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Artigo de Pesquisa

Recognizing Biogeomorphology: Analysis of Academic-Scientific Production and Distribution of Studies by Geomorphological Environments

Reconhecendo a Biogeomorfologia: análise da produção acadêmico-científica e distribuição dos trabalhos por ambientes geomorfológicos

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Abstract: Biogeomorphology focuses on the study of interactions between biotic and abiotic factors in geomorphological processes and systems, dealing with the dynamics between living organisms and their physical environments. It is an area of study between Geomorphology and Ecology, aiming to understand the influences between landforms and the distribution and development of organisms, and vice versa. In the present article the authors made a bibliometric analysis of scientific and academic production in biogeomorphology, using the *Scopus* database as the research source. The bibliometric research and analysis were carried out in two stages: in the first, the goal was to depict the state of art biogeomorphological research; while in the second phase, biogeomorphological works were inventoried according to the different geomorphological environments they focus on: i) coastal environments; ii) fluvial environments; and iii) slope environments. For better characterization, the research considered only works published until December 2024. As results, this work presents the historical evolution of Biogeomorphology as a discipline, both in general and through its subfields, identifying its main authors and works, research-leading countries, key bibliographic sources, and an analysis of the co-occurrence of keywords.

Keywords: Ecogeomorphology; Biogeodiversity; Bibliometric Analysis

Resumo: A biogeomorfologia trata dos estudos das interações entre fatores bióticos e abióticos em processos geomorfológicos, enfocando a dinâmica entre os seres vivos e os ambientes. É uma área de estudo na interface entre a Geomorfologia e a Ecologia ou Biogeografia, na qual se busca compreender as influências entre as formas de relevo na distribuição e desenvolvimento dos organismos, e vice-versa. O presente trabalho tem por objetivo realizar uma análise bibliométrica da produção acadêmica em biogeomorfologia, utilizando a base de dados *Scopus* como fonte de pesquisa. A pesquisa e análise bibliométricas foram realizadas em duas etapas: na primeira delas, buscou-se retratar o quadro de trabalhos biogeomorfológicos em geral; enquanto na segunda fase de buscas inventariaram-se os trabalhos biogeomorfológicos segundo os diferentes ambientes geomorfológicos aos quais se voltam: i) ambientes costeiros; ii) ambientes fluviais; e iii) ambientes de encostas. Em vista de uma melhor caracterização, a pesquisa considerou apenas trabalhos publicados até dezembro de 2024. Enquanto resultados, o presente trabalho delineia uma evolução histórica da Biogeomorfologia enquanto disciplina, no geral e a partir de suas subáreas, caracterizando seus principais autores e trabalhos; países-eixo de pesquisa; principais fontes bibliográficas e análise da coocorrência das palavras-chave.

Palavras-chave: Ecogeomorfologia; Biogeodiversidade; Análise bibliométrica

1. Introduction

Biogeomorphology or ecogeomorphology can be defined as the study of interactions, correlations, and interinfluences between biotic and abiotic factors in geomorphological processes and systems (Corenblit; Steiger, 2024; Larsen et al., 2020; Naylor, 2005; Naylor; Viles; Carter, 2002; Prugne et al., 2024; Viles, 2019). An interface discipline, combining knowledge and advances in ecology and geomorphology, biogeomorphology explains and describes those complex geomorphological environments and systems where the biotic kingdoms and abiotic elements are closely connected, especially in those aspects related to the landscape evolution and dynamics (Naylor; Viles; Carter, 2002; Viles, 2011; Viles, 2019).

The term was coined by Heather Viles in a seminal book in the field (Haussmann, 2010; Jones, 2012; Naylor, 2005; Osterkamp; Hupp, 2010), and the discipline was defined as the field of knowledge that is concerned with "influence of landforms/geomorphology on the distributions and development of plants, animals and micro-organisms; [and] the influence of plants, animals and micro-organisms on earth surface processes and the development of landforms" (Viles, 1988a apud. Viles, 2019).

In general terms, biogeomorphology can be subdivided into two main thematic sections: i) the different biotic kingdoms it considers, either through zoogeomorphology (*animalia*) or phytogeomorphology (*plantae*) (Butler, 1995; Howard; Mitchell, 1985; Larsen et al., 2020; Viles, 2019); or ii) the different geomorphological environments to which it focuses. Evidently, as geomorphological environments diversify in larger amounts, and a single geomorphological environment can support multiple biotic relationships, biogeomorphological studies are preferably divided according to such environments rather than by the biotic kingdoms considered (Larsen et al., 2020; Viles, 2019).

Although the term was only defined in the late 1980s (1988) (Haussmann, 2010; Jones, 2012; Naylor, 2005; Osterkamp; Hupp, 2009), biogeomorphological studies have been conducted for a long time. Correlations between landforms and life forms have been realized since Alexander von Humboldt (Martin; James, 1993; Marston, 2010), when the German naturalist correlated relief, climate, and the distribution of plant life forms, or even by naturalists such as Charles Darwin (Osterkamp et al., 2011; Viles, 2022) when studying coral reefs or when he highlighted that plant distribution would be related to geological events (Marston, 2010; Viles, 2022).

The advance in the understanding of the interrelationships and interinfluences between the forms and processes of relief sculpting and ecosystem dynamics of certain plant and animal species occurred mainly from the creation and development of concepts such as *biogeocenosis*, a term of historical importance in German and Russian literature, where the concepts of biocenosis and biotope were combined (Howard; Mitchell, 1985). From the 1970s onwards, however, the joint work of ecologists and geomorphologists, especially in English-speaking countries, allowed the advancement of specific studies in the field (Viles, 2022). The work by the American geomorphologist James C. Knox can be cited, for instance, where the expression "biogeomorphic feedback" (Viles, 2022) first appears, when he describes the interrelationships between vegetation and hydrogeomorphological processes.

Among the pioneering publications in the field, the classic *Phytogeomorphology,* by J. Howard and C. Mitchell (1985), stands out, a precursor study on the relationships between topography, landforms, and the distribution patterns of plant species. In 1995, seven years after the publication of the classic *Biogeomorphology*, by Viles, one published in the United States the first book focused exclusively on the interactions between fauna and geomorphological processes, *Zoogeomorphology: Animals as Geomorphic Agents*, by David R. Butler.

Since then, biogeomorphological research has diversified, directed not only at multiple geomorphological environments, but also focusing on the description of the ecological dynamics of certain species in relation to geomorphological dynamics. Despite this long history of development of biogeomorphological thought and the increasingly significant advances, only briefly presented in this introduction, it is worth noting that biogeomorphological research is relatively recent in geosciences, and the growth in the number of studies have occurred mainly from the second half of the first decade of the 21st century, as will be demonstrated in this paper.

In Brazil, specifically, biogeomorphological studies allow the expansion of the scope of geoscientific research, especially in the context of geographic and oceanographic sciences. In Geography, for example, the discipline is particularly fertile, since it combines two sub-areas that are already well-defined in Brazilian geographic studies: biogeography and geomorphology.

From a theoretical perspective, an example of the contributions of biogeomorphology is the potential to understand the intersection between biodiversity and geodiversity – or biogeodiversity –; from an applied point

of view, it is possible to mention the possibility of developing, promoting, and applying Nature-based solutions (NbS), an ever-increasing need in areas such as urban and territorial planning and issues related to environmental conservation in the 21st century (Coombes; Viles, 2021; Richards et al., 2024).

In view of this, this work aims to outline, through a bibliometric analysis of academic-scientific production, the nature of studies on biogeomorphology and its subdivisions, classifying them according to three distinct geomorphological environments proposed by Viles (2019): i) coastal and marine environments; ii) fluvial environments, and iii) hillslope environments. To this end, the authors used documents retrieved from the Scopus database (Elsevier).

This research was motivated by the lack of studies that characterize quantitatively the evolution of biogeomorphology and its subdivisions, and one sought to answer the following guiding questions: What are the total numbers of academic-scientific production in biogeomorphology? Who are the most productive authors in the current research scenario, and which co-authorship networks are they connected to? Which are the countries leading the research production and, therefore, which are the main research institutions in the area? What are the international co-authorship networks? In which academic journals and periodicals are the articles published, and which are the most relevant periodicals in the area, historically? The research was aimed at recognizing the scientific production in biogeomorphology, besides representing the way in which studies are distributed.

2. Materials and Methods

The research was conducted by means of bibliometric analysis, using the Scopus database (Elsevier) as a reference source. Data processing used R software (Bibliometrix), Zotero, VOSviewer and Excel. Data search and collection were completed in January 2025, and text analysis and writing in February 2025. For the research, documents published between 1972, – the year the biogeomorphological studies first appeared – and December 2024 – the month and year established as limits by the authors – were used as the timespan. This timespan was chosen so that the still low number of 2025 publications (three studies, up to the time of the text writing) would not interfere with the research results.

2.1 Choosing the database

Scopus was chosen due to the quality of the information and data available (Ferreira; Valdati, 2023). Furthermore, it is considered an excellent bibliographic and bibliometric data source in the geosciences field (Herrera-Franco et al., 2020), not only due to the practicality in handling bibliometric data but also to the number of local, regional, national, and international scientific journals and periodicals available, with more than 1.7 billion references cited since the 1970s, which maximizes the amount of information analyzed and avoids the loss of relevant data and information (Ruban et al., 2018).

A second argument for choosing Scopus is a higher volume of documents available for consultation. One constructed equivalent strings in two different international databases, Scopus (Elservier) and Web of Science (Clarivate), for the same temporal and thematic section. The string "TITLE-ABS-KEY ("biogeomorph*" OR "ecogeomorph*")" was used in Scopus, and 922 documents were retrieved; in Web of Science, one used a string equivalent to that, ("ALL= ("biogeomorph*")) OR ALL= ("ecogeomorph*")), and 908 documents were found. The decision was therefore to use the database with more documents available.

2.2. Design and 1st search phase

The first search phase structure was based on the logical-mathematical expression "biogeomorphology Δ ecogeomorphology," in order to construct a Venn diagram (Figure 1a). This representation was used as a preamble to the construction of a first search string.

In order to perform searches as broad as possible, the resulting diagram established a symmetrical differentiation between the terms "biogeomorphology" and "ecogeomorphology." Despite being distinct (Viles, 2019), both terms are equivalent and are used interchangeably in most scientific research. Therefore, when searching for documents where one term or the other occurs, the number of results available for analysis increases considerably, thus improving the quality of the resulting bibliometric analysis. Consequently, the diagram was made from that expression, which was used as a basis for the construction of the first search string. Initially, the

string used was the following: "TITLE-ABS-KEY ("biogeomorph*" OR "ecogeomorph*") AND PUBYEAR > 1971 AND PUBYEAR < 2025."

