for the study of living and fossil foraminifera. Other top-ranking journals, such as Palaeogeography, Palaeoclimatology, Palaeoecology (1,279 publications), Marine Micropaleontology (1,229), Paleoceanography (1,156), and Micropaleontology (1,100) showcase the interdisciplinary nature of foraminiferal studies, spanning paleontology, oceanography, and paleoclimatology. The presence of high-impact journals, such as Nature, Science, and Proceedings of the National Academy of Sciences, among the top publication outlets underscores the significance and broad relevance of foraminiferal research. These journals have published seminal papers on topics such as the role of foraminifera in global carbon cycling (Schiebel 2002), the impact of ocean acidification on foraminiferal calcification (Moy et al. 2009), and the use of foraminifera in reconstructing past climates (Zachos et al. 2001). The temporal distribution of publications in the top journals (text-fig. 12) reveals a steady increase since the 1970s, with a notable surge in the 1990s and 2000s. This pattern aligns with the overall growth trends observed in the field, reflecting the expanding scope and impact of foraminiferal studies. The sustained productivity in recent years highlights the continued importance of these publication outlets in advancing foraminiferal research and disseminating key findings to the broader scientific community.

### ***Interdisciplinary Scope and Research Categories***

Analyzing the research categories (text-fig. 14) provides a broader perspective on the disciplinary contexts of foraminiferal research. Geosciences, paleontology, and oceanography emerge as the dominant categories, collectively accounting for over 50% of the publications. This distribution underscores the interdisciplinary nature of foraminiferal studies, spanning geological, biological, and environmental domains (Murray 2006). The strong representation of geosciences reflects the fundamental role of foraminifera in understanding Earth's history, from the reconstruction of past climates and ocean conditions to the development of biostratigraphic frameworks and the analysis of sedimentary basins (Katz et al. 2010; Gradstein et al. 2012; K BouDagher-Fadel 2015). The prominence of paleontology highlights the importance of foraminifera as a model system for studying evolutionary processes, extinction events, and biogeographic patterns (Reiss and Hottinger 2012). The significant contribution of oceanography underscores the value of foraminifera as indicators of marine environmental conditions, from surface productivity and water column stratification to deep-sea circulation and benthic ecosystem health (Jorissen et al. 2007; Rillo et al. 2019; Gooday et al. 2020). The presence of other categories, such as environmental sciences, ecology, and biochemistry, reflects the growing application of foraminifera in tackling contemporary challenges, such as climate change, ocean acidification, and anthropogenic impacts on marine ecosystems (Doo et al. 2014; Schmidt et al. 2014; Bernhard et al. 2015). The temporal evolution of research categories (text-fig. 14) mirrors the growth patterns observed in the overall publication trends.





TEXT-FIGURE 10  
Education collaboration network.

The 1990s and 2000s stand out as particularly productive decades across multiple categories, reflecting the intensification of foraminiferal research during this period. The sustained growth in recent years highlights the continued expansion and diversification of foraminiferal studies, with increasing contributions from fields such as genetics, biogeochemistry, and ecological modeling (Katz et al. 2010; Lombard et al. 2011; Darling et al. 2016). The interdisciplinary scope of foraminiferal research is further evident in the co-occurrence of categories within individual publications. For example, studies combining paleontological, geochemical, and oceanographic approaches have provided invaluable insights into past climate dynamics, ocean circulation patterns, and carbon cycle perturbations (Kucera et al. 2005; Moy et al. 2009; Ezard et al. 2015). Similarly, the integration of ecological, molecular, and environmental perspectives has advanced our understanding of foraminiferal biodiversity, adaptive strategies, and responses to anthropogenic stressors (Darling and Wade 2008; Rillo et al. 2019).

