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Research trends in stable isotope ecology on unconsolidated intertidal ecosystems

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ABSTRACT

This study investigates the role of stable isotope ecology in unconsolidated sediment coastal systems, focusing on scientific production and research trends over time. Existing literature is analyzed to identify knowledge gaps and highlight the significance of stable isotope analysis in understanding coastal ecosystems. A comprehensive bibliometric analysis is employed, utilizing Scopus database to collect and categorize relevant publications on stable isotope ecology. Key indicators are focused on, including publication trends, authorship patterns, and the geographic distribution of research efforts. The temporal scale of studies is systematically analyzed, with attention given to methodological approaches used in these publications. Co-authorships networks and co-occurring keywords are examined to explore the intellectual structure of the field and identify collaborative patterns among authors. Over 140 publications are revealed, attributed to more than 400 researchers, with a significant increase in interest noted over time, particularly in trophic studies involving macrobenthos. Mudflats are identified as a focal point, receiving more attention than sandy beaches. The analysis indicates that seasonality is the predominant temporal scale, while mesoscale studies are observed to be more common in spatial investigations. A plateau in publication growth is noted, probably corresponding with the emergence of alternative methodologies for trophic ecology studies. Major contributions are attributed to France, the United States and Australia. Additionally, fragmented collaboration networks are illustrated through the co-authorship analysis, with limited international engagement among developing nations. Overall, the critical importance of stable isotope ecology in understanding coastal ecosystems is underscored, while the need for methodological diversity and increased collaboration in future research efforts is highlighted.

Keywords: soft-sediments intertidals, research output, trophic studies, geographic distribution, collaborative networks.

INTRODUCTION

Unconsolidated intertidal ecosystems refer to coastal areas that are regularly exposed and submerged by the tide, characterized by loose, unconsolidated sediments such as sand, mud, gravel, or a combination of these materials, and

lacking aquatic vegetation. These environments are exposed at low tide and submerged at high tide, and include both sandy and muddy sedimentary habitats. Historically, these sites have been less studied than other coastal ecosystems, for example, rocky shores, because life there may not be as evident (McLachlan & Defeo, 2018). However, in recent decades, research at these sites has grown exponentially. Sandy beaches have been the focus of attention due to their scenic and recreational value, as well as their status as a biodiverse site. They serve as a template for various processes and provide habitat for numerous species, from the most visible ones such as clams, snails, insects, crabs or worms; to really tiny ones, such as protozoans, bacteria, and microscopic plants (McLachlan & Defeo, 2018). Coastal flats have a more evident load of organic matter, which makes them more productive environments. All of these environments are open systems with high interconnection, and the proximity between them generates flows of energy and organic matter that determine the structure of the biological community (Polis & Hurd, 1996; Polis et al., 1997; Schlacher & Connolly, 2009)

In ecology, stable isotopes are helpful tools for tracking the cycling of nutrients, and clarify details about the origin and destination of the elements that circulate in the biosphere, with particular interest in those that represent an important fraction of the planet's organic matter, such as carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulfur (S) (Fry, 2006). In trophic ecology studies, stable isotopes provide space-time integrated information on trophic relationships between organisms (Layman et al., 2012). Carbon isotopes are used to determine the source of organic matter consumed by organisms due to the stretch relationship between the δ13C of consumers and their food source, with marked differences between primary producers depending on the type of photosynthesis and origin and availability of CO2 (DeNiro & Epstein, 1978; Peterson & Fry, 1987). Nitrogen isotopes are used to estimate trophic position, since deamination and transamination processes enrich δ15N in the tissues of consumers with respect to their diet in a proportion that is maintained across trophic transferences (DeNiro & Epstein, 1981; Peterson & Fry, 1987). Sulfur isotopes do not show enrichment between consumers and their diet, and allow differentiation between sources of organic matter, being useful to identify anthropogenic influence on the sulfur cycle and pollution (Peterson & Fry, 1987). Hydrogen and oxygen isotopes are highly used in hydrological studies due to their relationship with the water cycle and the fractionation processes during evaporation and condensation, allowing to track water movements in the biosphere (Fry, 2006; Penna et al., 2018). Additionally, oxygen isotopes in atmospheric O2 are useful for measuring respiration and photosynthesis processes (Fry, 2006).

In a context of growing research both in coastal ecosystems and in the use of stable isotopes, it becomes relevant to know how the scientific community is working with this methodology in this type of environment. A bibliometric approach consists in a quantitative analysis of publications from a scientific community, and is useful for measuring scientific production around a given field, as well as evaluating predominant areas of study, areas with information gaps, authors and prominent groups and their work dynamics, or countries with greater or lesser production (Bornmann & Mutz, 2015). Additionally, the creation of bibliometric networks or maps allows a friendly graphic representation of the information obtained (Van Eck & Waltman, 2010), allowing to exhibit the degree of connection between actors (co-authorship maps can be created between authors or countries, for example) or identify recurring topics of study (for example, through keyword co-occurrence maps). These approaches offer a systematic, transparent, and reproducible review system (Aria & Cuccurullo, 2017) to identify and predict trends in research, and thus outline

future work strategies.

The present work aims to quantitatively analyze worldwide research on isotopic ecology in coastal ecosystems of unconsolidated sediments. Specifically, it is sought; 1) carry out a bibliometric description of scientific production over time (e.g., number of publications, relevant works, main sources, authors and countries researching in this area; 2) identify the main topics of study in this research; and 3) analyze the collaboration dynamics between the authors and countries involved.

METHODS

The publications correspond to the Scopus (Elsevier) database, a major repository of scientific references. The work considers publications on a global scale, covering the period from the first work that meets the search criteria to the present. A preliminary list was prepared to satisfy the search criteria in terms of methodology (use of isotopes) and environment (sandy beaches, sandy coastal wetlands [sandflats], or muddy coastal wetlands [mudflats]). To do this, three searches were performed in Scopus, restricting the results to those works that contained the following terms in their title, abstract, or keywords: 1) (isotope*) AND (mud AND flat*) OR (mudflat*); 2) (isotope*) AND (sand AND flat*) OR (sandflat*); and 3) (isotope*) AND (sandy beach*). The documents resulting from these three searches were consolidated into a single list. Subsequently, through an abstract lecture, this list was refined by eliminating results unrelated to the field of ecology or that did not use stable isotopes (the final bibliographic file is included as Supplementary Material 1). The steps to obtain the final list were reported following the PRISMA diagram guidelines (Page et al., 2021), showing the selection conditions and the number of articles selected or discarded at each stage (Supplementary Material 2, Fig. S1).

Bibliometric description

For all the articles comprising the final list, several bibliometric indicators were collected. First, general information about the document list was gathered, including the following characteristics: the period covered, number of sources (such as journals, books, chapters), number of documents, annual growth rate, and average citations per document. Additionally, information about the authors was included: total number of authors, number of authors in single-authored or multi-authored documents, co-authors per document, and percentage of international co-authorship. The type of document was also considered, classifying the works as articles, notes, or books.

To evaluate the evolution of production over time, the annual scientific production, measured by the number of documents per year, was determined. To obtain an overview of the current situation, the main journals, authors, and countries publishing in this area were analyzed, and their dynamics over time were evaluated by measuring the number of documents per year. Additionally, the main works within this list were assessed considering the total and annual citations, and the corresponding countries of all authors. The bibliometric description was performed using the bibliometrix package in R (Aria & Cuccurullo, 2017).

Research topics

To evaluate the main research topics within this list, all the works were read, and several characteristics were analyzed,

including: 1) main focus of the research 2) secondary focus of the research, 3) number of taxa studied, 4) study group employed, 5) tissue sampled, 6) environment, 7) ocean, 8) oceanic region, 9) distance covered, 10) temporal scale, 11) spatial scale, and 12) isotopes used. The studies were categorized according to these attributes, and the frequency of appearance for each subject was analyzed. When insufficient information was available to categorize a document under a specific topic, the label “no data” (ND) was applied. When documents were eligible for more than one category, inclusion in one did not preclude their assignment to another, and they were counted in all applicable categories. This applied to the following categories: study group employed, tissue sampled, environment, and isotopes used.

To evaluate the focus of the work, two categories were created: “main focus”, defined as the primary topic that the study aims to investigate; and “secondary focus”, which refers to additional, but less critical, areas of investigation that complement or provide context to the main focus. For the number of taxa, the studies were divided into six categories: 1, 2-10, 11-20, 21-100, 101-200, and ND. The "study group" category aimed to classify the documents by the type of taxa, for living organisms, or material, for non-living components. Documents were also categorized based on the type of tissue sampled, complementing this classification. The "environment" category identified the field sites where the research was conducted (e.g., sandy beach, mudflat, sandflat). Since all studies were conducted in coastal systems, the ocean where the research took place was classified, along with the geographical region, defined by cardinal points (e.g., Northwestern Atlantic, Southwestern Pacific). Temporal scale was categorized based on the duration of the experiment or fieldwork into five groups: day-scale, month-scale, seasonal, annual, and multi-annual. The spatial scale classification was modified from McLachlan & Defeo (2018) and organized into micro-scale (single sampling site), meso-scale (multiple sites within the same system, such as a beach or mudflat), macro-scale (different systems within the same geographic region), biogeographic (sites in different geographic regions), and experimental (studies using laboratory microcosms or mesocosms instead of field sites). The isotopes used for the analysis were also considered and categorized.