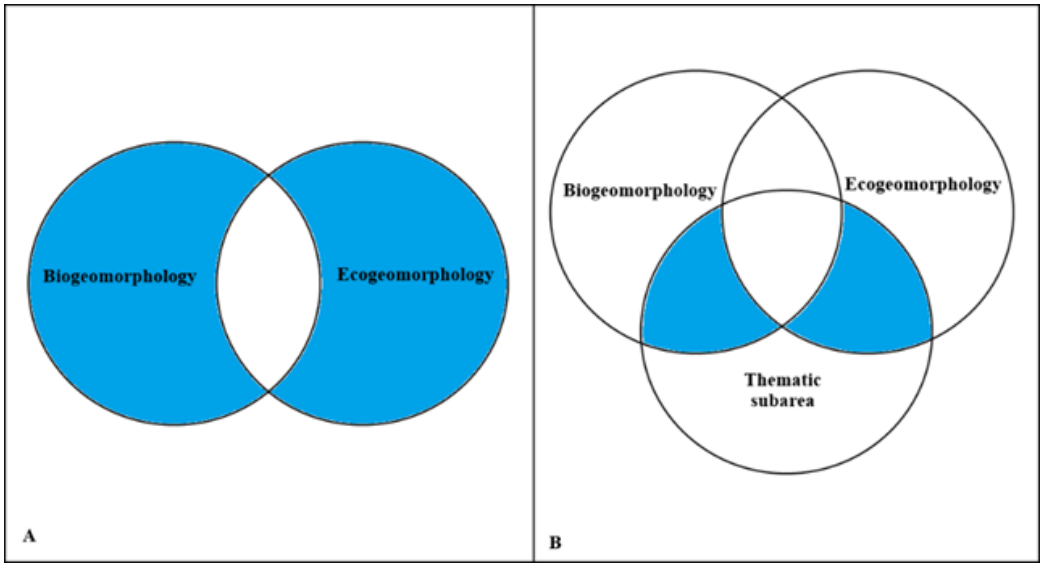

Figure 1. (a) Diagram of the 1st search phase; (b) Diagram of the 2nd search phase

2.3 Design and 2nd search phase

Based on the first search phase results, it was found that biogeomorphological publications were organized much more in relation to the different geomorphological environments than based on the biotic or ecological framework adopted.

Therefore, in addition to the classic subdivision of biogeomorphology between phytogeomorphology and zoogeomorphology, where relationships are classified according to the different biotic kingdoms involved in geomorphological processes, plant and animal, biogeomorphology can also be understood according to the environments and processes which the studies focus on. In view of that, and in accordance with the proposal by Viles (2019), the decision was to subdivide the data obtained into three large areas, according to the geomorphological environments considered in the studies, which are: i) coastal and marine environments; ii) fluvial environments, and iii) hillslope environments.

Based on the subdivision proposed by Viles (2019), there was a 2nd search phase. In this second moment, the logical-mathematical expression used was the following: "biogeomorphology ∩ subárea temática ou ecogeomorphology ∩ subárea temática" [biogeomorphology ∩ thematic sub-area or ecogeomorphology ∩ thematic sub-area]. (Figure 1b). The expression allowed us to arrive at those pieces of research in which either *biogeomorphology* or *ecogeomorphology* are terms associated with those terms that characterize the new research axes, through the intersection between the keywords.

Rewriting that string previously used in the 1st search phase from the new diagram, via sentence restructuring, the following string was constructed: "TITLE-ABS-KEY ("biogeomorph*" OR "ecogeomorph*" AND "subárea temática"[thematic sub-area]) AND PUBYEAR > 1971 AND PUBYEAR < 2025." The new expression is explained as follows: when searching and using the AND boolean operator, terms associated with the different thematic sub-areas were added to the first search string, but the previously defined timespan was maintained.

As for the asterisks in the suffixes of the keywords, they are explained as a semantic tool to allow for the possible variations of the terms used to be reached in the same way. The new keywords used as indexers for the thematic sub-areas were: "coastal*" OR "marine*," for coastal environments; "fluvial*" OR "river*," for fluvial environments; and "hillside*" OR "slope*" for hillslope environments.

2.4 Data processing and interpretation

The data set and references were exported from Scopus in CSV (Comma Separated Values) and RIS (Research Information System) files for later processing and organization. The Zotero software was used to data review. The review corrected random errors, based on the need to standardize the tags for later graphic production in the VOSviewer software (e.g., "process" and "processes" appeared as distinct tags, despite being equivalent terms), or even correcting random differences in the same term and/or author (e.g., "VILES, H". and "VILES, H. A.").

Once the nonconformities found had been reviewed and corrected, the data series was processed: the performance analysis (metrics) was performed mainly using the R software (Bibliometrix) and in Excel, together with the data analysis provided by Scopus itself; however, VOSviewer was used for the graphic production (science mapping). The conceptual scheme represents the research steps (Figure 2).

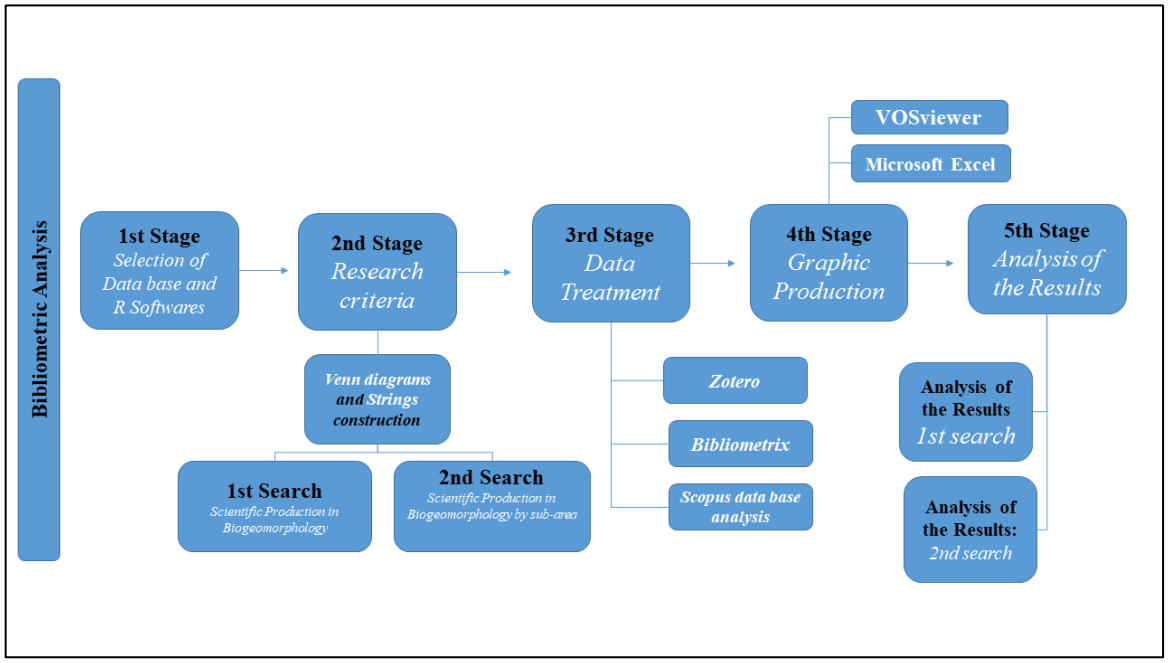

Figure 2. Methodological scheme

All methods used in this research were directed at founding the total number of documents published; the number of publications per year; the main journals and periodicals by thematic sub-areas; the main academic-production countries, and the most productive authors and their co-authorship networks, also generating the graphical representation of the resulting bibliometric data and networks as products of bibliometric analysis.

3. Results and discussion

The results were subdivided based on the study search phases. The order in which the results are presented is not qualitative but chronological, according to the publication date of the studies. The following data are presented, in general and by biogeomorphological research area: total number of publications; analysis of annual scientific production; main authors and co-authorship networks; main bibliographic sources, and analysis of co-occurrence of keywords listed.

Also regarding the order in which the results are presented, the 2nd search phase results, subdivided by geomorphological environments, are displayed together, in order to make the text clearer and more rhythmic. Nevertheless, the 1st search phase results are presented separately, given that they represent the general scientific production in biogeomorphology.

3.1. 1st search phase results

In total numbers (Figure 3), one retrieved 922 studies where the terms *biogeomorphology* and *ecogeomorphology*, or their variations (e.g., *biogeomorphological* or *ecogeomorphological*) occur. Regarding those 922 documents, the search found 745 articles (80.8%) in academic-scientific journals; 69 reviews (7.5%); 55 book chapters (6.0%); 35

abstracts in conference or congress proceedings (3.8%); five notes (0.5%); two errata (0.2%); one book (0.1%), and one conference review.

The listed studies are connected to 2,293 authors. The analyzed set of documents presented a co-authorship rate of 4.29 authors per work. In the universe of more than 2,000 authors, only 86 have pieces of research with no co-authorship. The co-authorship rate – which measures collaboration between different countries in academic-scientific research – is 32.86%, a little less than a third (1/3) of the total documents listed, which points to a considerable network of international collaboration between authors and research institutions.

With regard to where studies were published, one found 258 bibliographic sources, including academic journals, conference and congress proceedings, and books.

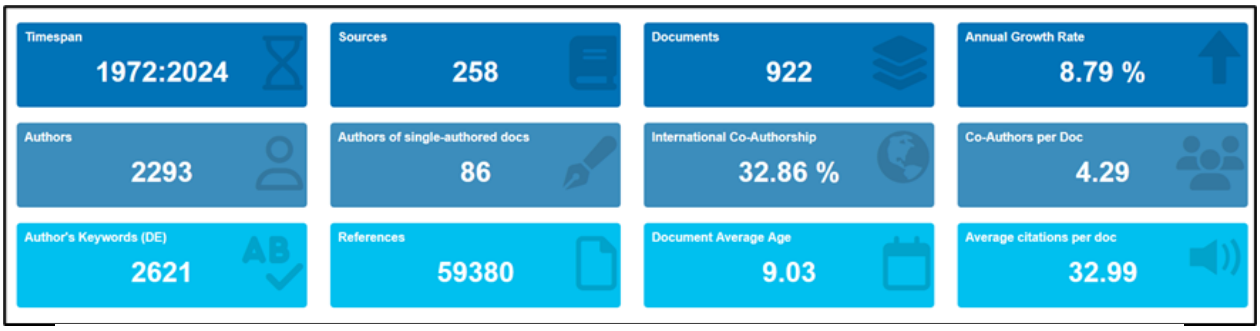

Figure 3. Total numbers in biomorphology

The five studies with the majority of citations available for consultation were selected. Of these, four were articles in scientific journals, and one was a book.

In the top position it is the article published in the Geophysical Research Letters journal, by Kirwan et al. (2010), with 630 citations. It is followed by the article by Corenblit et al. (2007), published in the Earth-science Reviews journal, with 595 citations. Ranked third and fourth, respectively, the article in the area of zoogeomorphology by Trimble and Mendel (1995), published in the Geomorphology journal, with 481 citations, and the book written by David M. Butler, Zoogeomorphology (1995), with 371 citations. Ranked fifth, the article by Temmerman et al. (2007), published in the Geology journal, with 353 citations (Table 1).

Table 1. Main studies on biogeomorphology

Type of document	Title	Authors	Journal	Year	Numbers of citations
Article	*Limits on the adaptability of costal marshes to rising sea level*	Kirwan, M. L. et al.	*Geophysical Research Letters*	2010	630
Article	*Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches*	Corenblit, D. et al.	*Earth-science Reviews*	2007	595
Article	*The cow as a geomorphic agent – A critical review*	Trimble, S.W.; Mendel, A. C.	*Geomorphology*	1995	481

Book	*Zoogeomorphology: animals as geomorphic animals*	Butler, D. R.		1995	371
Article	*Vegetation causes channel erosion in a tidal landscape*	Temmerman, S. et al.	*Geology*	2007	353

3.1.2 Annual scientific production

For the thematic and temporal scope used and by means of the analysis of bibliometric data on annual scientific production, one found an annual growth rate of 8.79% per year, which is relatively significant.