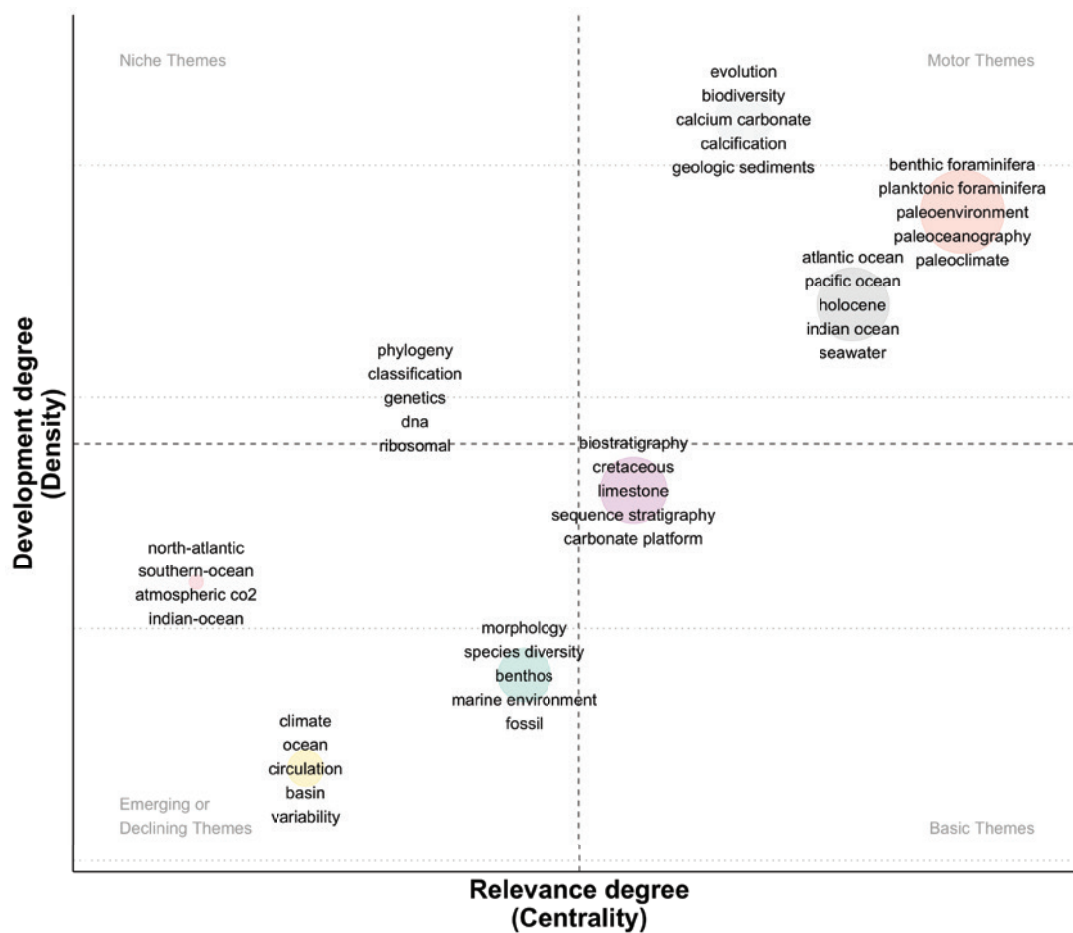
## DISCUSSION

### *The Exponential Growth of Foraminiferal Research*

The scientometric analysis conducted in this study reveals the exponential growth and evolving landscape of foraminiferal research over the past two centuries. This growth may be attributed to several factors, including technological advancements, the proliferation of ocean drilling programs, and the increasing awareness of anthropogenic impacts on marine ecosystems (Hallock 1987; Alve 1995; Kucera et al. 2005; Katz et al. 2010).

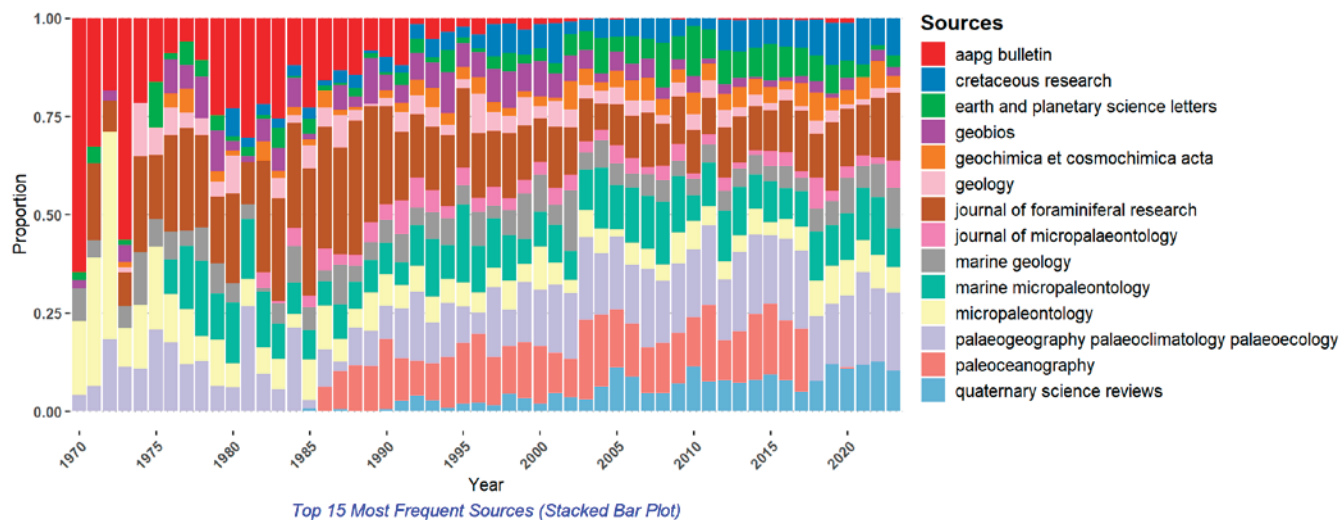
Advanced analytical techniques have revolutionized our ability to extract information from foraminiferal shells. The development of stable isotope analysis (Emiliani 1955; Shackleton 1967) and trace element geochemistry (Elderfield and Ganssen 2000; Lear et al. 2000) has enabled researchers to reconstruct past changes in ocean temperature, salinity, and productivity, as well as global ice volume and atmospheric CO<sub>2</sub> levels. The integration of these geochemical proxies with foraminiferal assemblage data has greatly advanced our understanding of past climate dynamics and ocean circulation patterns. Ocean drilling programs, such as the Deep-Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), and International Ocean Discovery Program (IODP), have provided access to continuous sedimentary records spanning millions of years (Winterer 2000). These programs have yielded valuable insights into the long-term evolution of Earth's climate system, ocean chemistry, and marine biota. Foraminiferal data from these sediment cores have been crucial in reconstructing past climate variability, carbon cycle dynamics, and biotic responses to environmental change (Norris and Röhl 1999; Zachos et al. 2001).