Additionally, a keyword co-occurrence network was created using VOSViewer software (Van Eck & Waltman, 2010). This network considered keywords that appeared in more than five documents, excluding those implicit in the search that do not enrich the results, such as "stable isotope" and its variants (isotope, isotopes, stable isotope, stable isotopes, stable isotope analysis, stable isotope ratio, isotopic analysis, isotopic ratio, isotopic composition).

Scientific collaboration

Two co-authorship networks were created using VOSViewer: one to evaluate the working dynamics among different authors, and another to analyze the collaboration between the countries of the corresponding authors. In the authors' co-authorship network, a maximum of 25 authors per document was set, and all authors with at least two documents in the list were considered. For the countries' co-authorship network, a maximum of 25 countries per document was set, and all the countries in the list were considered. Countries that did not show interconnection were excluded from the figure.

RESULTS

Bibliometric description

Thirty-nine years is the timespan between the first document that matches the criteria (1985) and the most recent one (2024). Between that time, 135 works were published, from 58 different sources. There has been an annual growth rate of 3.62% and an average of 30.07 citations per document. 457 authors were involved in the documents from the list, with 4.53 authors per document, only existing three single-authored documents. There is a percentage of international co-authorship of 34.07%. The documents from the list encompass 132 articles, 2 conference papers and 1 note (Table 1).

Table 1: Bibliometric information of the published documents regarding stable isotope ecology on unconsolidated sediment coastal systems in the Scopus database.

Description	Results
Main information	
Timespan	1985-2024
Sources	57
Documents	135
Annual Growth Rate %	3.62
Average citations per doc	30.07
Authors	
Authors	457
Single-authored docs	3
Co-Authors per Doc	4.53
International co-authorships %	34.07
Document type	
Article	132
Conference paper	2
Note	1

Annual scientific production showed a range between 0 and 9 articles per year (Fig. 1). There have been three peaks in production (9 articles) in 2008, 2011 and 2019. There was a period of nine years between 1988 and 1995 where there were not published articles that fit the criteria.

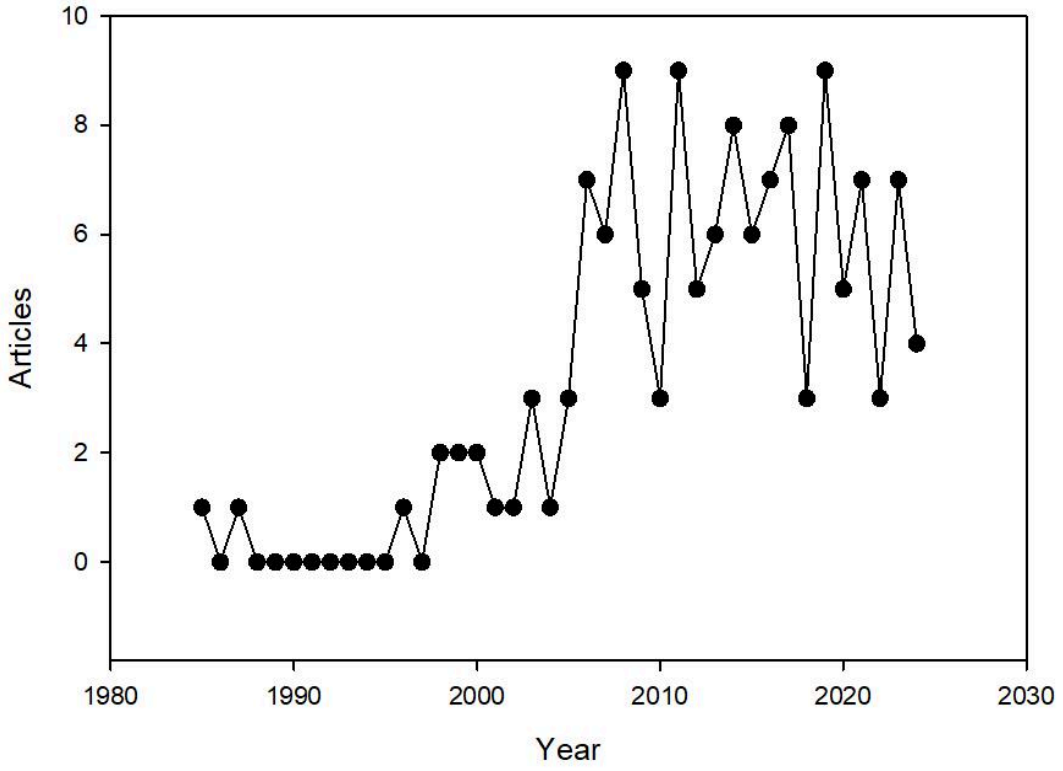

Fig. 1. Annual scientific production regarding stable isotope ecology on unconsolidated sediment coastal systems from the Scopus database.

The two most relevant journals are Marine Ecology Progress Series (22 papers) and Estuarine, Coastal and Shelf Science (20 papers), the latter being the source of the first article on the list: 'Biological and granulometric controls on sedimentary organic matter of an intertidal mudflat' (1985). Since 1996, Marine Ecology Progress Series has been the leading journal in this field. Although Estuarine, Coastal and Shelf Science took 18 years to publish another article that met the search criteria (2003), it subsequently published a large number of papers, placing it second in terms of publications up to the present day (Fig. 2).

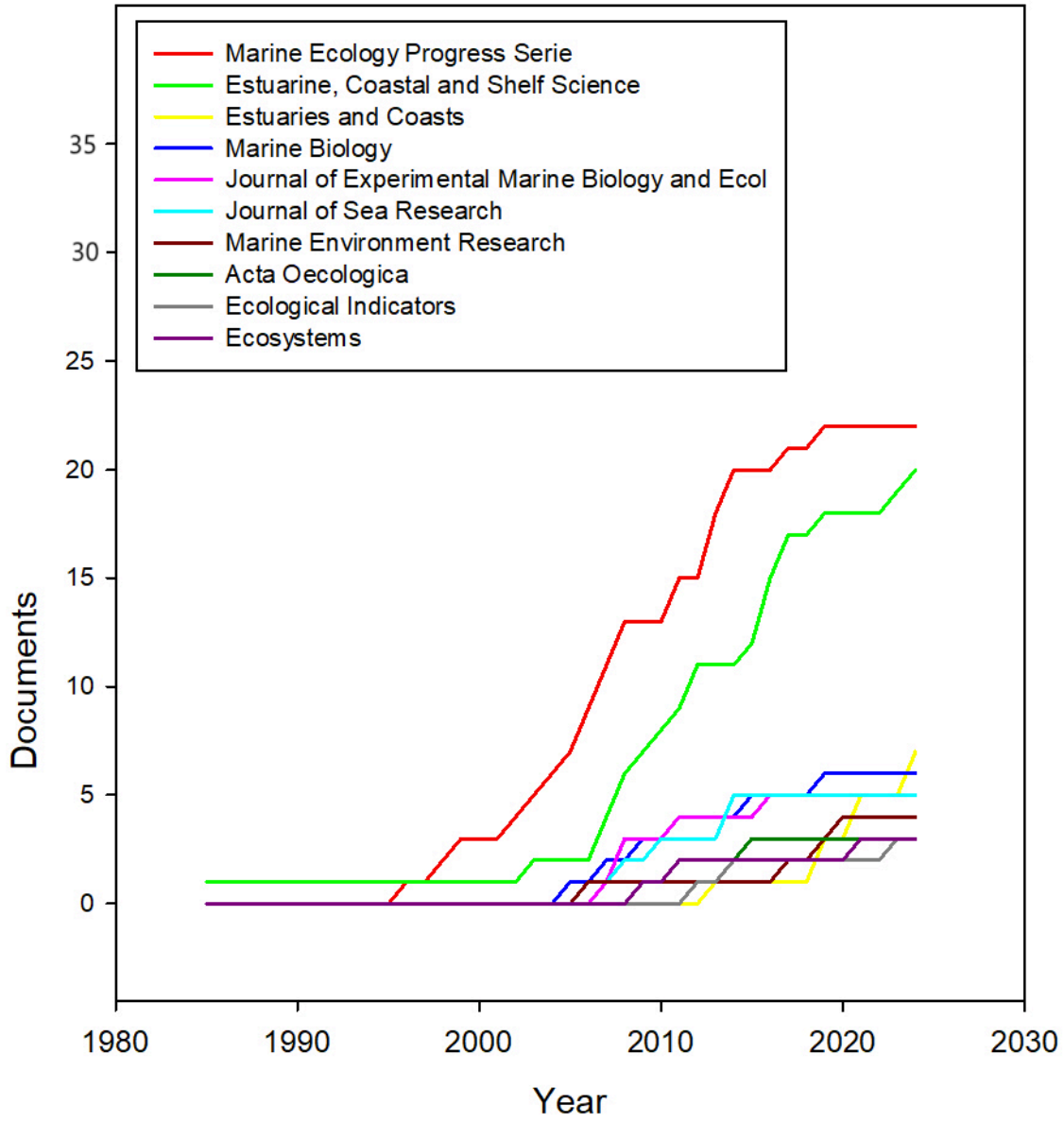

Fig. 2. Document production over time by the ten most productive sources regarding stable isotope ecology on unconsolidated sediment coastal systems from the Scopus database.