From the analysis, it is clear that although the first document was published in 1972, the first significant year of scientific production in biogeomorphology was 1988, with six documents published, the highest number since the initial publication. In relation to the six 1988 studies, two were by Viles (1988a; 1988b), followed by the pieces of research of Hupp (1988), Spencer (1988), Thomas (1988), and Williams (1988).

After 1988, there was a decrease in production, with approximately 1.3 documents being published per year. There was a slight increase in academic production in 1995, when seven documents were published. Nonetheless, this peak was followed by another period of low production, between 1995 and 2002, when the average number of documents was 3.2 studies per year. The production increased again in 2002, with publication of nine studies.

Between 2002 and 2007, documents in the area began to appear at a less irregular pace and in increasingly higher numbers, and the average for the period is 6.8 studies per year. It was only from 2008 onwards, however, that there was stronger growth in biogeomorphological research, when 22 studies were published in the area, the highest number in a single year since the first occurrence of the term, in 1972. From then on, between 2008 and 2024, biogeomorphology research continued to grow, with an average of 49.47 documents per year. The most productive years and respective number of publications in the area were: 2008 - 22; 2010 - 39; 2013 - 64; 2021 - 75, and 2024 - 80 (Figure 4).

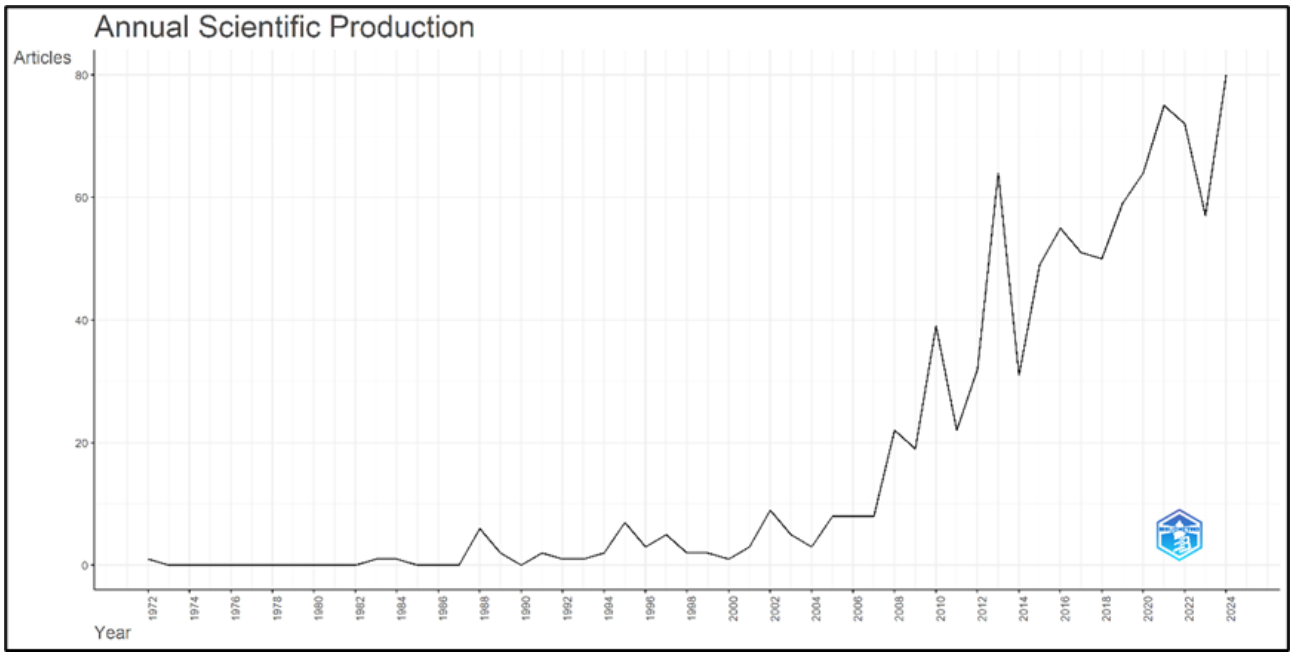

Figure 4. Annual scientific publication on biomorphology

3.1.3 Most productive authors and co-authorship networks

Considering authorship and co-authorship, the most productive authors and respective number of documents were: Tjeerd J. Bouma (Royal Netherlands Institute for Sea Research), 45; Dov Corenblit (Université de Toulouse), 41; Johannes Steiger (Université de Clermont Auvergne), 34; Stijn Temmerman (University of Antwerp), 24, and Peter M. J. Hermann (Delft University), 20.

The articles with the highest number of citations from the five authors mentioned above are presented below (Table 2), with their names highlighted on the table.

Table 2. Top 5 authors' most cited studies in the field

Type of document	Title	Authors	Journal	Year	Numbers of citations
Article	*Limits on the adaptability of coastal marshes to rising sea level*	Kirwan, M.L.; Gunterspergen, G.R.; D'Alpaos, A.; Morris, J.T.; Mudd, S.M.; **Temmerman, S**.	*Geophysical Research Letters*	2010	630
Article	*Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches A review of complementary approaches*	**Corenblit, D**.; Tabacchi, E.; **Steiger, J.**; Gurnell, A.M.	*Earth-science Reviews*	2007	595
Article	*Vegetation causes channel erosion in a tidal landscape*	**Temmerman, S**.; **Bouma, T.J.** ; Van de Koppel, J. ; Van der Wal, D. ; De Vries, M,B ; **Herman, P.M.J**.	*Geology*	2007	353

It is possible to note that, with the exception of Stijn Temmerman (4th author with the highest volume of documents available in Scopus) – who has the most cited article, with 630 citations – all the other names on the list appear as co-authors.

Thus, the most cited article by Dov Corenblit (2nd most productive author) is the same as that by Johannes Steiger (3rd most productive author), given that they are co-authors on the study. Similarly, the most cited work by Tjeerd Bouma (1st in production in the area) is connected to Peter Hermann (5th most productive author), because they co-authored the research.

It is worth noting that, from Table 2, with the exception of the research by Tjeerd Bouma (1st most productive author) and Peter Hermann (5th most productive author), the referenced study of Stijn Temmerman (2010) and that of Tjeerd Bouma and Peter Hermann (2007) also appear in the table presented in section 3.1.1. of this work, which deals with the most cited studies in Scopus for the current thematic scope. Therefore, the conclusion is that three out of the five most productive authors are also co-authors on studies present on the list of the five most cited documents in Scopus, thus guaranteeing a prominent place for their names in the current development of the discipline.

Regarding the analysis of co-authorship networks, carried out using VOSviewer, considering authors who had at least four published documents in the area and excluding those who were not related to any collaboration network, this study found 14 co-authorship networks, determined from clusters obtained during the analysis, and revealed 125 authors connected to such networks.

Of these networks, three with the highest number of studies stand out and refer to, respectively, Tjeerd Bouma (red cluster), Dov Corenblit (green cluster), and Heather Viles (beige cluster) (Figure 5).

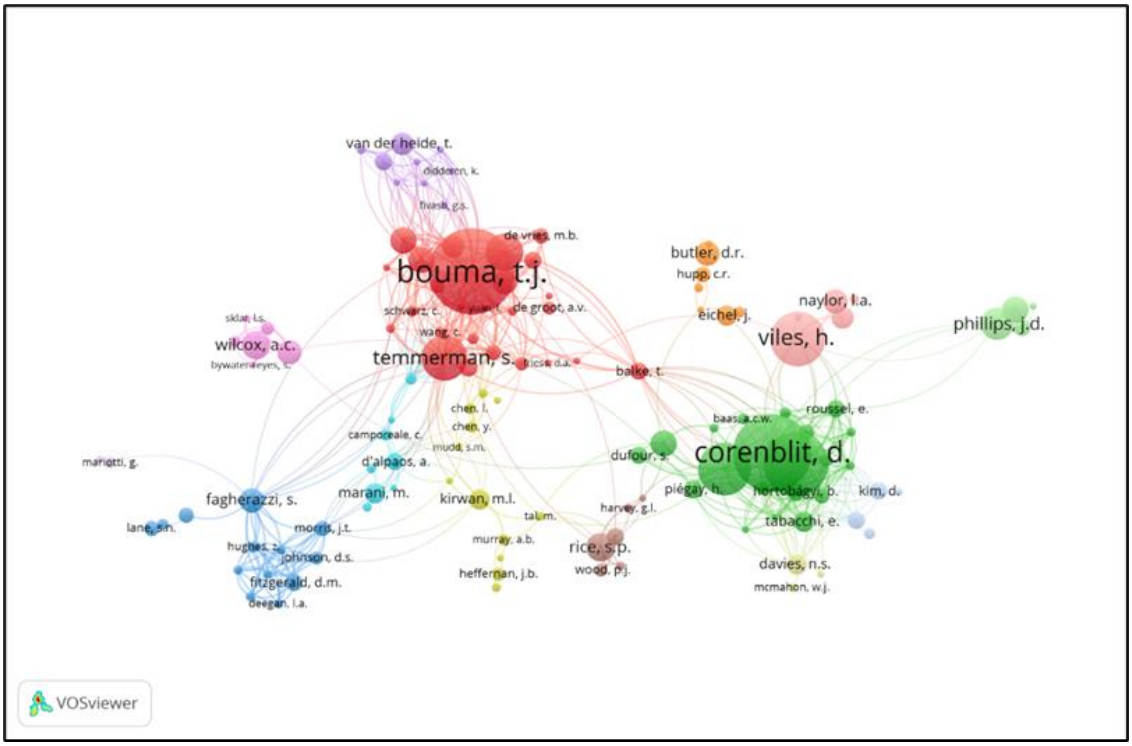

Figure 5. Co-authorship networks

Using the overlay visualization tool (Figure 6), VOSviewer allows users to understand these co-authorship networks based on their historical evolution, presenting the user with a view from the oldest to the most recent co-authorship networks, always considering a timespan of every two years.

Based on Figure 6, it can be seen that the co-authorship networks began in 2012, related to Naylor, Butler, Hupp, Osterkamp and De Vries, to name the most significant. Between 2014 and 2020, the most significant co-authorship networks of the analysis appeared, which present the majority of studies and refer to Viles, Corenblit, Bouma, Bertoldi, Temmerman, Wilcox, and Rice. From 2022 onwards, there was evolution of co-authorship networks related mainly to authors such as Van der Heide and Zhou.