The increasing recognition of anthropogenic impacts on marine ecosystems has spurred the application of foraminifera as bio-indicators of environmental stress. Benthic foraminifera, in particular, have been widely used to monitor the ecological effects of pollution, eutrophication, ocean acidification, and deoxygenation (Kaiho 1994; Alve 1995; Schönfeld 2012). The sensitivity of foraminiferal assemblages to changes in water quality, pH, and



TEXT-FIGURE 11

Comprehensive thematic map depicting the intellectual structure and research frontiers in the field of foraminifera studies.



TEXT-FIGURE 12

Temporal distribution of publications from the top 15 journal sources in foraminifera research (1970-2023).



TEXT-FIGURE 13  
Median frequency of publications for top journal sources in foraminifera research.



oxygen levels has made them valuable tools for assessing the health of marine habitats and the effectiveness of conservation efforts (Yanko et al. 1998; Kaminski 2012; Uthicke et al. 2013). The citation analysis highlights the transformative impact of key publications and the increasing visibility of foraminiferal research within the broader scientific community. The "golden era" of the 1990s and 2000s saw the publication of seminal works that shaped our understanding of past climate dynamics, ocean circulation, and ecological processes. For example, the development of the Mg/Ca paleothermometer by Nürnberg et al. (1996) and the application of benthic foraminiferal assemblages as proxies for deep-water circulation by Schmiedl et al. (1997) and Kaiho (1999) have become cornerstone methods in paleoceanography. Similarly, the use of foraminiferal shell geochemistry to reconstruct past seawater carbonate chemistry and atmospheric CO<sub>2</sub> levels by Spero et al. (1997) and Barker and Elderfield (2002) has greatly advanced our understanding of the Earth's climate system and its response to perturbations. The sustained growth in citation impact in recent years underlies the ongoing relevance of foraminiferal studies in addressing contemporary challenges, such as climate change, ocean acidification, and biodiversity loss. The increasing frequency and severity of marine heatwaves, the widespread bleaching of coral reefs, and the expansion of oxygen minimum zones have heightened the urgency of understanding the resilience and adaptive capacity of marine ecosystems (Hoegh-Guldberg and Bruno 2010; Hughes et al. 2018). Foraminifera have emerged as key players in these efforts, providing valuable insights into the response of marine organisms to environmental stress and the potential for ecosystem recovery (Schmidt et al. 2018; Narayan et al. 2022).

### **The Interconnected Landscape of Foraminiferal Research**

The keyword co-occurrence network analysis unveils the complex and interconnected landscape of foraminiferal research, highlighting its thematic diversity and interdisciplinary scope. The identification of five major research domains – ecological and environmental aspects, paleoceanography and paleoclimatology, sedimentological and stratigraphic applications, biostratigraphy and evolutionary history, and environmental monitoring and bioindicator potential – demonstrates the versatility of foraminifera as a research tool as well as their practical applications in the oil industry (Murray 2006; Jorissen et al. 2007; Armstrong and Brasier 2013; Hughes et al. 2019). The strong connectivity between these research domains underscores the integrative potential of foraminiferal studies in addressing complex Earth system questions. For example, the integration of paleoceanographic and paleoclimatic data from foraminiferal proxies with sedimentological and stratigraphic information has enabled the reconstruction of past sea-level changes, ocean circulation patterns, and carbon cycle dynamics (Lisiecki and Raymo 2005; Elderfield et al. 2012). Similarly, the combination of biostratigraphic and evolutionary data from foraminiferal assemblages with geochemical proxies has provided insights into the timing and drivers of major biotic turnovers and extinction events in Earth's history (Norris 1991).