The most relevant authors from the list are Connolly, R.M. (Australia), Pascal, P. Y. (France), and Richard, P.J. (France), with 6 documents each. Chong, V. C. (Malaysia), de Troch, M. (Belgium), Dupuy, C. (France), García, A.M. (Brazil) and Niquil, N. (France) are matched in second place with 5 documents each. The most cited article from the list is titled "Spatial analysis of stable isotope data to determine primary sources of nutrition for fish" by Melville and Connolly (Table 2).

Table 2: Most globally cited articles regarding stable isotope ecology on unconsolidated sediment coastal systems from the Scopus database. TC = total citations; TCY = total citations per year.

Paper	Authors	Sources	TC	TCY
Spatial analysis of stable isotope data to determine primary sources of nutrition for fish	Melville & Connolly, 2003.	Oecologia	166	7,5

Marine macrophytes directly enhance abundances of sandy beach fauna through provision of food and habitat	Ince *et al.*, 2007.	Estuarine Coastal and Shelf Science	131	7,3
Food sources of the infaunal suspension-feeding bivalve *Cerastoderma edule* in a muddy sandflat of Marennes-Oléron Bay, as determined by analyses of carbon and nitrogen stable isotopes	Kang *et al.*, 1999.	Marine Ecology Progress Series	121	4,7
Intraspecific variations in d13C indicate ontogenetic diet changes in deposit-feeding polychaetes	Hentschel, 1998.	Ecology	121	4,5
Food source of intertidal nematodes in the Bay of MarennesOleron (France), as determined by dual stable isotope analysis	Riera *et al.*, 1996.	Marine Ecology Progress Series	110	3,8
Parasites alter host phenotype and may create a new ecological niche for snail hosts	Miura et al., 2006.	Proceedings of the Royal Society B: Biological Sciences	103	5,4
The importance of mangroves, mud and sand flats, and seagrass beds as feeding areas for juvenile fishes in Chwaka Bay, Zanzibar: gut content and stable isotope analyses	Lugendo *et al.*, 2006.	Journal of Fish Biology	101	5,3
Stable isotope addition reveals dietary importance of phytoplankton and microphytobenthos to saltmarsh infauna	Galván *et al.*, 2006.	Marine Ecology Progress Series	93	5,5
Isotopic evidence for phytoplankton as a major food source for macrobenthos on an intertidal sandflat in Ariake Sound, Japan	Yokoyama et al., 2005.	Marine Ecology Progress Series	91	4,6
Preferential food source utilization among stranded macroalgae by *Talitrus saltator* (Amphipod, Talitridae): a stable isotopes study in the northern coast of Brittany (France)	Adin & Riera, 2006.	Estuarine Coastal and Shelf Science	90	4,1

Regarding countries, the one with the highest number of correspondence authors is France (21 authors), followed by the USA (13 authors), and then Australia and Japan (12 authors). France also appears as the first country in terms of scientific production (100 published documents) followed by Japan (64) and the USA (51). The first article in the selection had a U.S. affiliation, and the USA maintained the top spot in production until 2007, when it was overtaken by France. Since then, France has held the lead in production, followed by Japan and the USA (Fig. 3).

Research topics

The majority of the documents from the list (121) have trophic ecology as their main focus. The other primary subjects of study reported are nutrients at the environment (6), environmental (5), spatial distribution (2) and intraspecific competition (1) (Fig. 4a). As a secondary focus, the documents are mainly centered in diet (40 documents), community (38 documents), and ecosystem (28 documents). Also nutrients cycling, behavior, eutrophication and parasitology appear as secondary approaches (Fig. 4b).

Of the documents reviewed, 42 carried the investigation on a single taxon, 71 used a multispecies approach, and for 22,

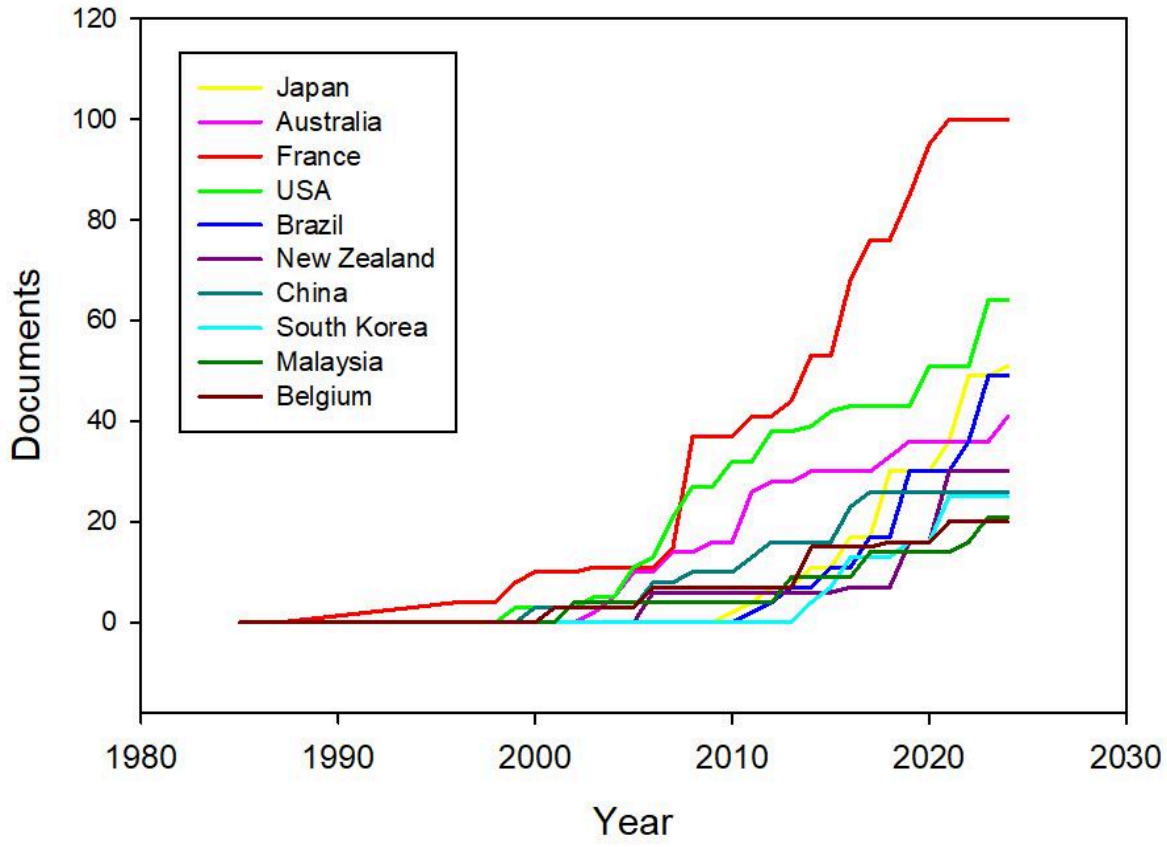

Fig. 3. Document production over time by the ten most productive countries regarding stable isotope ecology on unconsolidated sediment coastal systems from the Scopus database.

this information could not be determined (no data). Among the 71 studies employing a multispecies approach, 53 included 2 to 10 taxa, 7 included 11 to 20 taxa, 10 included 21 to 100 taxa, and 1 study included 101 to 200 taxa (Supplementary Material 2, Fig. S2).

Macrobenthos was by far the most studied group, followed by meiobenthos, nekton and vertebrates (Fig. 5a). Most of the studies documented the use of whole-body samples for stable isotope analysis (53 documents), as well as muscle tissue (52 documents) (Fig. 5b).

Mudflats resulted as the most popular environment where the research was conducted, with 66 papers documenting working in this type of systems. Sandy beaches were also a popular location for the investigation (40 documents), while sandflats were reported on 14 occasions. Artificial mudflats and sandflats, and a polychaete reef were also present. Additionally, there were documents which did not specify the type of sediment of the environment, and cataloged it as intertidal environments, or tidal flats (Fig. 6a). Referring to oceans, research was carried out on the Atlantic (65 documents), Pacific (45 documents) and Indian (23 documents) coasts, and in one case, in several (Fig. 6b). The region of each ocean where the research took part is reported in Fig. 6c, being the most reiterated the Northeastern Atlantic (39) and the Northwestern Pacific (24) (Fig. 6c).