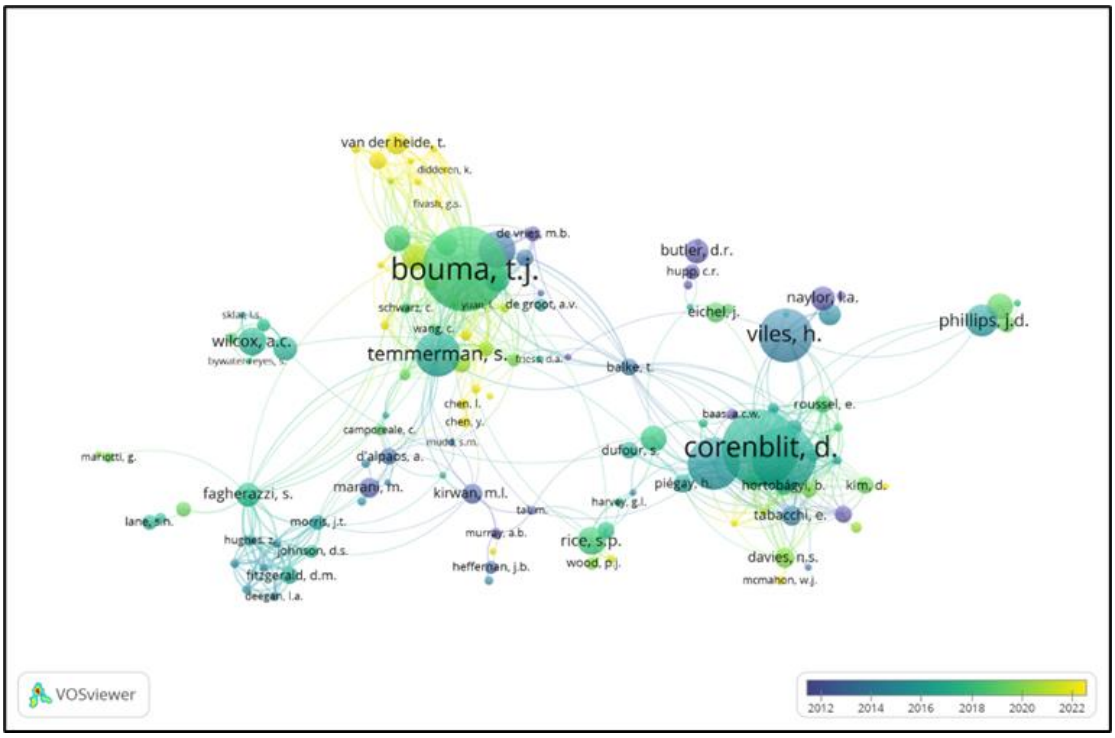

Figure 6. Historical evolution of co-authorship networks

3.1.4 Hub countries, co-authorship by country and main research institutions

According to data taken from the analysis of the Scopus database itself, considering the five countries with the majority of publications, the analysis shows that scientific production in biogeomorphology and ecogeomorphology is concentrated mainly in English-speaking countries, with 384 documents published in the United States (1st place, 41.64%), and 184 in the United Kingdom (2nd place, 19.95%). The analysis then points to the Netherlands (3rd place) and France (4th place), with 103 (11.17%) and 80 (8.67%) documents, respectively. Italy ranked fifth, with 79 publications (8.56%) (Figure 7).

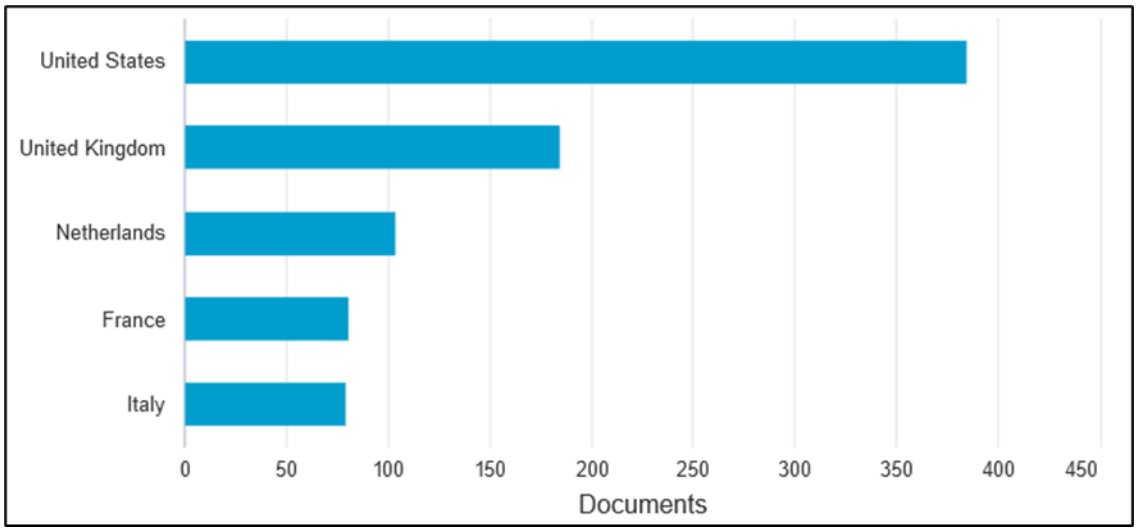

Figure 7. Biogeomorphological research-related hub countries

Co-authorship by country refers to the number of studies where a given author from a specific country is considered a co-author, and the analysis through VOSviewer found five clusters (Figure 8), where the connections between countries can be evaluated. According to this analysis, the United States (19 connections), the United Kingdom (18 connections), Italy (15 connections), the Netherlands (14 connections), and France (14 connections)

stand out. Although Italy is ranked fifth in number of documents, it has more connections compared to France and the Netherlands, nations that present more published studies, which demonstrates a more active international collaboration in Italian research.

On the other hand, there is a small variation with respect to the Total Link Strength (TLS), which serves as an index of a given country's impact on co-authorship. In spite of the United States presenting more documents and links, the studies produced in the United Kingdom have a stronger TLS in relation to that presented by the United States' studies. Thus, as for the five countries mentioned above, we have, in decreasing order: the United Kingdom (TLS=172); the United States (TLS=166); the Netherlands (TSL=111); France (TLS=92), and Italy (TLS=90).

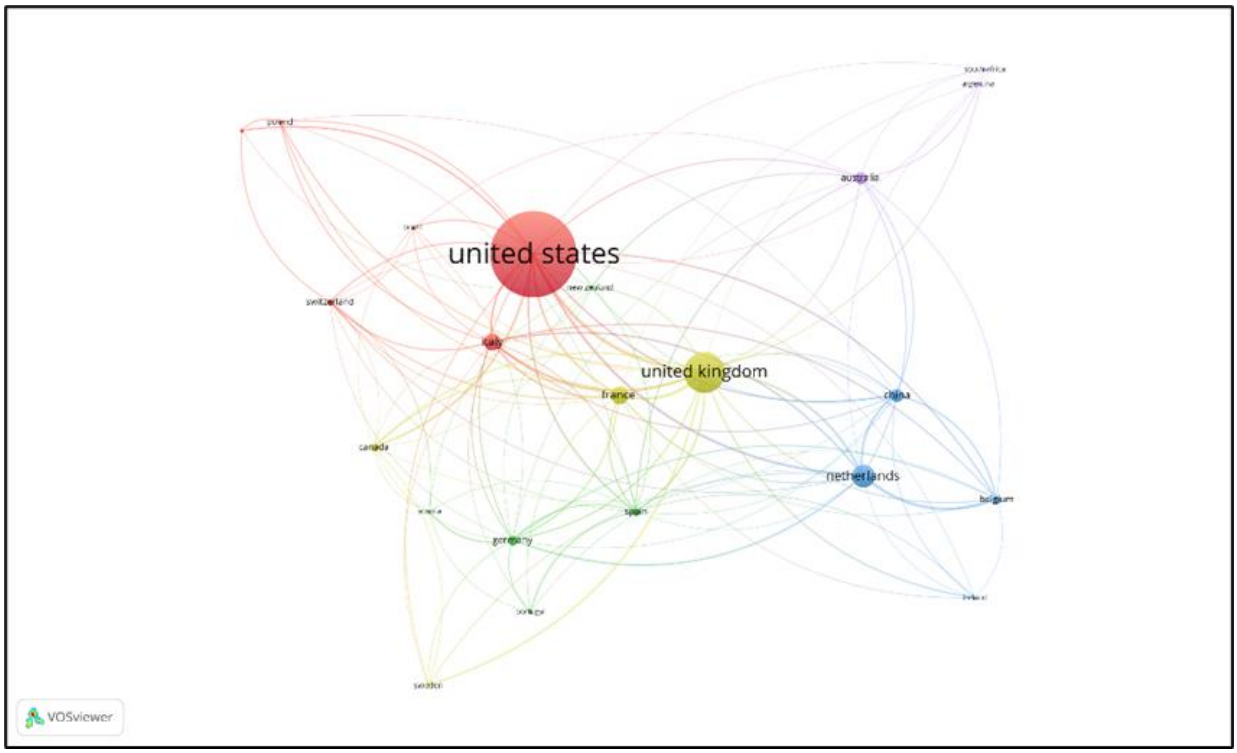

Figure 8. Co-authorship network by country

The analysis of countries necessarily leads to the question about which are the main research institutions with biogeomorphology studies (Figure 9). According to the analysis carried out by the Scopus database, the institutions with the largest number of documents are, respectively: Utrecht University, the Netherlands, 59 documents (6.39%); Royal Netherlands Institute for Sea Research (NIOZ), the Netherlands, 51 (5.53%); Centre National de la Recherche Scientifique (CNRS), France, 47 (5.09%); United States Geological Survey (USGS), the United States, 43 (4.66%), and Laboratoire de Géographie Physique et Environnementale, Université Clermont Auvergne, France, 41 (4.44%).

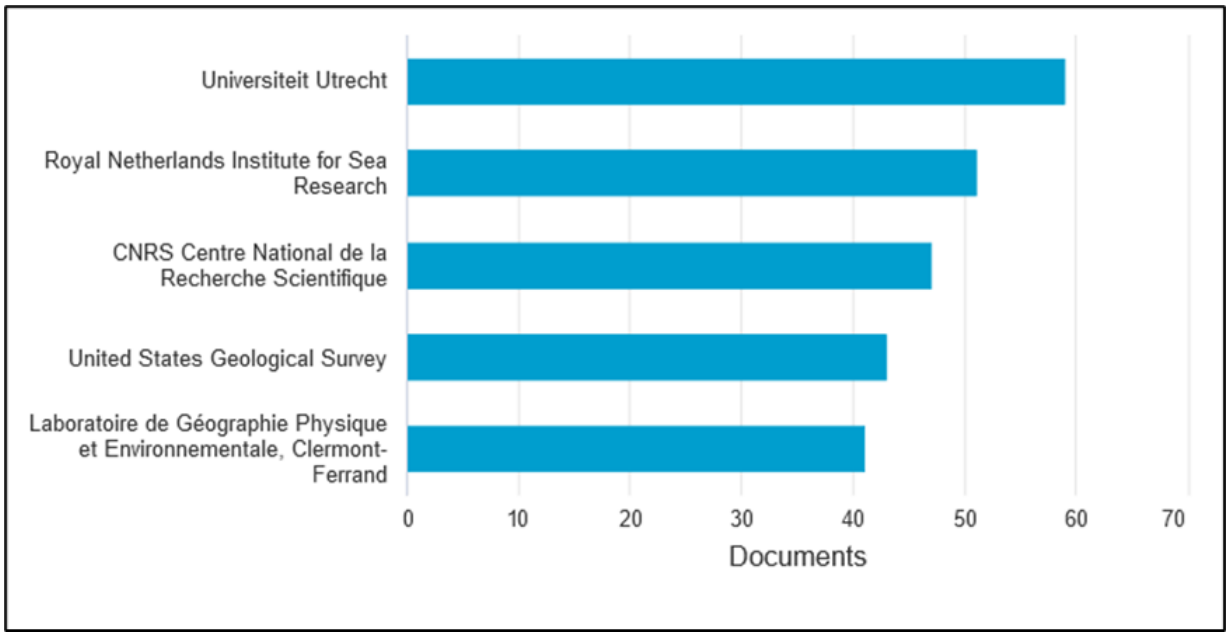

Figure 9. Main research institutions on biogeomorphology

It can therefore be concluded that, although countries such as the United States and the United Kingdom have more published studies, the main research institutions on biogeomorphology are currently located in the Netherlands (Utrecht University and NOIZ) and in France (CNRS and Université Clermont Auvergne). This is in line with the conclusions made in section 3.1.3, where four out of the five most productive authors are affiliated with sometimes Dutch (Bouma, Hermann) and sometimes French (Corenblit, Steiger) academic-scientific contexts.