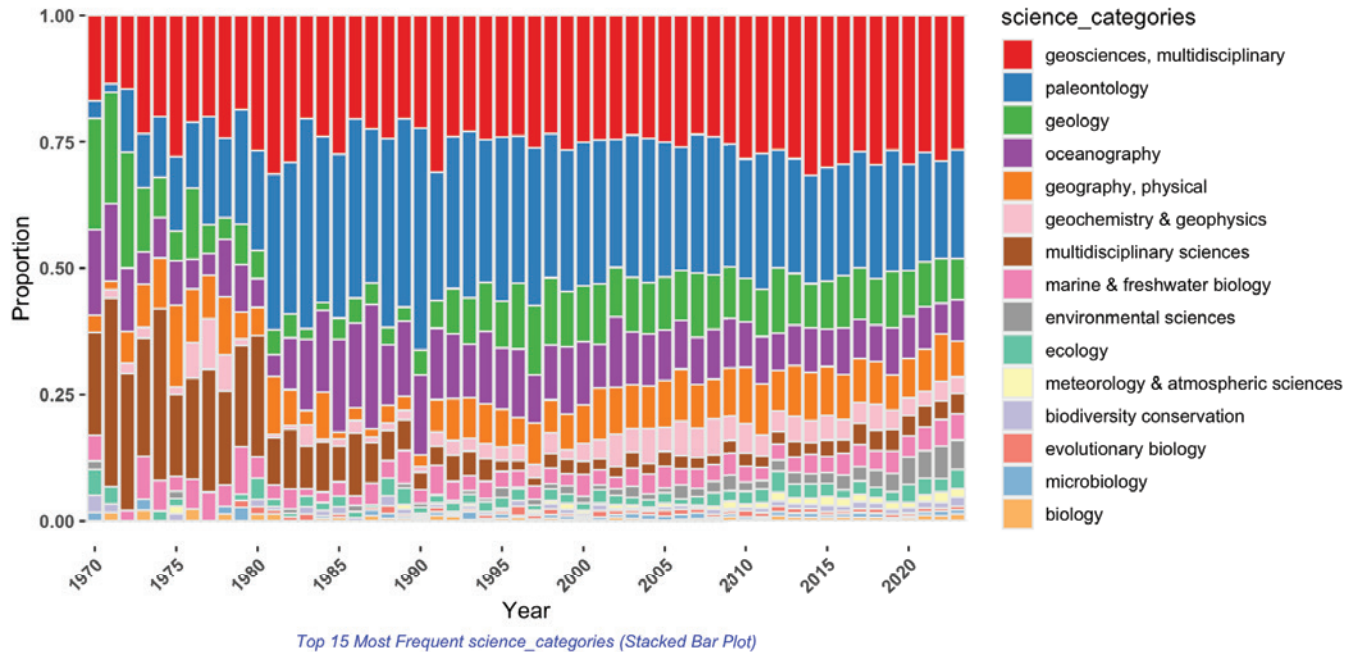
Cross-cutting nature of themes such as stable isotopes, geochemistry, and paleoceanography highlights the importance of foraminifera in unraveling the coupled dynamics of climate, ocean circulation, and biogeochemical cycles (Ravelo and Hillaire-Marcel 2007; Schiebel and Hemleben 2017). Stable isotope ratios of oxygen and carbon in foraminiferal shells have been widely used to reconstruct past changes in ocean temperature, salinity, and productivity, as well as global ice volume and atmo-

spheric CO<sub>2</sub> levels (Shackleton 1967; Pearson 2012; Birch et al. 2013). The application of element ratios, such as Mg/Ca and B/Ca, has provided additional constraints on past ocean temperature and carbonate chemistry, respectively (Elderfield et al. 2000; Yu et al. 2007; Allen et al. 2016). The prominence of specific foraminiferal taxa, such as *Globigerinoides ruber*, *Neoglobobulimina pachyderma*, and *Ammonia beccarii*, across different research contexts demonstrates their value as model organisms for understanding ecological, biological, and geochemical processes (Kucera 2007; Darling and Wade 2008; Keul et al. 2013). The cosmopolitan distribution and abundance of these species have made them prime targets for paleoceanographic and paleoclimatic reconstructions, as well as for studying the impacts of environmental stress on foraminiferal biology and ecology (Kuroyanagi et al. 2008).

The temporal analysis of keyword usage reveals the evolution of research priorities and the emergence of new themes and approaches. The growing emphasis on topics such as paleoenvironment, ecology, and climate change reflects the increasing recognition of foraminifera as sensitive indicators of environmental variability and their potential for implementing conservation and management strategies (Gooday 2003; Schönfeld 2012). The application of foraminifera in ecological monitoring and environmental impact assessments has gained momentum in recent years, as evidenced by the increasing frequency of keywords such as "pollution," "heavy metals," and "anthropogenic impact" (Alve et al. 2016; Bouchet et al. 2018). The rising prominence of molecular techniques, such as DNA barcoding and next-generation sequencing, highlights the ongoing integration of foraminiferal studies with cutting-edge methodologies from other fields (Pawlowski and Holzmann 2014; Morard et al. 2016; Hayward et al. 2023). The application of molecular tools has revolutionized our understanding of foraminiferal diversity, phylogeny, and ecology, revealing a high degree of cryptic speciation and ecological partitioning within morphologically defined taxa (Darling and Wade 2008; Weiner et al. 2014; Morard et al. 2019). The integration of molecular and morphological data has enabled the development of a more robust and comprehensive taxonomic framework for foraminifera, which is essential for accurate paleoenvironmental reconstructions and biodiversity assessments (Langer 1993; Langer and Hottinger 2000; Pawlowski et al. 2013; Holzmann and Pawlowski 2017; Förderer et al. 2018).