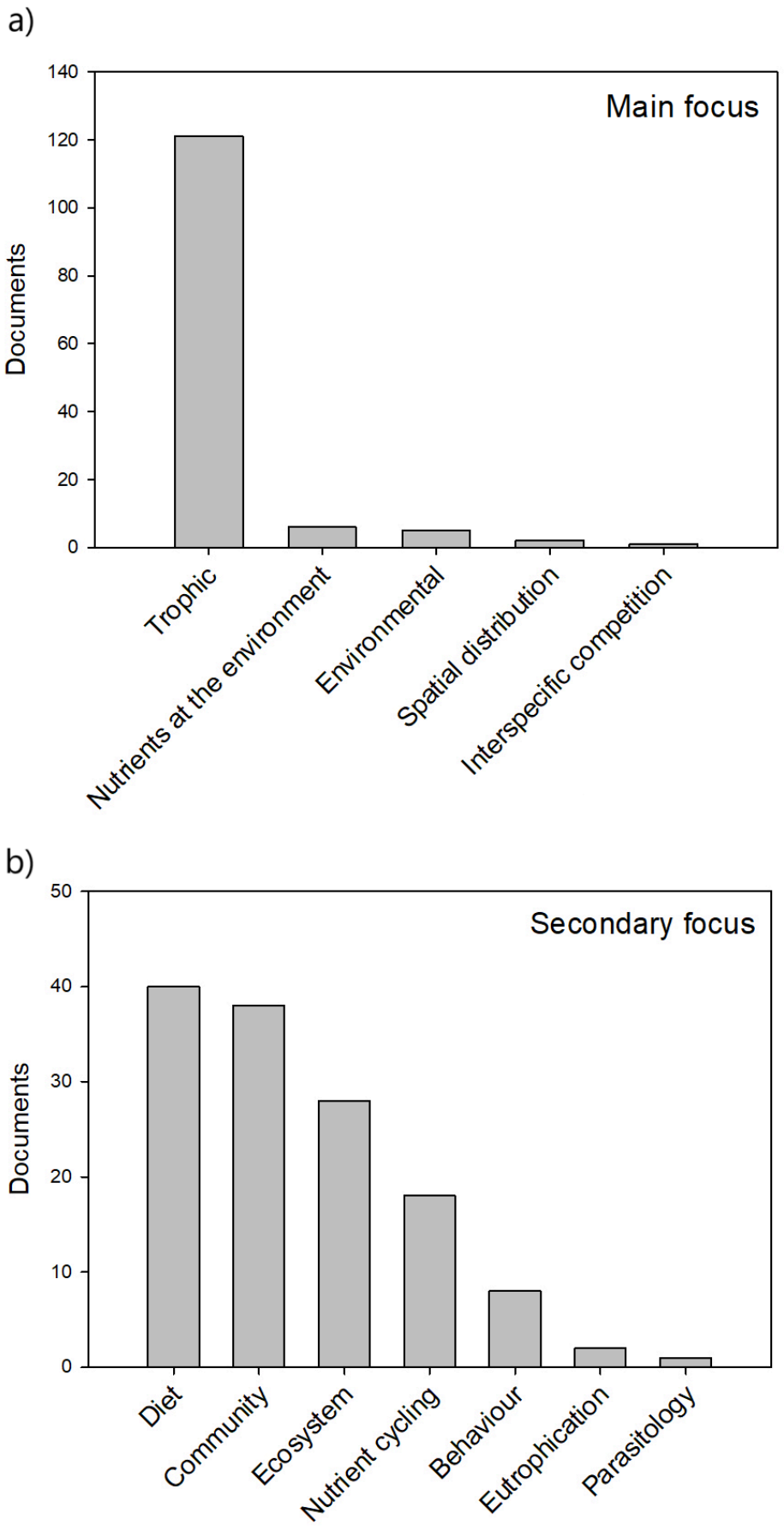

Fig. 4. a) Main and **b)** secondary focus of the documents from the list regarding stable isotope ecology on unconsolidated sediment coastal systems from the Scopus database.

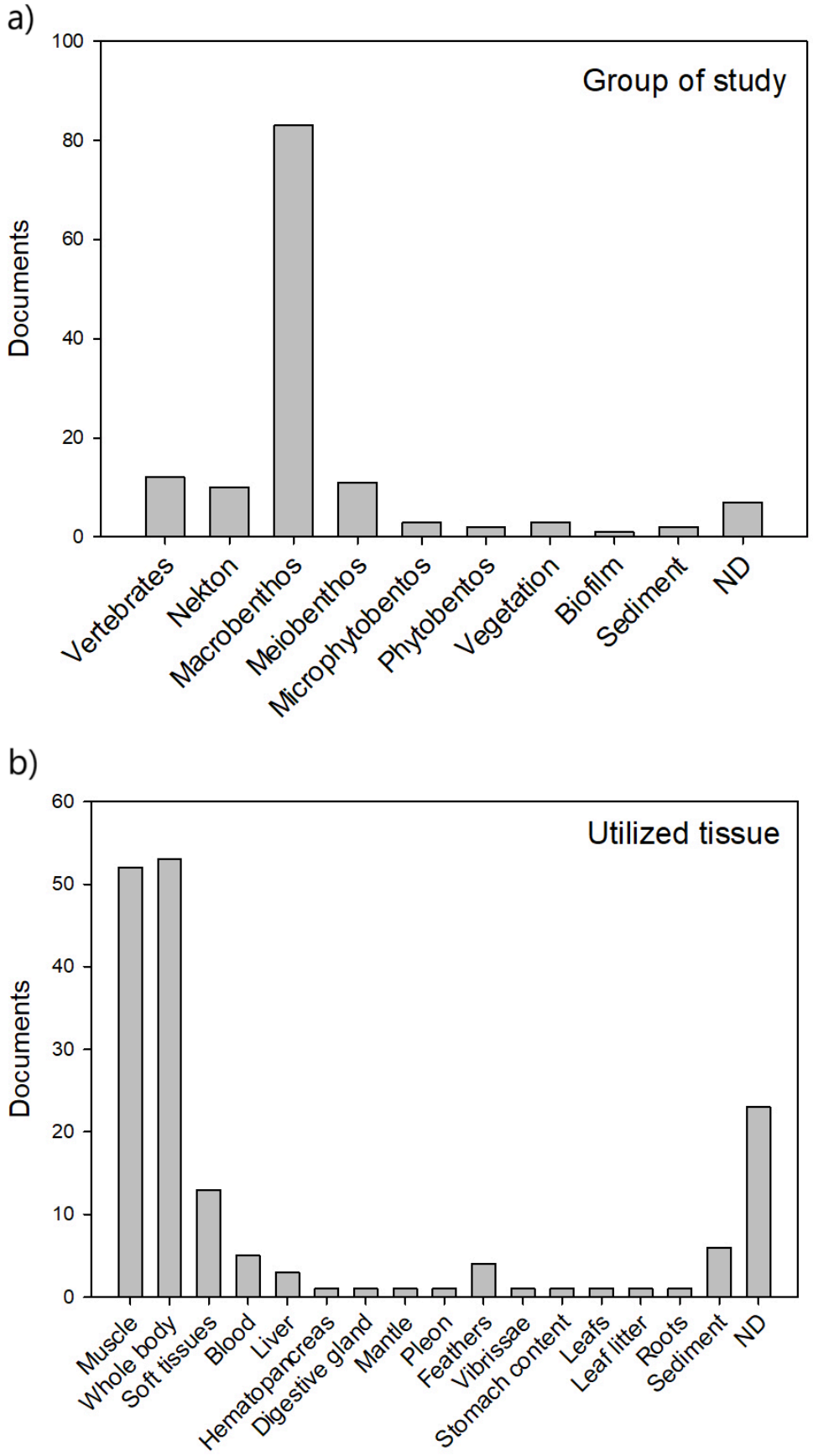

Fig. 5. a) Group of study employed and **b)** utilized tissue during the research in the documents from the list regarding stable isotope ecology on unconsolidated sediment coastal systems from the Scopus database. ND = no data.

In terms of time scale, the majority of studies that reported this information were conducted on a seasonal scale (55 documents), with additional reports on a daily scale (43), monthly scale (7), annual scale (1), and multi-annual scale (17) (Fig. 7a). On the other hand, the spatial scale of most of the fieldwork was meso-scale level (61 documents) (Fig. 7b). We could gather information on the distance covered during sampling from 103 documents. Of these, 20 reported distances of less than 1 km, 36 covered distances between 1 and 10 km, 26 ranged from 11 to 50 km, 7 reported distances between 51 and 100 km, 9 covered 101 to 500 km, 1 reported a distance between 501 and 1000 km, and 4 recorded distances greater than 1000 km (Supplementary Material 2, Fig. S3).

Referring to stable isotopes utilized, the most frequently used was carbon (δ13C), appearing in 130 works, followed by nitrogen (δ15N), used in 115 studies (Supplementary Material 2, Fig. S4). These isotopes were often analyzed together, with 112 documents reporting combined carbon-nitrogen stable isotope analysis. Sulfur stable isotopes (δ34S), in 4 studies; and hydrogen stable isotopes (δ2H), in 1 study, were also included.

The keyword co-occurrence network was composed of 234 keywords, and three clusters were formed (Fig. 8). Cluster 1 focuses heavily on the physical and biological components of ecosystems (e.g., mudflats, sediments, feeding patterns). Cluster 2 emphasizes biological interactions, particularly invertebrates and algae on sandy beaches, highlighting how trophic interactions and diet are central to understanding ecosystem dynamics. Cluster 3 centers on estuarine environments and their biotic components, such as fish and crustaceans, emphasizing food webs and habitat use. Each cluster represents a different facet of stable isotope ecology, with distinct emphasis on physical environments, trophic interactions, and community structure in coastal systems.