In relation to the main institutions mentioned above, and in decreasing order considering the total number of citations, the most cited documents (Table 3) are authored by: Kirwan et al. (2010), affiliated with USGS, 630 citations; Corenblit et al. (2007), affiliated with CNRS and with Laboratoire de Géographie Physique et Environnementale, 595; Balke et al. (2014), affiliated with NOIZ, 241, and Temmink et al. (2022), affiliated with Utrecht University, 158.

Table 3. Main studies by research institution

Type of document	Title	Authors	Journal	Year	Affiliation	Numbers of citations
Article	*Limits on the adaptability of costal marshes to rising sea level*	Kirwan L. et al.	*Geophysical Research Letters*	2010	***United Geological Survey***	630
Article	*Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches A review of complementary approaches*	Corenblit et al.	*Earth-science Reviews*	2007	***CNRS*** and ***Laboratoire de Géographie Physique et Environnementale***	595
Article	*Critical transitions in disturbance-driven ecosystems: Identifying*	Balke et al.	*Journal of Ecology*	2014	***Royal Netherlands Institute for Sea Research***	241

	windows of opportunity for recovery					
Article	*Recovering wetland biogeomorphic feedbacks to restore the world's biotic carbon hotspots*	Temmink et al.	*Science*	2022	***Universiteit Utrecht***	158

3.1.5. Main bibliographic sources

Using Excel, one performed an analysis of the five journals with the majority of publications on biogeomorphology (Figure 10). The analysis showed the following journals with their respective publications: Geomorphology, 108 (11.71%); Earth Surface Processes and Landforms, 107 (11.60%); River Research And Applications, 32 (3.47%); Journal of Geophysical Research: Earth Surface, 31 (3.36%), and Science of the Total Environment, 24 (2.60%).

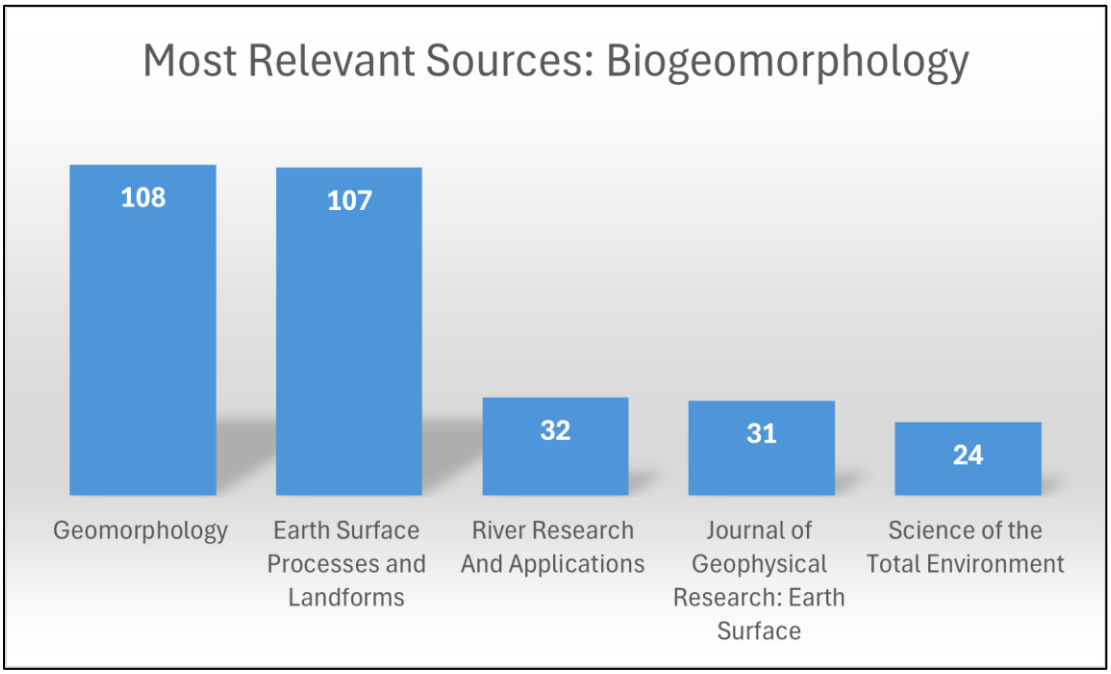

Figure 10. Number of studies in the main biogeomorphology-related bibliographic sources

The Geomorphology journal is the bibliographic source with the oldest publications, dating back to 1995, when the journal published five papers in the area. Since then, the number of publications in this journal continued to grow, and in the second half of the 1990s it published the majority of papers in the area, which continues to this day. On the other hand, Earth Surface Processes and Landforms, the 2nd journal with the majority of publications in the area, only began to present a significant number of publications in the second half of the 2000s.

In fact, the same could be said for most of the bibliographic sources listed: although many journals published papers in biogeomorphology in the second half of the 1990s, graphical analysis shows that biogeomorphological production in general only began to grow around the second half of the 2000s (2005 to 2010).

The analysis of the most cited documents listed in this research seems to highlight this fact even more: the most cited documents were published between dates close to the second half of the 1990s and the first decade of the 2000s. Figure 11, generated from Scopus analysis, shows the historical number of publications of the five journals with the highest number of publications.

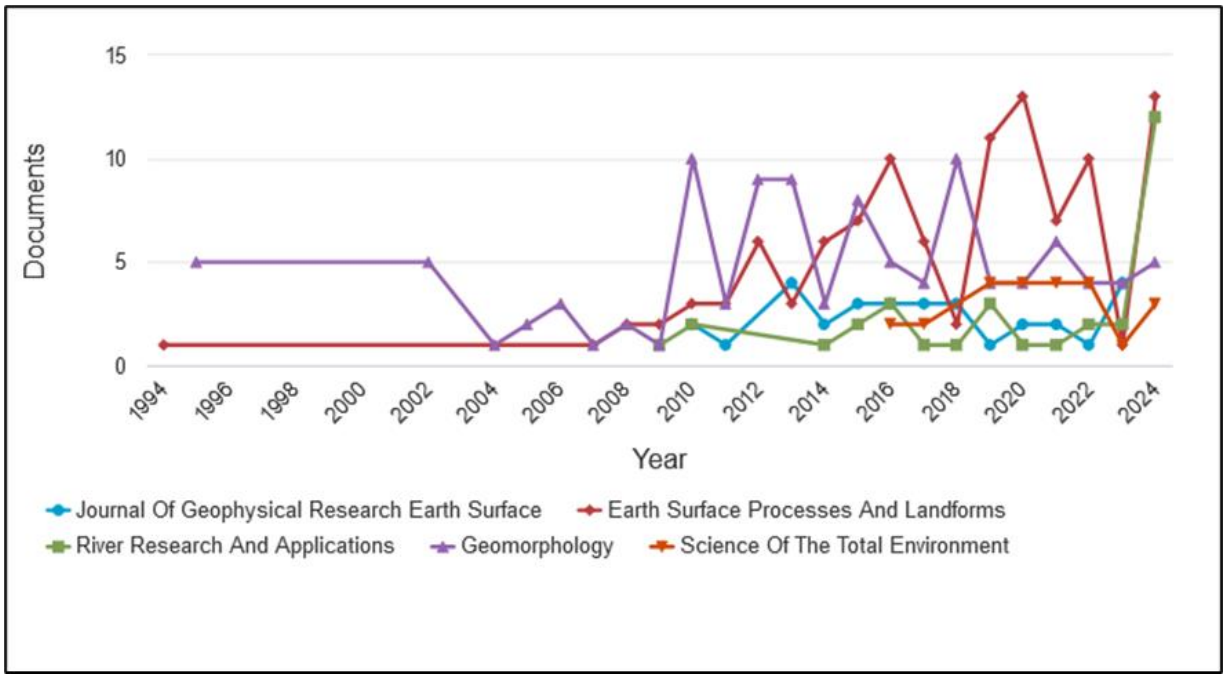

Figure 11. Historical production of the main periodicals

3.1.6 Analysis of co-occurrence of keywords

The analysis of co-occurrence of keywords (Figure 12), performed using VOSviewer, and filtering by words that occurred at least 15 times, showed 144 words presented in six distinct clusters.

Among the highlighted words, the 10 most cited were: *biogeomorphology*, 329 occurrences; *geomorphology*, 285 occurrences; *vegetation*, 196 occurrences; *United States*, 147 occurrences; *sediment transport*, 127 occurrences; *fluvial geomorphology*, 108 occurrences; *ecogeomorphology*, 103 occurrences; *rivers*, 87 occurrences; *riparian vegetation*, 86 occurrences, and climate change, 85 occurrences.

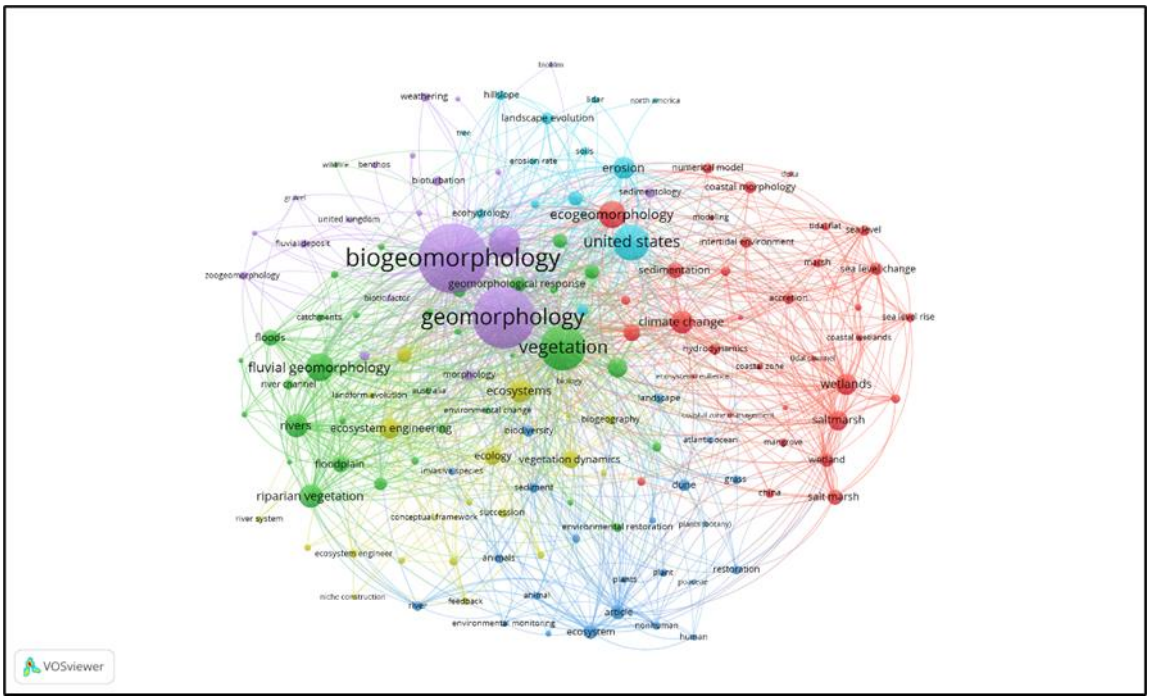

Figure 12. Co-occurrence of keywords in biogeomorphology

From the data analysis, it is clear that biogeomorphological research is organized much more according to the environments it investigates than in relation to the classic division based on the biotic kingdom, phytogeomorphology (*plantae*) or zoogeomorphology (*animalia*). Likewise, it is noted that some environments are areas of study that receive a greater focus in scientific research, especially fluvial and coastal/marine environments.