### **The Shifting Landscape of Scientific Productivity and Collaboration**

The geographic analysis of foraminiferal research output reveals the dominant contributions of North America and Europe, reflecting their long-standing tradition of micropaleontological research, funding and extensive network of research institutions (Lipps 1981; Culver 1987; Murray 2006; Horton and Culver 2008). The United States and the United Kingdom, in particular, have been at the forefront of foraminiferal research since the early 20th century, thanks to the pioneering work of researchers such as Joseph Cushman, Alfred Loeblich and Helen Tappan, Fred Phleger, Bill Berggren, and John Murray to name but a few. The establishment of specialized research centers, such as the Cushman Laboratory for Foraminiferal Research and the Natural History Museum in London, provided a strong institutional framework for the development and dissemination of foraminiferal knowledge. However, the rapid rise of China and the increasing contributions from Asia and other regions underscore the shifting landscape of scientific productivity and the grow-



TEXT-FIGURE 9

Author collaboration network based on the top 500.

ing globalization of foraminiferal studies (Lei et al. 2015). The remarkable growth of Chinese publications in recent decades can be attributed to several factors, including the increasing investment in scientific research, the expansion of marine science programs, and the strengthening of international collaborations. The establishment of key research institutions, such as the Institute of Oceanology of the Chinese Academy of Sciences and the State Key Laboratory of Marine Geology, has provided a strong platform for foraminiferal research in China (Lei et al. 2015). The increasing contributions from other Asian countries, such as Japan, South Korea, and India, reflect the growing recognition of the importance of foraminifera in understanding regional oceanographic and environmental changes (Kuroyanagi et al. 2006; Kang et al. 2010; Dubey et al. 2018). For example, the intergration of foraminiferal data with other paleoceanographic and paleoclimatic proxies has provided valuable insights into the long-term variability of the Asian monsoon system and its impacts on regional climate and ecosystems (Suokhrrie et al. 2018). The collaboration network analysis reveals the formation of research communities around shared themes, geographic foci, and influential authors and institutions. The centrality of key researchers in these networks underscores their role in driving innovation, fostering interdisciplinary collaboration, and training the next generation of foraminiferal scientists. The prominence of leading universities and oceanographic institutions, such as the University of Bremen, the Alfred Wegener Institute, GEOMAR, the Woods Hole Oceanographic Institution, ETH Zurich, and the University of Southampton, highlights their importance as hubs of foraminiferal research, providing access to state-of-the-art facilities, diverse sample collections, and intellectual resources. The presence of regional clusters, such as the European, North American, and Asian groups, reflects the historical development and institutional landscape of foraminiferal research in these regions. The strong connectivity within these clusters highlights the importance of regional collaborations in addressing specific

research questions and leveraging local expertise and resources (Langer and Mouanga 2016). However, the relatively weak connectivity between clusters suggests that there is still potential for greater integration and knowledge exchange across regions and research communities.

### Thematic Landscape and Research Frontiers

The thematic map analysis sheds lights on a comprehensive overview of the intellectual structure and research frontiers within foraminiferal studies. The identification of motor themes, such as benthic foraminifera, Atlantic Ocean, and evolution, highlights the core research areas that have significantly influenced the development of the field (Jorissen et al. 2007; Schiebel and Hemleben 2017). These themes represent the foundational knowledge and well-established methodologies that have shaped our understanding of foraminiferal ecology, biogeography, and evolutionary history (Gooday 2003; Murray 2006; Holzmann and Pawlowski 2017). The Atlantic Ocean has been a focal point of foraminiferal research, thanks to its pivotal role in global ocean circulation, climate variability, and biogeochemical cycling (Kucera 2007; Schiebel and Hemleben 2017). The study of benthic foraminiferal assemblages from Atlantic sediments has provided key insights into the history of deep-water circulation, glacial-interglacial climate dynamics, and the response of marine ecosystems to environmental perturbations (Schnitker 1980; Hallock 1987; Schmiedl et al. 1997). The application of geochemical proxies, such as stable isotopes and trace elements, to Atlantic foraminifera has greatly advanced our understanding of past changes in ocean temperature, salinity, and productivity (Shackleton 1967; Elderfield and Ganssen 2000).