Scientific collaboration

Of the 457 authors on the list, 99 were present in two or more documents, thus becoming part of the authors' collaboration network (Fig. 9a). Among these authors, 18 show interconnections with authors from other groups. For example, certain clusters of authors (Niquiel, N. Richard, P. and Pascal P.Y.) are interconnected and correspond to authors from France (see below), reflecting the country's significant contributions to this area of knowledge. Connolly, R.M. is at the center of a cluster of researchers from Australia, while de Torch, M. serves as the central author from Belgium. Regarding countries, we found that from the 44 countries listed, 40 are interconnected. The ones that are not interconnected are excluded from the figure (Fig. 9b). The country clusters in stable isotope ecology research reveal key geographical and linguistic patterns. Cluster 1 includes European and Southern Hemisphere countries like Germany, Australia, and Spain, connected through global academic networks. Cluster 2 is dominated by France, with strong ties to French-speaking regions such as French Guiana and Uruguay. Cluster 3 features a mix of European countries like Belgium and global partners such as Brazil and India, reflecting diverse international collaborations. Cluster 4 is led by the United States and Netherlands, with links extending to Africa and the Caribbean. Cluster 5 consists mostly of English-speaking nations like Canada and the UK, while Cluster 6 centers on Asia, with Japan and Malaysia forming regional hubs, and cross-continental links to Panama. These clusters illustrate how geography and language shape global research partnerships.

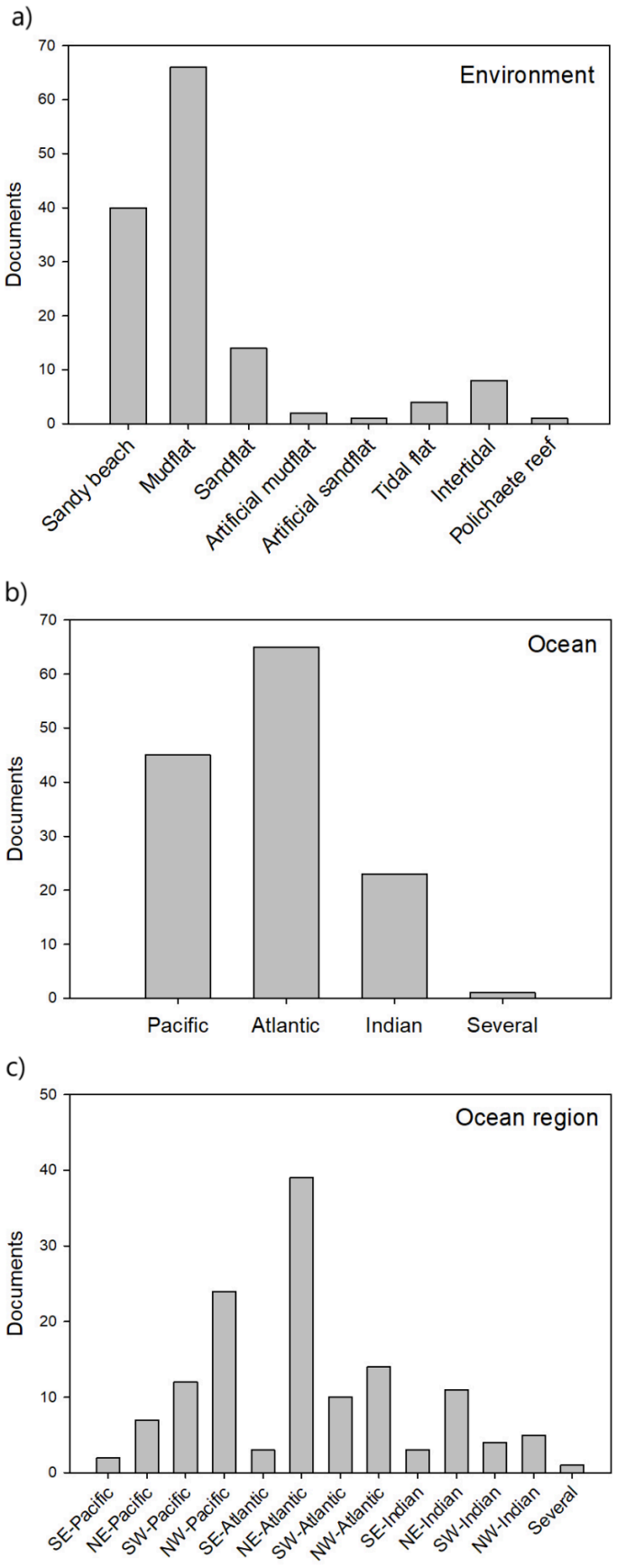

Fig. 6. a) Environment, **b)** ocean, and **c)** region where the research was conducted, from the documents of the list regarding stable isotope ecology on unconsolidated sediment coastal systems from the Scopus database.

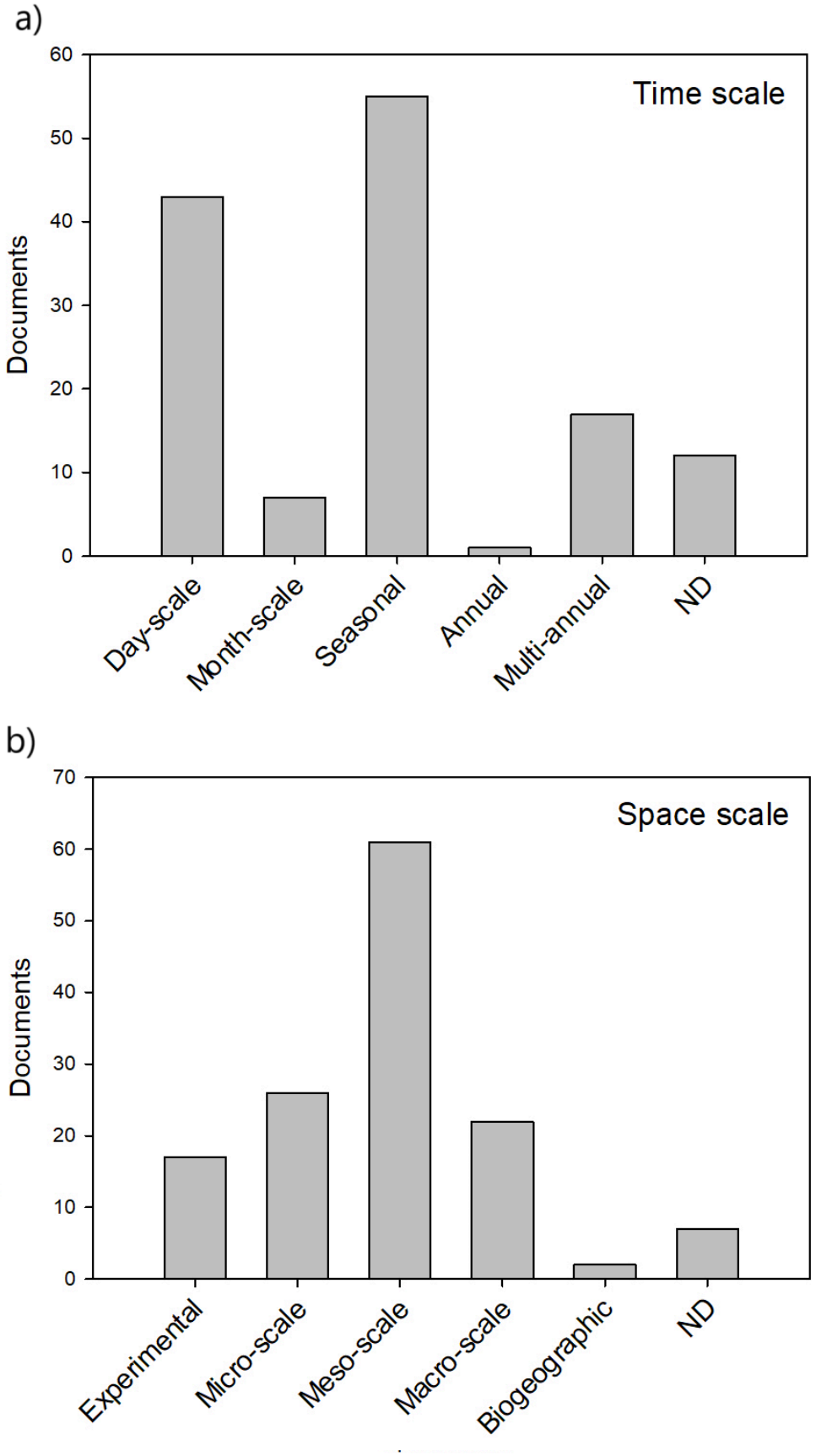

Fig. 7. a) Time-scale, and **b)** space-scale in which the research was conducted, from the documents of the list regarding stable isotope ecology on unconsolidated sediment coastal systems from the Scopus database. ND = no data.