Also from the occurrence of keywords, it is clear that there is still a predominance of biogeomorphological studies in relation to the interactions between geomorphological processes and environments and vegetation, especially in fluvial systems. The term *vegetation*, as previously mentioned, is the 3rd most frequently used, with 196 occurrences; *riparian vegetation*, in turn, appeared 86 times in the analysis performed. This indicates that the interaction between plant life forms and geomorphological processes is already a consolidated object of study in biogeomorphological science.

On the other hand, there is decreased focus on zoogeomorphological studies, where geomorphological processes are associated with the animal kingdom, an area that has only recently begun to receive more attention, although studies such as those by David Butler (1995) were written at the end of the last century. The analysis made by VOSviewer indicates that the term *zoogeomorphology* began to be used more frequently especially from 2018 onwards, which demonstrates that today zoogeomorphology is an area of interest.

3.2. Specificities of academic-scientific production by geomorphological environments

3.2.1 Total numbers by geomorphological environments

Of the 922 studies listed in this work, 756 documents (81% of the total) are associated with those three geomorphological environments and distributed across 285 sources.

Classified by type, the studies on coastal or marine biogeomorphology – 291 publications (Figure 13) –, are divided into: 244 articles in periodicals (83.8%); 22 reviews (7.5%); 12 book chapters (4.1%); 11 conference abstracts (3.7%); one editorial document (0.3%), and one erratum (0.3%). The studies refer to 963 authors, across 122 sources. The average number of authors per work was 4.87. The annual growth rate was 8.59%. The international co-authorship rate, which will be analyzed in more detail below, was 35.74%. Therefore, a little over (1/3) of the total listed documents present international co-authorship.

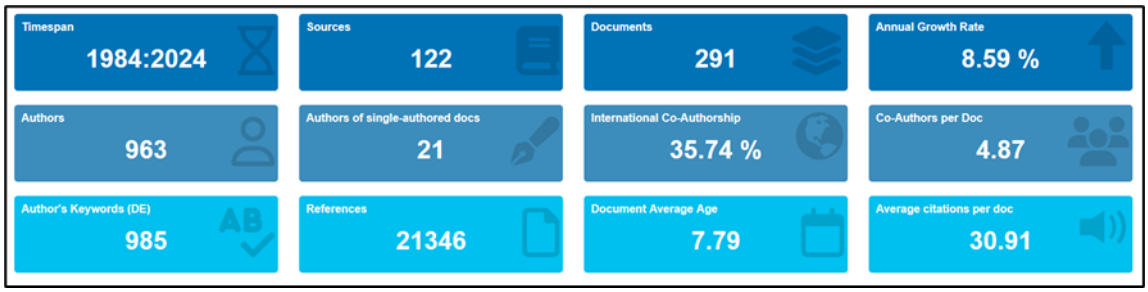

Figure 13. Total numbers in coastal and marine biogeomorphology

In coastal and marine biogeomorphology, regarding the five most cited documents (Table 4), one listed four articles in academic journals and one review. The article by Kirwan et al. (2010), published in Geophysical Research Letters, stands out in the field and in biogeomorphology as a whole, with 631 citations. Next we have the review by Day et al. (2008) and the article by Ravai et al. (2008), with 277 and 240 citations, respectively; ranked forth, the article by Collins et al. (2012) also with 240 citations, and with 208 citations, another article by Kirwan et al. (2012).

Table 4. Main publications on coastal and marine biomorphology

Type of document	Title	Authors	Journal	Year	Numbers of citations
Article	*Limits on the adaptability of coastal marshes to rising sea level*	Kirwan L. et al.	*Geophysical Research Letters*	2010	631
Review	*Consequences of climate change on the ecogeomorphology of coastal wetlands*	Day et al.	*Estuaries and Coasts*	2008	277
Article	*Global controls on carbon storage in mangrove soils*	Rovai et al.	*Nature and Climate Change*	2018	240
Article	*The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific Costal region*	Collins et al.	*Geomorpholohy*	2012	240
Article	*Feedbacks between inundation, root production, and growth in a rapidly submerging brackish marsh*	Kirwan; Gunterspergen	*Journal of Ecology*	2012	208

In relation to biogeomorphological studies on fluvial environments (Figure 14), 357 documents were retrieved, divided into: 272 articles in academic periodicals (72.19%); 28 reviews (7.84%); 27 book chapters (7.56%); 22 studies in conference and congress proceedings (6.16%); four editorials (1.12%); two notes (0.56%); one book (0.28%), and one erratum (0.28%). The studies refer to 983 authors, with an average of 4.3 authors per document, across 115 bibliographic sources. The annual growth rate was 13.08%, indicating that fluvial biogeomorphology is the fastest growing research area in the context of biogeomorphological studies.

Figure 14. Total numbers in fluvial biogeomorphology

The five most cited fluvial biogeomorphological pieces of research (Table 5) were the following: Corenblit et al. (2007) and Temmerman et al. (2007), 595 and 355 citations, respectively; Davies and Gibling (2010), 275 citations; Fetherston et al. (1995), 255 citations, and Balke et al. (2014), 242 citations. It is worth noting that Tjeerd Bouma, one of the main authors in coastal biogeomorphology, appears as a co-author in two out of the five most cited studies that had fluvial environments as their spatial focus, which highlights the scope of Bouma's research in biogeomorphology.

Table 5. Main studies on fluvial biogeomorphology

Type of document	Title	Authors	Journal	Year	Numbers of citations
Article	*Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches*	Corenblit et al.	*Earth-science Reviews*	2007	595
Article	*Vegetation causes channel erosion in a tidal landscape*	Temmerman et al.	*Geology*	2007	355
Review	*Cambrian to Devonian evolution of alluvial systems: the sedimentological impact of the earliest land plants*	Davies; Gibling	*Earth-science Reviews*	2010	275
Article	*Large wood debris, Physical process, and riparian forest development in montane river networks of the Pacific Northwest*	Fetherston et al.	*Geomorphology*	1995	255
Article	*Critical transitions in disturbance-driven ecosystems: Identifying windows of opportunity for recovery*	Balke et al.	*Journal of Ecology*	2014	242

With respect to biogeomorphological studies on hillside environments, 108 publications were retrieved (Figure 15), divided into: 94 articles in academic periodicals (87.03%); 9 reviews (8.33%); 3 book chapters (2.85%), and 2 abstracts in conference and congress proceedings (1.90%). The studies refer to 309 authors, with an average of 3.55 authors per publication, and are found across 48 bibliographic sources, with an estimated growth rate of 6.94% per year.

Figure 15. Total numbers in hillslope biogeomorphology

As for the five most cited publications in the area of hillslopes (Table 6), the following stand out: Lavee et al. (1998), 274 citations; Fetherston et al. (1995) and Vandenbruwaene et al. (2011), 255 and 172 citations, respectively; Viles et al. (2008), 161 citations, and Marston (2010), 159 citations.

Table 6. Main studies on hillslope biogeomorphology

Type of document	Title	Authors	Journal	Year	Numbers of citations
Article	*The impact of climate change on Geomorpholohy and desertification along a Mediterranean-arid transect*	Lavee et al.	*Land Degradation and Development*	1998	274
Article	*Large woody debris, Physical process, and riparian forest development in montane river networks of the Pacific Northwest*	Fetherston et al.	*Geomorphology*	1995	255
Article	*Flow interaction with dynamic vegetation patches: Implications for biogeomorphic evolution of a tidal landscape*	Vandenbruwaene et al.	*Journal of Geophysical Research: Earth Surface*	2011	172
Article	*Biogeomorphological disturbance regimes: Progress in linking ecological and geomorphological systems*	Viles et al.	*Earth Surface Processes and Landforms*	2008	161
Article	*Geomorphology and vegetation: Interactions, dependencies, and feedbacks loops*	Marston	*Geomorphology*	2010	159

3.2.2 Annual scientific production

The analysis of annual scientific production in relation to thematic sub-areas showed that for coastal and marine biogeomorphology, the annual growth rate was 8.59% (Figure 16).

The oldest occurrence listed points to the article by Babikir (1984), from the Qatar University, published in the GeoJournal, entitled *Vegetation and environment on the coastal sand dunes and playas of Khor El-Odaid area, Qatar*. However, after the publication of this article there was a four-year hiatus, and then two articles were published in 1988, the studies by Spencer (1988) and Viles (1988b). Between 1989 and 2001, scientific production in the area decreased, not exceeding an average of 0.3 articles per year. In 2002, 3 articles were published, the highest number since the first publication. Nevertheless, between 2002 and 2007, academic production declined again, to be resumed in 2008, when 7 articles were published. The production in the area increased between 2008 and 2024, with approximately 17 articles being published per year. The year 2021 had the highest number of publications, 31 articles.

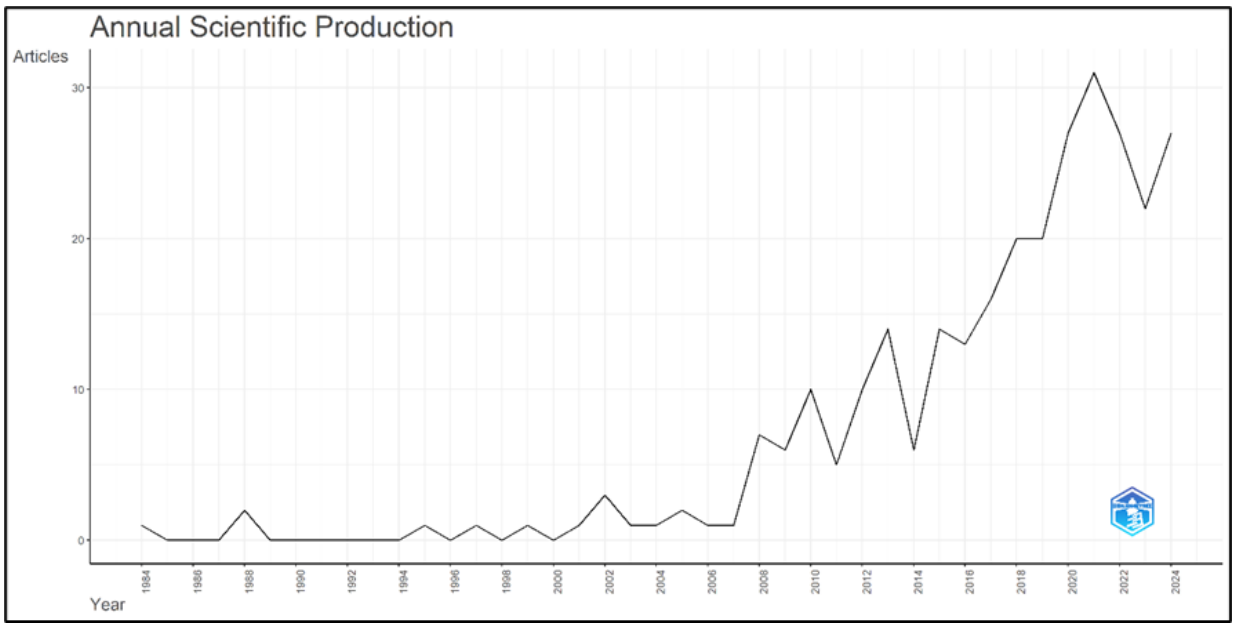

Figure 16. Annual scientific production on coastal and marine biogeomorphology

Biogeomorphological studies on fluvial environments (Figure 17) presented an annual growth rate of 13.08%, 4.49% higher than that of studies on coastal and marine environments, drawing attention to studies on such environments in the discipline.