The study of foraminiferal evolution has been a long-standing research focus, thanks to the group's rich fossil record, morphological diversity, and ecological significance (Tappan and Loeblich 1988; Pawlowski et al. 2003). The integration of paleontological,

molecular, and ecological data has provided new insights into the patterns and processes of foraminiferal evolution, from the Precambrian to the present day (Kaminski et al. 2010; Förderer et al. 2018). The application of evolutionary models, such as phylogenetic analysis and adaptive radiation, has shed light on the drivers of foraminiferal diversification, extinction, and biogeographic distribution (Hallock and Hansen 1979; Hallock 1979; 1981; Aze et al. 2011; Morard et al. 2019). The study of foraminiferal evolution has also provided valuable insights into the response of marine organisms to past environmental changes, such as ocean acidification and global warming (Moy et al. 2009; Knoll 2011; Hennehan et al. 2013). The presence of basic themes, such as biostratigraphy, reflects the enduring importance of foraminifera as biostratigraphic markers and their applications in industry and paleoceanographic studies (Berggren 1998; Gradstein et al. 2012). The development of high-resolution biostratigraphic frameworks based on foraminiferal assemblages has greatly improved the dating and correlation of sedimentary sequences, from the Paleozoic to the Cenozoic (Berggren et al. 1995; Wade et al. 2011). The integration of biostratigraphic data with other stratigraphic tools, such as magnetostratigraphy and chemostratigraphy, has provided a robust framework for reconstructing the timing and rates of environmental change across multiple timescales (Berggren et al. 1995; Gradstein et al. 2004; Berggren and Pearson 2005).

The identification of emerging and declining themes, such as morphology, North Atlantic, and climate, highlights the dynamic nature of the research landscape and the potential for future growth or shifts in research focus (Thornalley et al. 2011; Morard et al. 2013; Schmidt et al. 2022). The study of foraminiferal morphology has experienced a resurgence of interest in recent years, thanks to the development of new imaging and analytical techniques, such as micro-computed tomography and 3D geometric morphometrics (Speijer et al. 2008; Caromel et al. 2016). These approaches have provided new insights into the ontogenetic development, functional morphology, and evolutionary history of foraminifera, as well as their response to environmental stress (Schmidt et al. 2013; Caromel et al. 2017). The integration of morphological data with molecular and ecological information has opened up new avenues for studying the diversity, biogeography, and paleoenvironmental significance of foraminifera (Weinikau et al. 2016; Angeles et al. 2023). The North Atlantic region has been a hotspot of foraminiferal research, thanks to its sensitivity to climate variability, its role in deep-water formation, and its high sedimentation rates (Thornalley et al. 2011). The study of foraminiferal assemblages and geochemistry from North Atlantic sediments has provided key insights into the history of the Atlantic Meridional Overturning Circulation (AMOC), the dynamics of glacial-interglacial climate transitions, and the impacts of abrupt climate events, such as Heinrich events and Dansgaard-Oeschger cycles (Bond et al. 1997; McManus et al. 2004; Lynch-Stieglitz et al. 2007). The integration of foraminiferal data with other paleoceanographic proxies, such as ice-rafted debris and alkenone biomarkers, has greatly advanced our understanding of the mechanisms and impacts of past climate change in the North Atlantic region (Bond et al. 1997; Van Nieuwenhove et al. 2011).

The study of foraminiferal response to climate change has emerged as a major research frontier, thanks to the increasing recognition of the sensitivity and vulnerability of marine ecosystems to global warming, ocean acidification, and deoxygenation (Moy et al. 2009; Kroeker et al. 2013). The application of foraminifera as bioindicators of climate change impacts has gained

momentum in recent years, as evidenced by the growing number of studies on the effects of temperature, pH, and oxygen stress on foraminiferal biology, ecology, and geochemistry (Haynert et al. 2012; Prazeres et al. 2015; Lintner et al. 2021). The integration of experimental, field, and modeling approaches has provided new insights into the adaptive capacity and resilience of foraminifera to future climate change, as well as their potential role in carbon cycling and ecosystem functioning (Roy et al. 2015; Doo et al. 2020). The positioning of phylogeny as a highly developed and isolated theme underscores its specialized nature and its potential for bridging different research areas, such as taxonomy, ecology, and evolution (Darling and Wade 2008; Ujiie et al. 2010; Morard et al. 2019). The application of molecular phylogenetic analysis has revolutionized our understanding of foraminiferal evolution and systematics, revealing a high degree of cryptic diversity and convergent evolution within morphologically defined taxa (Pawlowski et al. 2013). The integration of molecular and morphological data has led to the development of a revised taxonomic framework for foraminifera, based on a combination of shell morphology, wall structure, and genetic relatedness (Pawlowski and Holzmann 2014; Holzmann and Pawlowski 2017). The phylogenetic approach has also provided new insights into the ecological and biogeographic patterns of foraminifera, as well as their evolutionary response to past environmental changes (Kucera and Darling 2002; Weiner et al. 2014).