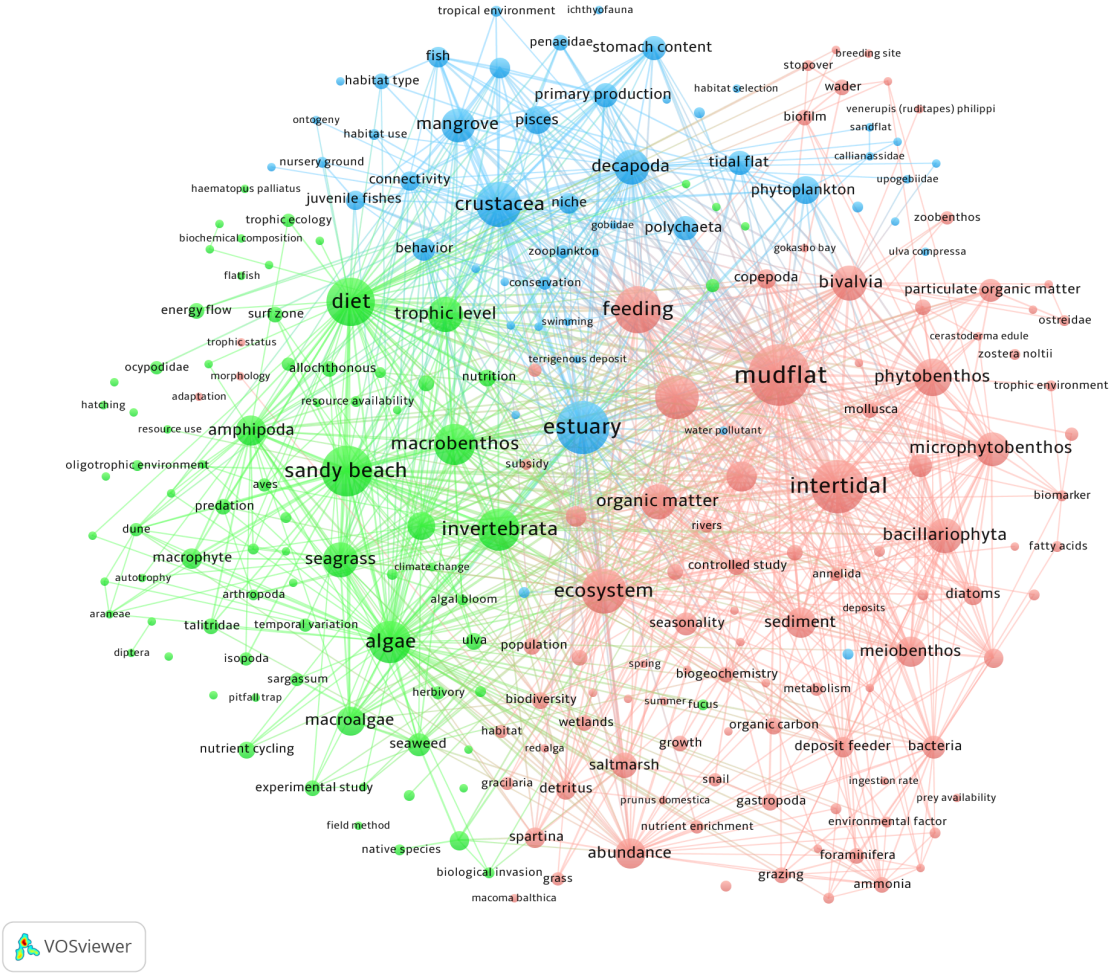

Fig. 8. Network visualization of keywords on documents regarding stable isotope ecology on unconsolidated sediment coastal systems from the Scopus database.

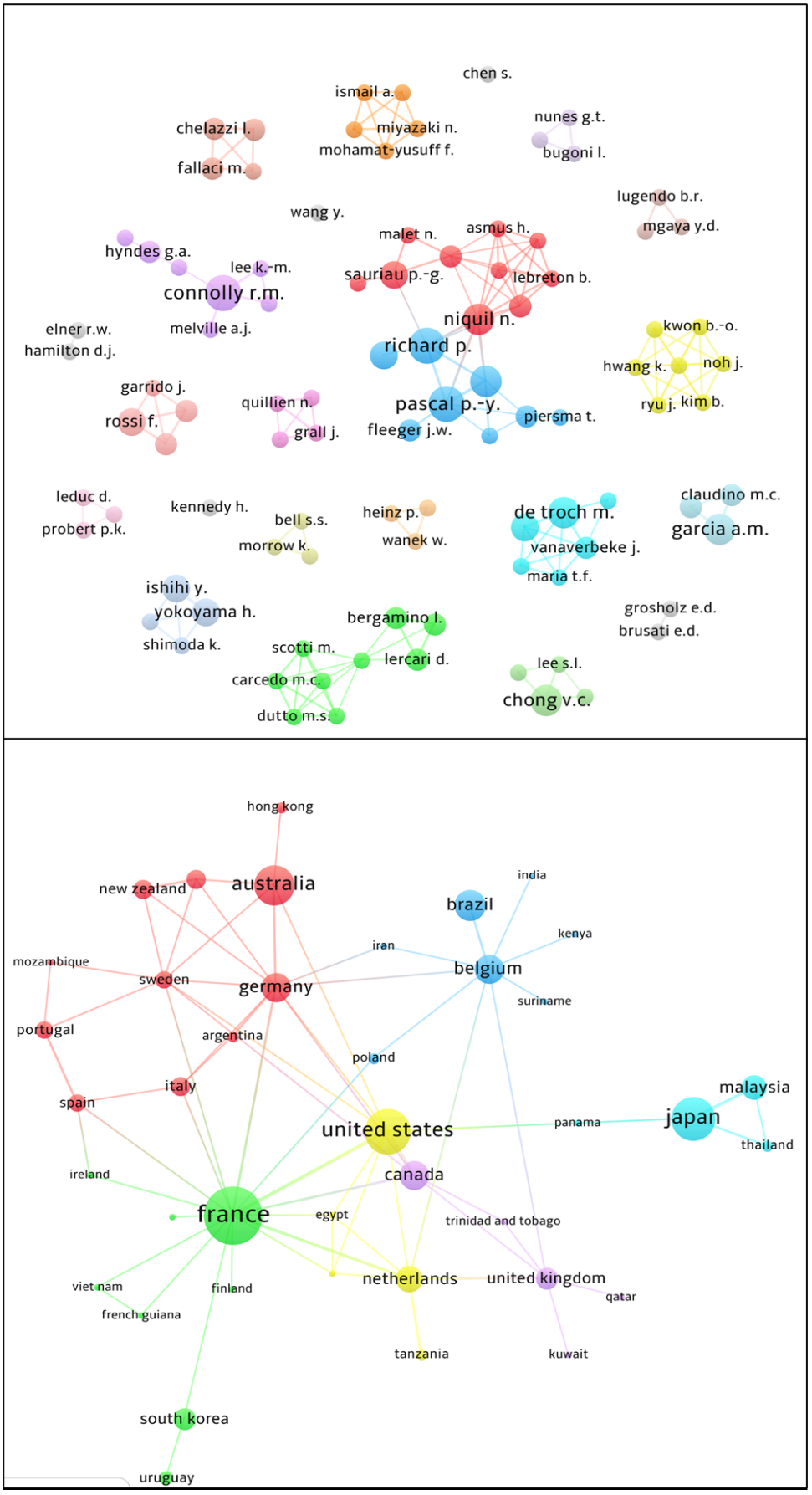

Fig. 9. Co-authorship network among **a)** authors and **b**) countries producing documents related to stable isotope ecology on unconsolidated sediment coastal systems from the Scopus database.

DISCUSSION

Introduction to Findings

Our science mapping analysis revealed over 140 documents and more than 400 authors, indicating a growing interest in stable isotope ecology within unconsolidated sediment coastal systems, with an increase in publications that reached an asymptote characterized by significant fluctuations. Two dominant classic journals in the field were identified, and the main papers garnered over 100 citations each. France, the United States, and Australia emerged as the leading countries in this research area. The primary topic highlighted was trophic studies and the diet of entire communities, with macrobenthos being the most studied community. Mudflats were researched more frequently than sandy beaches, and seasonality was the most commonly analyzed temporal scale, while the mesoscale (hundreds of kilometers) was identified as the most typical spatial scale. Additionally, three conceptual clusters based on environments (beaches, estuaries, and mudflats) were found, along with several clusters of authors and countries that exhibited significant disconnections among themselves.

Scientific Production and Temporal Trends

Publications on stable isotope ecology in unconsolidated intertidal environments have shown a steady increase over the years, reaching a plateau in recent times, with marked interannual fluctuations. The initial growth was gradual, but from the early 2000s onward, a noticeable acceleration occurred, largely driven by the expanded use of isotopic mixing models. These models, particularly Bayesian approaches, allowed for more complex analyses by incorporating multiple sources and addressing uncertainties. Notable peaks in publication volume were observed in 2008, 2011, and 2019, likely linked to technological advancements and an increased focus on diverse ecological applications of stable isotopes, particularly in coastal ecosystems. However, the recent stagnation in growth could be attributed to the emergence of alternative methods for trophic analysis, such as fatty acid profiling and environmental DNA (eDNA), which have gained traction in ecological research. These methods offer different insights into trophic interactions and biodiversity assessments, potentially leading to a shift in research priorities away from traditional stable isotope analysis. A similar growth pattern in stable isotope studies was observed in other regions, as shown by a systematic review of research in Baltic Sea food webs (Eglite et al., 2023), reflecting a broader global trend. Additionally, the rise in stable isotope research parallels advancements in other areas such as megafauna studies, insect ecology, and climate change impacts (França et al., 2022; Liu et al., 2023; Quinby et al., 2020). This highlights the versatility of stable isotope analysis but also underscores how emerging techniques are shaping the future of ecological research.