The oldest study listed is that by Trimble (1995), published in the Earth Surface Processes and Landforms journal, and deals with the erosive effects of cattle on riverbanks. The production in the area was not very significant between 1994 and 2007, with an average of 1.6 publications per year. In 2008, however, 10 studies were published, a year that marked the beginning of growth in the discipline, albeit markedly irregular. On the other hand, in the 15 years between 2008 and 2023, the expressive amount of 19.7 studies per year were published. In 2024, the limit year of the timespan analyzed, was the period with the majority of publications – 40 studies –, which demonstrates the current research on fluvial environments.

The analysis of the publication years thus shows a growth of 97.5% in 30 years (1994-2024), with an annual growth rate of 13.08%, which allows estimating an ever-increasing growth in the discipline. This is an expressive number, demonstrating that fluvial environments are the predominant focus in biogeomorphology.

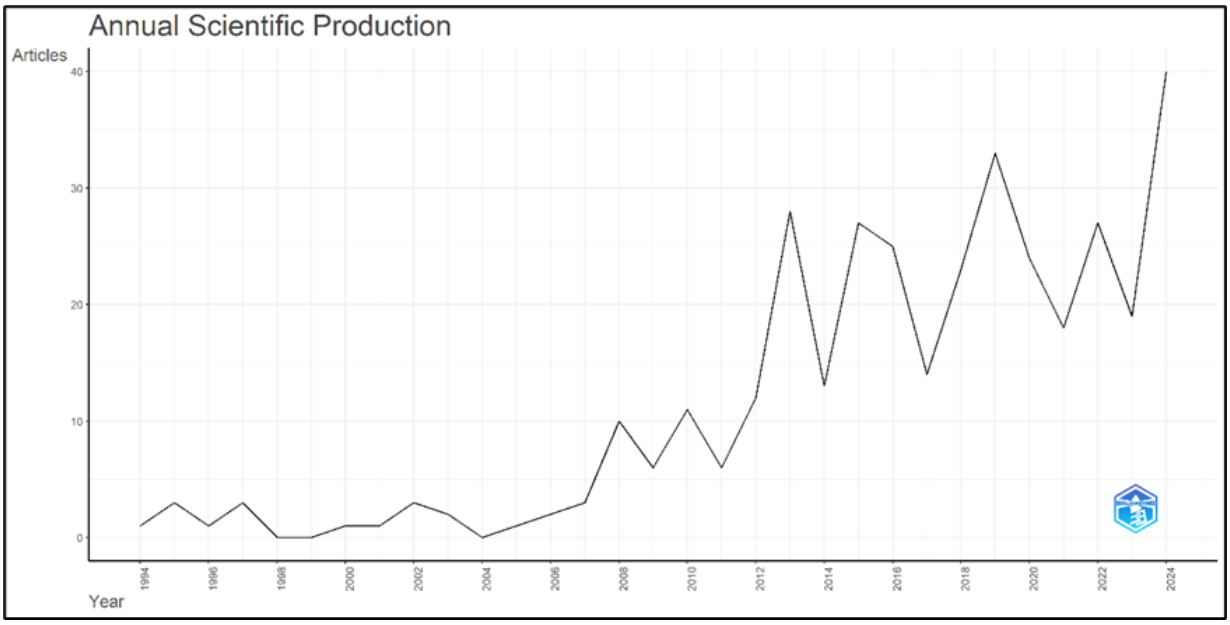

Figure 17. Annual scientific production on fluvial biogeomorphology

The annual growth rate of scientific production on hillslope biogeomorphology (Figure 18) was 6.94%, 1.65% lower than that of studies on coastal and marine environments, with a marked difference of 6.14% in relation to fluvial biogeomorphological studies.

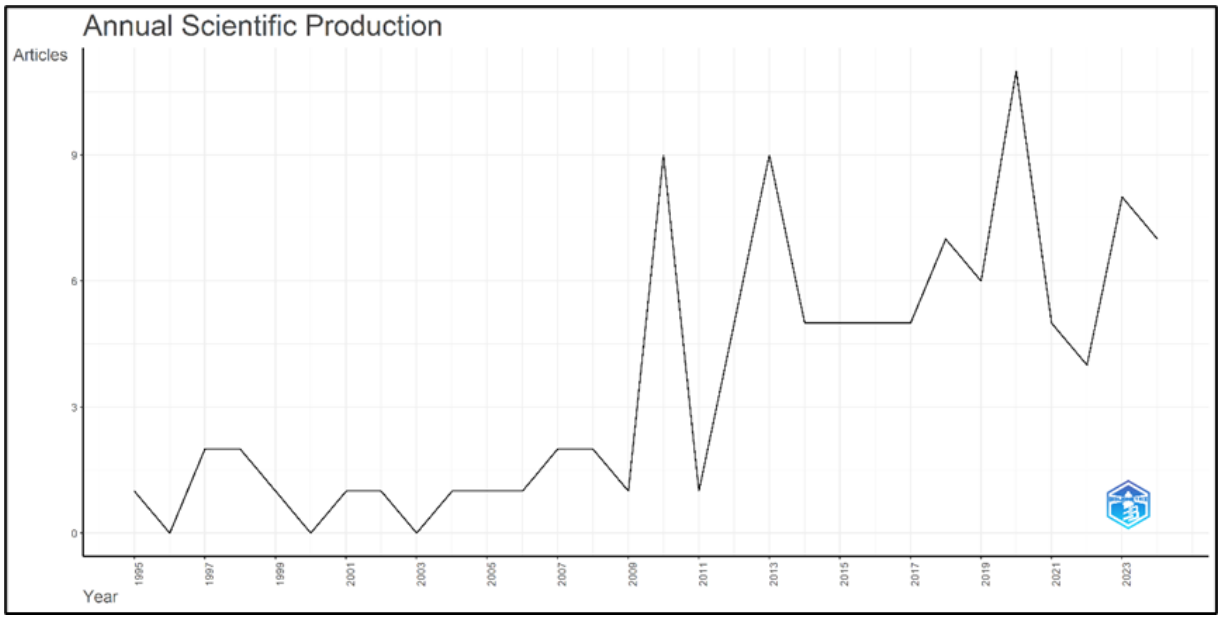

Figure 18. Annual scientific production on hillslope biogeomorphology

The oldest study listed is by Fetherston et al. (1995), published in the Geomorphology journal, and deals with the physical processes involving woody debris in mountain river systems. Between 1995 and 2009, the production in the area was low but continuous, with an average of 1.06 publications per year. In 2010, however, there was an increase in the number of publications, and 9 papers were published. From 2010 onwards, academic production increased, but the graph still shows ups and downs in marked imbalances. Between 2010 and 2024, the average

number of publications was 6.57 papers per year. Among the historical series analyzed, the year with the highest number of publications was 2020, with 11 documents published.

3.2.3. Most productive authors and co-authorship networks

In relation to the most productive authors, their most cited pieces of research, and the co-authorship networks in which they are included, the following stand out: in coastal and marine biogeomorphology, Tjeerd Bouma (Royal Netherlands Institute for Sea Research), 26 documents; Larissa Naylor (University of Glasgow), 11 documents; Peter M.J. Hermann (Delf University of Technology), 10 documents; Tjisse Van der Heide (University of Groningen), 10 documents, and Bas W. Borsje (University of Twente), 9 documents.

The five most cited studies (Table 7) are: Temmink et al. (2022), 163 citations; Viles et al. (2008), 161 citations; Reed et al. (2018), 76 citations; Hu et al. (2021), com 51 citations, and Willemsen et al. (2018), 43 citations. The analysis of the documents shows that Tjeerd Bouma appears as a co-author in three out of the five listed studies, a 60% occurrence among the studies listed. Bas W. Borsje also stands out, appearing as a co-author in two out of the five studies, with a 40% occurrence.

Table 7. Most relevant authors and their most cited studies on coastal and marine biogeomorphology

Type of document	Title	Authors	Journal	Year	Numbers of citations
Review	*Recovering wetland biogeomorphic feedbacks to restore the world's carbon hotspots*	Temmink; Lamers; Angelini; **Bouma**; Fritz; Koppel; Lexmond; Rietkerk; Silliman; **Van der Heide**	*Science*	2022	163
Article	*Biogeomorphological disturbance regimes: Progress in linking ecological and geomorphological systems*	Viles; **Naylor**, Carter; Chaput	*Earth Surface Processes and Landforms*	2008	161
Review	*Tidal flat-wetland systems as flood defenses: Understanding biogeomorphic feedbacks*	Reed; Wesenback; **Herman**; Meselhe	*Estuarine, Coastal and Shelf Science*	2018	76
Article	*Mechanistic Modeling of Marsh Seedling Outlook for Coastal Wetland Restoration Under Global Climate Change*	Hu; **Borsje**; Belzen; Pim; Willemsen; Wang; Peng; Dominics; Wolf; Stijn; **Bouma**	*Geophysical Research Letters*	2021	51
Article	*Quantifying Bed Level Change at the Transition of Tidal Flat and Salt Marshe: Can We Understand the lateral Location of Marshe Edge?*	Willemsen; **Borsje**; **Hulscher**; Van der Wal; Zhu; Evans; Moller; **Bouma**	*Journal of Geophysical Research: Earth Surface*	2018	43

The analysis of the co-authorship networks in the coastal area (Figure 19) indicates the existence of three clusters. The first cluster refers to Matthew Kirwan, with seven co-authored documents. Next, there is the cluster associated with Tjeerd Bouma, with 21 co-authored studies, standing out as the most productive author in the area. The third cluster refers to Tjisse Van der Heide, with 10 co-authored studies.