### Challenges and Future Directions

Despite the significant advancements and growth of foraminiferal research, several challenges and opportunities lie ahead. The need for standardization and harmonization of methods across studies and disciplines is crucial for facilitating data comparison, synthesis, and integration (Schönfeld et al. 2012). The development of common protocols and benchmarks for data collection, analysis, and reporting will enhance the reproducibility and comparability of results, promoting collaborative research efforts. The establishment of international working groups and consensus-building initiatives, such as the SCOR/IGBP Working Group "Planktonic Foraminifera" and the FOBIMO (Foraminiferal Bio-Monitoring) expert workshops, has provided a framework for the development and implementation of best practices in foraminiferal research. The creation of robust and accessible databases of foraminiferal distributions, ecology, and genetics is essential for accelerating the pace of discovery and fostering new collaborations (Siccha and Kucera 2017). The development of online data repositories, such as the ForCenS (Foraminifera Census) database, foraminifera.eu database, World Register of Marine Species (WoRMS) and the Mikrotax online taxonomic atlas, has greatly improved the accessibility and usability of foraminiferal data for the scientific community (Appeltans et al. 2012; Hesemann 2015; Horton et al. 2017; Siccha and Kucera 2017; Hayward et al. 2020; Costello et al. 2021). However, there is a need to continue the work of Loeblich and Tappan (1964, 1987) to keep track of the foraminiferal genera and produce an updated version of "Foraminiferal Genera and their Classification". One laudable effort is the work of the agglutinated foraminiferal community in organizing workshops during which the newly described genera are discussed and compiled. There are regular post-1987 updates to the list of recently published agglutinated foraminiferal genera (Kaminski 2000, 2004, 2008, 2011, 2017), and an updated classification that expands upon the work of Loeblich and Tappan (Kaminski 2004; 2014), but such an effort needs to be initiated for other taxonomic groups such



as miliolids, fusulinids, and calcareous benthics. Finally, there is still a need for more comprehensive and integrated databases that combine taxonomic, ecological, and genetic information across different spatial and temporal scales (Pawlowski et al. 2014). The development of standardized data formats and metadata standards, as well as the implementation of data quality control and assurance procedures, will be crucial for ensuring the long-term value and interoperability of foraminiferal databases.

Increased investment in research infrastructure, such as museum collections, culture facilities, and analytical instrumentation, is crucial for maintaining the long-term viability and legacy of foraminiferal studies. The maintenance and expansion of museum collections, such as the Cushman Collection at the Smithsonian Institution, the Heron-Allen Library at the Natural History Museum in London, and the newly established European Micropaleontological Reference Centre in Kraków is crucial for preserving the primary type specimens of foraminifera and archiving valuable published collections, as well as for providing reference material for future studies (Kaminski et al., 2023; Kowal-Kasprzyk et al., 2023). The establishment of culture facilities, such as the Foraminifera Culture Collection at the University of Angers and the Symbiont-Bearing Foraminifera Collection at the University of Tokyo, is central for experimental studies on foraminiferal biology, ecology, and geochemistry, as well as for the development of new proxies and applications (Fujita et al. 2011). The development of advanced analytical instrumentation, such as high-resolution imaging systems, laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), nanoscale secondary ion mass spectrometry (NanoSIMS), and confocal microscopy has greatly expanded the capabilities and applications of foraminiferal geochemistry and biomineralization studies. However, access to these cutting-edge technologies is often limited by their high cost and technical complexity, requiring significant investments in infrastructure, training, and maintenance. The development of collaborative research networks and shared facilities, as well as the implementation of training and capacity-building programs, will be essential for promoting the wider adoption and application of these technologies in foraminiferal research. The training and support of a diverse and globally distributed workforce of foraminiferal researchers will promote innovation, inclusivity, and sustainability in the field. The development of educational and outreach programs, such as the International School on Foraminifera Urbino (ISF-Urbino), the Urbino Summer School on Paleoclimatology (USSP), and the foraminifera research consortium (FRESCO) summer school, has provided valuable opportunities for students and early-career researchers to acquire the knowledge and skills needed to conduct cutting-edge foraminiferal research. The promotion of diversity and inclusion in the field, through initiatives such as the Cushman Foundation's Johanna M. Resig Foraminiferal Research Fellowship, the student research grants of the Cushman Foundation, the Todd and Low Award of the Micropaleontological Society, the W. Storrs-Cole Award of the Geological Society of America, the Brian J. O'Neill memorial grant-in-aid of the Grzybowski Foundation, and the Willi Dansgaard Student Award in the fields of paleoceanography or paleoclimatology for a mid-career scientist, have helped broaden participation and foster a more inclusive and supportive research community.