In the realm of stable isotope ecology, particularly within unconsolidated intertidal ecosystems, Marine Ecology Progress Series and Estuarine, Coastal and Shelf Science have emerged as the predominant journals. Gattuso et al. (2005) identified Marine Ecology Progress Series as a leading source in coastal biogeochemistry, a finding echoed by Akdeniz and Inam (2024), who highlighted its role in marine spatial planning. Lercari (2023) further reinforced the journals' significance, noting their prevalence in publications about sandy beaches. The rise in publications in these sources aligns with broader trends of increased focus and complexity in marine research, driven by advancements in

stable isotope techniques and growing specialization in the field Lercari (2023). However, despite their prominence, it is essential to expand research to include other journals with diverse scopes to capture a wider range of perspectives and methodologies in marine ecology and environmental management. This expansion would not only enrich the scientific discourse but also facilitate the identification of new dynamics and challenges in marine research, promoting a more comprehensive understanding of coastal and marine ecosystems.

Geographical Distribution of Research

Our results generally align with global scientific production trends of leading countries, as reflected in the Nature Index. France has emerged as the leading country in our field, surpassing the USA, which had been dominant until 2007. This shift mirrors broader research trends observed in other studies. For instance, Shellock et al. (2024) noted the USA's initial leadership in ocean literacy, complemented later by significant contributions from the UK and Canada. Similarly, Sun et al. (2012) highlighted the USA's long-standing dominance in estuary pollution research, with increasing contributions from China. The Nature Index also highlights France's growing influence and the USA's continued high output across various fields. Japan's consistent role as a top contributor in our results, as well as in other studies, underscores its stable and significant position in marine and environmental research. Additionally, these findings may be influenced by the historical development of intertidal ecology in different countries and geographical factors, such as the prevalence of mudflats and sandy beaches in major research regions. The dominance of specific countries in these environments could reflect their historical focus and regional advantages in studying these ecosystems.

The analysis of country connections in stable isotope ecology research highlights significant disparities in global collaboration (see Figure 9). While 40 out of 44 countries are interconnected, the central role of Belgium's (e.g. Torch, M.) within predominantly European networks emphasizes a geographical concentration that marginalizes developing nations like Brazil and India. Clusters dominated by French and English-speaking countries illustrate linguistic barriers that hinder broader partnerships, particularly with regions facing ecological challenges in Africa and the Caribbean. This mirrors trends in overall ecological research, where the Global North produces the majority of knowledge and citations, leaving the Global South underrepresented. Consequently, there is an urgent need for inclusive research frameworks that engage developing nations to enhance ecological understanding and inform global conservation efforts (Fisher & Christopher, 2007; Martin et al., 2012).

The co-authorship network analysis of authors and countries producing documents on stable isotope ecology in unconsolidated sediment coastal systems reveals a fragmented landscape of research collaboration. Out of the total of 457 authors identified, only a limited number—99—contributed to multiple publications, thus forming a collaborative network. Within this network, interconnections among authors are sparse, indicating that while there are clusters of collaboration, many researchers operate in isolation or with minimal ties to other groups. For instance, specific clusters of authors, such as Niquil, N., Richard, P., and Pascal, P.Y., demonstrate strong connections and highlight France's significant contributions to the field. In contrast, Connolly, R.M. represents a central figure among Australian researchers, while de Torch, M. emerges as a pivotal author from Belgium. Despite these notable examples, the overall co-authorship landscape is characterized by disjointed groups of researchers who may be conducting parallel studies without sufficient collaboration. This lack of extensive interconnectivity among authors and research groups suggests

opportunities for enhanced collaboration and knowledge exchange including molecular information in the field of stable isotope ecology (Glibert et al., 2019). Strengthening these connections could lead to more integrated research efforts, fostering a deeper understanding of ecological dynamics in coastal systems and potentially facilitating innovative approaches to shared challenges. Such collaboration could be instrumental in advancing the scientific community's collective understanding of stable isotope methodologies and their applications across different geographic regions and ecological contexts.

Research Topics and Methodological Approaches

Consistent with our results, stable isotopes represent a useful tool within research areas of trophic ecology and the understanding of diets, especially for ecologists that work on species difficult to observe in their natural environments (Boecklen et al., 2011). This is based on the application of trophic discrimination factors to the consumer's isotopic values that can be compared directly and associated to those of its diet and can vary according to diet, physiology and behavior (Fry, 2006). Stable isotope analysis offers methods that increase the resolution in the food web studies at various temporal and spatial focus (Boecklen et al., 2011).

Our findings reveal a predominant focus on studies conducted at a seasonal time scale, with 55 documents reporting this frequency, followed by daily, monthly, annual, and multi-annual scales. This pattern reflects a strong interest in capturing temporal variability over relatively short periods, likely due to the dynamic nature of coastal ecosystems and logistical constraints in fieldwork. On the other side, the spatial scale of most studies was at the meso-scale level, as seen in 61 documents. This preference for meso-scale research aligns with the observations of Wiens (1989) and Levin (1992), who emphasize the importance of intermediate scales in understanding ecological processes. The data on sampling distances further supports this, with the majority of studies covering areas between 1 and 50 km, reinforcing the trend toward meso-scale investigations. Only a minority of studies extended beyond 100 km, highlighting the challenges associated with conducting large-scale ecological studies, which may be constrained by logistical, financial, or temporal limitations (Heffernan et al., 2014). Thus, our analysis underscores the continued relevance of meso-scale research in ecology, while also pointing to opportunities for more extensive studies at broader spatial and temporal scales, particularly in the context of global change and biogeographic patterns (Wiens & Bachelet, 2010). It should be noted for future studies in unconsolidated intertidals, that isotopic trophic metrics are strongly influenced by sampling spatial extent, which controls the environmental heterogeneity experienced by individual consumers, as greater sub-habitat heterogeneity leads to greater variation in resource use (Reddin et al., 2018). This idea reinforces the recognition for isotopic studies to consider temporal variation in baseline food webs due to for example seasonal variation in allochthonous inputs that makes the determination of baseline across study period and geographic ranges imperative (Reddin et al., 2018).

The network visualization of keywords from documents on stable isotope ecology in unconsolidated sediment coastal systems reveals a well-defined structure with multiple thematic clusters (see Figure 8). These clusters represent different aspects of coastal systems, including physical environments, biological interactions, and community structure. For example, one cluster focuses on mudflats, emphasizing the role of primary producers like phytobenthos and phytoplankton, while other highlights the trophic dynamics on sandy beaches, particularly the interactions between

invertebrates and stranded algae. Estuarine environments, which combine elements of both sandy beaches and mudflats, feature prominently in another cluster, with attention to food webs and habitat use among fish and crustaceans. Overall, the relatively strong integration of these clusters suggests that stable isotope methodology serves as a unifying scientific tool across various intertidal environments. Despite the diversity of ecosystems studied, stable isotope analysis consistently links studies regarding biogeochemical cycling, trophic interaction, paleoenvironments and baseline tracking, demonstrating its versatility and broad applicability in ecological research (Glibert et al., 2019). This cohesive framework enables scientists to bridge gaps between different coastal systems, deepening our understanding of ecological processes and interactions across these dynamic landscapes.

Environmental and Oceanographic Focus

In line with Lercari (2021), who extensively analyzed the scientific focus on sandy beaches, our findings reveal a greater emphasis on mudflats in stable isotope research. This preference likely stems from the more complex biogeochemical processes in mudflats, where factors such as nutrient cycling and sediment dynamics are more intricate compared to the relatively simpler processes observed in sandy beaches. Furthermore, consistent with Gattuso et al. (2006), we observed a significant concentration of studies in the Atlantic Ocean, particularly in the Northeastern Atlantic. This geographic focus can be attributed not only to the high density of researchers based in the USA and Europe but also to the uneven distribution of mudflats and sandy beaches across oceans. Notably, the Atlantic and Pacific Oceans, which account for the largest shares of tidal flats (Murray et al., 2019), host vast macrotidal mudflats along coasts such as Northern Europe, Southeast Asia, and Australia. The historical development of marine science in European institutions, especially along the tidal flats of the North Sea, likely reinforces this trend. These observations align with Potter & Pearson (2023), who highlight significant regional disparities in research output and stress the importance of international collaboration. The concentration of research in the Atlantic and Pacific Oceans underscores the need for more balanced global studies, as these ocean basins currently dominate the scientific discourse on coastal ecosystems.