The role played by societies in encouraging research collaboration cannot be understated. The Cushman Foundation organizes a scientific session at the GSA meetings, the Micropaleontological Society holds its annual general meeting in various countries

in Europe, and additionally hosts more informal meetings of its "Foraminiferal-Nannofossil Group". The Grzybowski Foundation hosts the International Workshops on Agglutinated Foraminifera and sponsors the micropaleontological session at the annual Czech-Polish-Slovak paleontological conferences. The FORAMS conference draws together researchers from the entire world, in spite of the fact that some of the meetings have been held in rather far-flung places. These meetings provide the opportunity for researchers to interact and forge new collaborative research networks. As foraminiferal research continues to evolve and expand, it is essential to align scientific priorities with societal needs and global challenges, such as climate change, biodiversity loss, and ocean acidification. The development of interdisciplinary research programs and collaborations, such as the PAGES (Past Global Changes) working group on "Ocean Circulation and Carbon Cycling" and the IODP (International Ocean Discovery Program) expedition on "Paleoclimate, Paleoceanography, and Sea Level Change", has provided a framework for addressing these challenges through the integration of foraminiferal data with other paleoceanographic and paleoclimatic proxies. The application of foraminifera as bioindicators of anthropogenic impacts and environmental change, such as ocean acidification, deoxygenation, and pollution, has provided valuable insights into the resilience and adaptive capacity of marine ecosystems, as well as the potential impacts of future climate change on marine biodiversity and ecosystem services. By leveraging the unique strengths of foraminifera as model organisms and environmental sentinels, researchers can contribute to the development of evidence-based strategies for mitigating and adapting to global change, such as the design of marine protected areas, the restoration of degraded habitats, and the implementation of sustainable management practices. The integration of foraminiferal data into decision-support tools and policy frameworks, such as the United Nations Sustainable Development Goals and the Intergovernmental Panel on Climate Change (IPCC) assessment reports, will be crucial for informing science-based decision-making and promoting the sustainable use and conservation of marine resources (Turley et al. 2007).

The future of foraminiferal research lies in the integration of cutting-edge methodologies, the fostering of interdisciplinary collaborations, and the translation of scientific insights into actionable solutions for societal and environmental challenges. The development of new technologies and analytical approaches, such as high-throughput sequencing, 3D imaging, and machine learning, has opened up new frontiers in foraminiferal biology, ecology, and evolution, providing unprecedented insights into their diversity, adaptability, and resilience. The integration of these technologies with traditional paleontological and geochemical approaches, as well as the development of coupled physical-bio-geochemical models, will greatly enhance our understanding of the mechanisms and impacts of past and future environmental change, as well as the role of foraminifera in the Earth system (Roy et al. 2015).

## CONCLUSIONS

This scientometric analysis conducted in this study has provided a comprehensive and data-driven overview of the enduring legacy of foraminiferal research. By mapping the intellectual landscape, collaborative networks, and emerging trends, we have illuminated the key drivers and future directions of this dynamic field. The exponential growth of foraminiferal studies, the interconnectivity of research themes, and the shifting landscape of scientific productivity all underscore the vitality and relevance of

this discipline in the 21<sup>st</sup> century. As we enter the third century of foraminiferal research, the stage is set for groundbreaking discoveries and transformative applications. The integration of cutting-edge methodologies, such as molecular genetics, high-resolution imaging, and machine learning, is poised to unlock new insights into foraminiferal biology, ecology, and evolution. At the same time, the growing recognition of foraminifera as sensitive bioindicators of environmental change is driving their increased use in ecological monitoring and conservation efforts. To fully realize the potential of foraminiferal research, however, several challenges must be addressed. First, there is a need for greater standardization and harmonization of methods across studies and disciplines. The development of common protocols and benchmarks for data collection, analysis, and reporting will facilitate the comparison and synthesis of results from different research groups and regions. Second, there is a need for more robust and accessible databases of foraminiferal taxonomy, distributions, ecology, and genetics. Older publications in defunct journals need to be scanned and added to the available on-line resources. The creation of open-access, user-friendly platforms for data sharing and exploration will accelerate the pace of discovery and foster new collaborations. Finally, there is a need for greater investment in foraminiferal research infrastructure and human capital by providing research grants and scholarships. The maintenance and expansion of museum collections, culture facilities, and analytical instrumentation will ensure the long-term viability of foraminiferal studies. Likewise, the training and support of a diverse and globally distributed workforce of foraminiferal researchers will promote innovation and inclusivity in the field. As we embark on this new era of foraminiferal research, we must also remain mindful of the broader societal and environmental context in which our work takes place. The urgent challenges of climate change, biodiversity loss, and ocean acidification demand a renewed commitment to translating our scientific insights into actionable solutions. By leveraging the unique strengths of foraminifera as model organisms and environmental sentinels, we can contribute to the development of more effective strategies for mitigating and adapting to global change. In the end, the enduring legacy of foraminiferal research lies not only in the knowledge we have gained but also in the scientific and societal impact we have achieved. As we continue to explore the fascinating world of foraminifera, let us also strive to use our research to build a more sustainable and resilient future for all.

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