Most studies in stable isotope ecology primarily utilize carbon (δ13C) and nitrogen (δ15N), with 112 studies focusing on these isotopes. This dominance reflects their efficacy in tracing organic matter sources and trophic relationships. However, sulfur (δ34S) and hydrogen isotopes are rarely used, though their potential in coastal ecology is increasingly recognized. For instance, sulfur isotopes, when used alongside carbon and nitrogen, can help differentiate between benthic and pelagic organic matter sources, especially in coastal environments with complex salinity gradients (Davis et al., 2024; Raoult et al., 2024). Sulfur isotopes offer unique insights into sediment processes and may complement carbon isotopes in identifying primary producer sources that share similar δ13C values (Holmer & Hasler-Sheetal, 2014; Peterson & Howarth, 1987). The potential of δ34S is becoming more evident in studies aimed at distinguishing carbon pathways, suggesting future applications in coastal systems. Moreover, nitrogen isotopes play a crucial role in ecotoxicology, where they help quantify contaminant biomagnification, such as mercury and PCBs, through the food web (Cabana & Rasmussen, 1996; Hobson et al., 2023). Furthermore, ammonium inputs on coastal systems originated from treated effluent discharge are enriched in 15N compared to nitrate (Savage, 2005). Despite the growing application of isotopes in various contexts, their use in intertidal ecosystems remains limited, presenting new challenges and opportunities for future research. Stable isotopes may help to better understand how different populations and

communities respond to different habitat stressors including urbanization as has been suggested recently addressing ecological and physiological impact of urban development on freshwater fishes (Burbank et al., 2022). It should be noted that physiological status among individuals will also influence δ13C and δ15N and consequently trophic metrics through metabolic fractionations, making this interpretation complex and should be considered with caution (Gorokhova, 2018; Karlson et al., 2018). In this sense, integrating stable isotopes with other biochemical tracers like fatty acids enhances the ability to trace carbon sources and assess the nutritional quality of organic matter in aquatic food webs (Bergamino & Richoux, 2015; Twining et al., 2020). This multi-isotope and multi-tracer approach broadens the understanding of complex food web dynamics and ecological processes in coastal environments. Finally, experimental studies may enhance stable isotope interpretation. For example, experimental studies manipulating the presence and absence of an invasive species may give new light regarding trophic shifts of native species as a response to the presence of an invasive species. Since stable isotopes only reveal information regarding energy flow and limit interpretation regarding functional relationships including abundance controls of a predator, experimental manipulation may provide additional useful information (Layman et al., 2012).

Citation and Influence of Key Studies

Studies on stable isotope ecology vary widely in their focus, publication sources, and methodologies, highlighting the diversity in the field (see most cited documents). Research such as that by Kang et al. (1999) in Marine Ecology Progress Series focused on nutrient dynamics in muddy sandflats by examining the food sources of bivalves, while Ince et al. (2007) in Estuarine Coastal and Shelf Science explored how marine macrophytes enhance sandy beach fauna through habitat provision. Miura et al. (2006) combined stable isotope analysis with parasitology to explore ecological niches in Proceedings of the Royal Society B: Biological Sciences. Other foundational studies, such as Melville & Connolly (2003) and Hentschel (1998), published in Oecologia and Ecology, respectively, provide broader ecological frameworks and methodologies that subsequent research has expanded upon.

A significant proportion of these studies focus on defining food sources across a variety of species, including filter feeders, nematodes, amphipods, and fish, advancing knowledge on trophic structures in unconsolidated intertidal food webs. Typically, the isotopic composition of terrestrial organic matter (OM) is distinct from marine OM (Lamb et al., 2006), and sandy beach studies confirm that these environments receive diverse food sources, such as terrestrial inputs, freshwater discharges, macro- and microalgal production, and coastal phytoplankton. Most research concentrates on macrobenthic species, although meiobenthic fauna has also been studied. For example, Riera et al. (1996) and Couch et al. (1989) examined meiobenthos, with Riera highlighting the importance of microphytobenthos as a principal carbon source for tidal flat nematodes. Seasonal variability in isotopic composition was another focus, as seen in Kang et al. (1999), who found that seasonal shifts in primary producer availability significantly affected bivalve suspension feeders. However, studies on higher trophic levels, including nekton and vertebrates, remain sparse. Melville & Connolly (2003) made significant contributions by identifying key food sources—such as microphytobenthos, seagrass epiphytes, and detritus—across multiple locations, demonstrating spatial variations in food sources for fish consumers. These foundational analyses promote the understanding of fundamental ecological mechanisms in unconsolidated intertidal ecosystems, advancing research in this domain.

Limitations of the Study

Our study, based solely on Scopus, faces limitations related to data omissions, such as important research not indexed in Scopus or published in non-English journals, as well as non-peer-reviewed works like theses and technical reports, which can lead to underrepresentation of certain regions or emerging fields. Additionally, there may be biases toward certain taxa and ecosystems, with sandy beaches and mudflats receiving more attention than other unconsolidated intertidal habitats. The ambiguity in defining environments, such as mangroves associated with mudflats, further complicates the inclusion of relevant studies, potentially excluding research that fits the scope of our analysis. These factors suggest a need for future research to address underrepresented taxa and environments and to broaden the scope beyond a single database.

CONCLUSION

Growing Research Landscape: The expansion of publications and the increasing number of authors working on stable isotope ecology indicate a growing interest in understanding coastal ecosystems, particularly those involving unconsolidated sediment environments like sandy beaches and mudflats. With established methodologies such as isotopic mixing models driving the field forward, the research landscape is becoming more specialized. Looking ahead, combining stable isotope analysis with other techniques like environmental DNA (eDNA) and fatty acid profiling could open new avenues for research, offering more comprehensive insights into ecosystem processes and their response to environmental changes.

Temporal and Spatial Trends: The focus of most studies on seasonal dynamics and meso-scale spatial resolutions reflects the naturally dynamic behavior of coastal ecosystems. However, there is a clear gap in studies that provide long-term interannual comparisons or large-scale spatial replication, which limits our understanding of ecosystem stability and change over time. Future research should prioritize long-term monitoring programs that capture seasonal and interannual variability, providing a clearer picture of ecosystem responses to climatic and anthropogenic pressures, as well as a broader spatial representation across multiple sites and regions.

Climate Change and Ecological Monitoring: Stable isotope records offer valuable insights into how ecological interactions shift under climate change, particularly in terms of species' dietary adaptations and nutrient sources. However, few studies have leveraged the full potential of isotopic analysis for long-term monitoring, limiting our ability to track these changes over extended periods. Expanding the use of long-term stable isotope records could greatly improve our capacity to understand and predict ecosystem responses to climate change, facilitating better management strategies for ecosystems affected by environmental stressors such as rising temperatures, ocean acidification, and habitat loss.

Geographical Disparities and Collaboration: The geographic distribution of stable isotope research is uneven, with most studies coming from countries like France, the USA, and Australia, while other regions, particularly developing countries, remain underrepresented. This disparity in research output is further exacerbated by fragmented collaboration networks, often hindered by linguistic and institutional barriers. To overcome these limitations, future efforts should focus on fostering more inclusive and equitable international collaboration, especially to involve regions facing pressing

ecological challenges and promote a more balanced distribution of scientific knowledge and resources.

Methodological Diversity: Carbon and nitrogen isotopes dominate the field of stable isotope ecology, reflecting their central role in understanding nutrient cycling and food web dynamics in coastal systems. However, other isotopes like sulfur and hydrogen remain underutilized, despite their potential to provide complementary insights into ecological processes. Future research should encourage a broader application of these lesser-used isotopes to enhance the depth of ecological understanding. Additionally, integrating stable isotope data with trophic models like Ecopath could improve food web representation and ecosystem management, especially in coastal regions where anthropogenic impacts are significant.

Focus on Mudflats and Atlantic Regions: Mudflats have received more attention than sandy beaches in stable isotope studies, likely due to their more complex biogeochemical processes. Additionally, research in the Atlantic Ocean, particularly in the Northeastern Atlantic, dominates the field, reflecting the historical development of marine science in this region. This imbalance in geographic focus highlights the need for more research in underrepresented ecosystems and ocean basins, such as the Pacific and Indian Oceans. Broadening the geographical scope of stable isotope studies could lead to a more comprehensive understanding of coastal ecosystems globally, addressing regional differences in biogeochemical processes and ecosystem services.

Novel Applications and Emerging Techniques: While stable isotope analysis has traditionally been used to study nutrient cycling and food web dynamics, its potential in emerging ecological contexts, such as climate change resilience, is increasingly recognized. Integrating stable isotopes with emerging methodologies, such as eDNA and fatty acid profiling, can provide more nuanced insights into ecological responses to environmental stressors. Future research should explore these novel applications, offering new perspectives on how ecosystems function under changing environmental conditions and how they may adapt to future challenges posed by climate change and other anthropogenic pressures.

Importance of Collaboration: Collaboration plays a critical role in advancing the field of stable isotope ecology, particularly in integrating isotopic data with other ecological models and frameworks. By fostering international and multidisciplinary collaborations, researchers can better address global ecological challenges and advance ecosystem science. Future studies should emphasize multi-scalar and experimental research designs, combining stable isotope analysis with other approaches, such as trophic modeling and ecosystem monitoring, to enhance the understanding of coastal ecosystems and inform better management and conservation practices.

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AUTHOR CONTRIBUTION

N.S.: Conceptualization; Investigation; Formal Analysis; Writing – original draft; Writing – review & editing

L.B.: Investigation; Writing – original draft; Writing – review & editing

D.L.: Conceptualization; Investigation; Writing – original draft; Writing – review & editing; Supervision

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