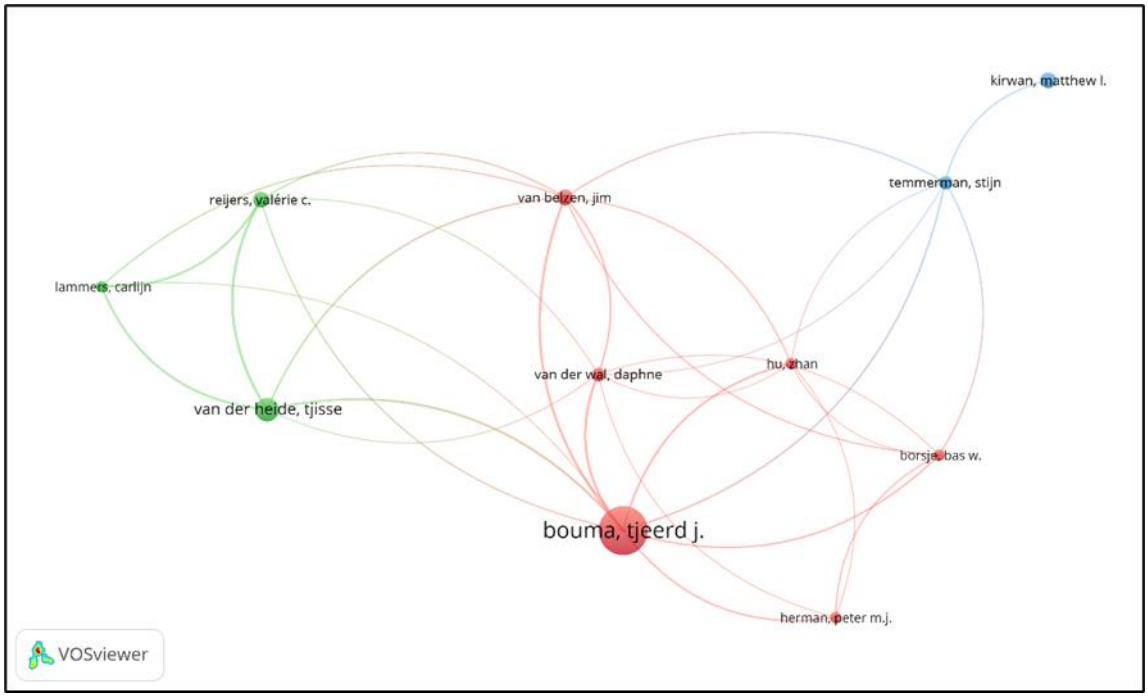

Figure 19. Coastal and marine biogeomorphology-related co-authorship networks

In fluvial biogeomorphology, the most productive authors include: Dov Corenblit (CNRS/Université Toulouse), studies; J. Steiger (CNRS/ Université Clermont Auvergne), 27 studies; Angela Gurnell (Queen Mary University of London), 17 studies; Stephen Rice (Manchester Metropolitan University), 15 studies, and Walter Bertoldi (University of Trento), 14 studies.

Considering studies where one or more authors appear as co-authors, three studies were listed (Table 8), in ascending order according to the number of citations: Corenblit et al. (2007), 595 citations; Bertoldi et al. (2009), 135 citations, and Harvey et al. (2011), 61 citations. The connections are as follows: Corenblit, Steiger, and Gurnell appear as coauthors in the most cited study (Corenblit et al., 2007); Bertoldi and Gurnell are coauthors in the second most cited study (Bertoldi et al., 2007), and Rice appears as coauthor in the third most cited study (Harvey et al., 2011).

Table 8. Most relevant authors and their most cited studies on fluvial biogeomorphology

Type of document	Title	Authors	Journal	Year	Numbers of citations
Article	*Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in rivers corridors: a review of complementary approaches*	Corenblit et al.	*Earth-Science Reviews*	2007	595
Article	*Understanding reference processes: linkages between river flows, sediment dynamics and vegetated landforms along the Tagliamento River, Italy*	Bertoldi et al.	*River Research Applications*	2009	135

Article	*Evaluating the role of invasive aquatic species as drivers of fine sediment-related river management problems: the case of the signal crayfish (Pacifastacus leniuschulus)*	Harvey et al.	*Progress in Physical Geography*	2011	61

The analysis by VOSviewer of the co-authorship networks related to fluvial biogeomorphology showed the existence of 4 clusters (Figure 20). The first cluster refers to Dov Corenblit, with 27 co-authored studies, and Johannes Steiger, with 24 co-authored documents. The second cluster relate to Angela Gurnell, with 12 co-authored documents. The third and fourth clusters concern, respectively, John Stella, with 10 co-authored studies, and Hervé Piégay, with 9 documents.

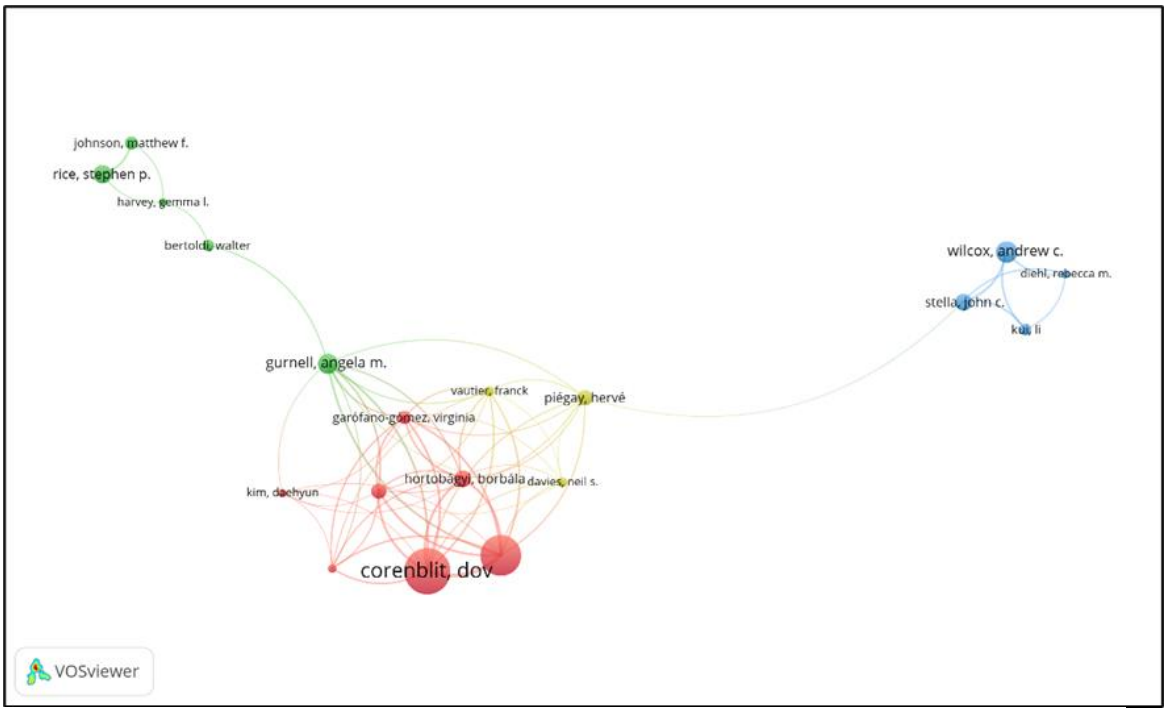

Figure 20. Fluvial biogeomorphology-related co-authorship networks

In hillslope biogeomorphology, the following authors are cited: Pavel Šamonil (Mendel University/The Silva Tarouca Research Institute), 10 publications; Jonathan Phillips (University of Kentucky), 8 publications; Pavel Daněk (The Silva Tarouca Research Institute), 7 publications; Jana Eichel (Utrecht University), 7 publications, and Łukasz Pawlik (University of Silesia /The Silva Tarouca Research Institute), 7 publications.

As for the five studies that stand out, with or without co-authorship (Table 9), the following are cited, according to the number of citations: Pawlik et al. (2016), 125; Eichel et al. (2016), 91, and Phillips et al. (2017), 56. Of the three documents listed, Pawlik, Phillips and Šamonil appear in two of them as co-authors; Eichel appears in one, in the second most cited study. Daněk appears in the study with the lowest number of citations among the three listed, in co-authorship with Pawlik, Phillips and Šamonil.

Table 9. Most relevant authors and their most cited studies on hillslope biogeomorphology

Type of document	Title	Authors	Journal	Year	Numbers of citations
Review	*Roots, rock and regolith: Biomechanical and Biochemical weathering by trees and its impact on hillslopes – A critical literature review*	**Pawlik; Phillips; Samonil.**	*Earth-science Reviews*	2016	125
Article	*Conditions for feedbacks between geomorphic and vegetation dynamics on lateral moraine slopes: A biogeomorphic feedback window*	**Eichel** et al.	*Earth Surface Processes And Landforms*	2016	91
Article	*Domination of hillslope denudation by tree uprooting in a old-growth forest*	**Phillips**; **Samonil**; **Pawlik**; Trochta; **Danek**	*Geomorphology*	2017	56

Regarding the co-authored studies on hillslope environments (Figure 21), filtering by those authors with a minimum number of five documents, and excluding those that do not have co-authored documents, a single cluster was reached, represented by the following authors: Šamonil, nine documents; Phillips, seven documents; Pawlik, seven documents; and Daněk, six documents.

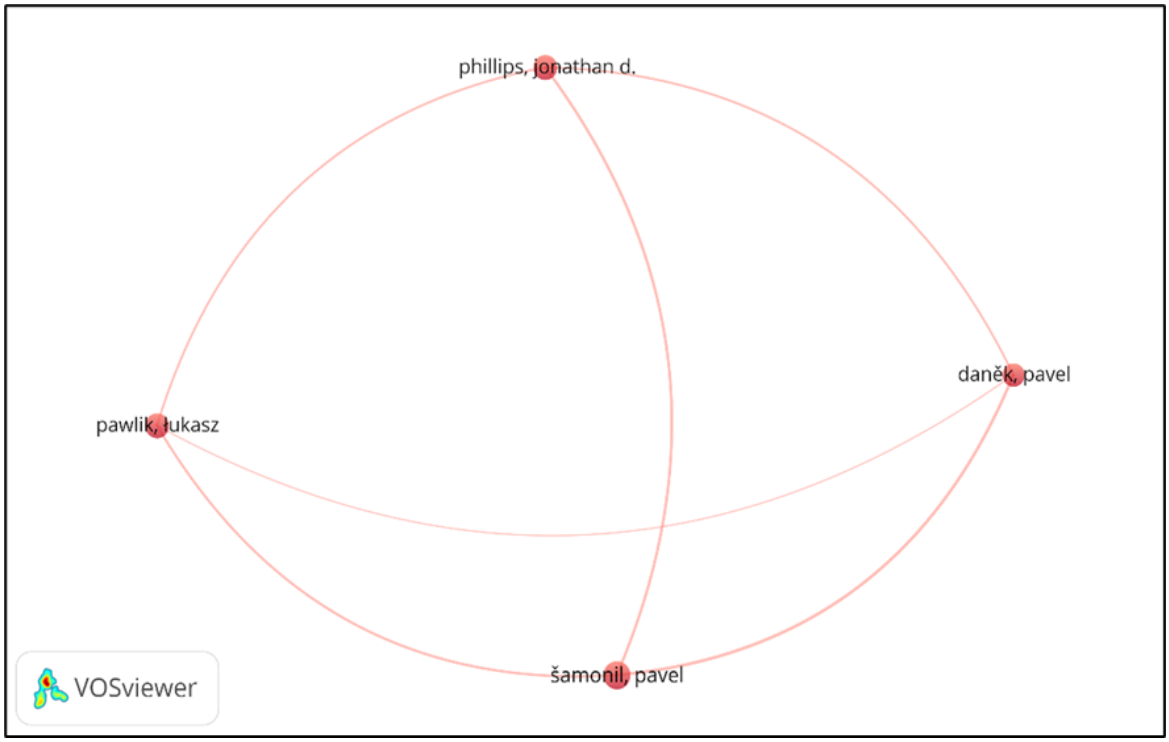

Figure 21. Hillslope biogeomorphology-related co-authorship networks

3.2.4. Hub countries, co-authorship by countries and main institutions

The following hub countries and main research institutions on biogeomorphology stand out: in coastal and marine biogeomorphology (Figure 22), the United States, 121 documents (41.58%); the United Kingdom, 59 documents (20.27%); the Netherlands, 54 documents (18.55%); Italy, 34 documents (11.68%), and China, 25 documents (8.59%).

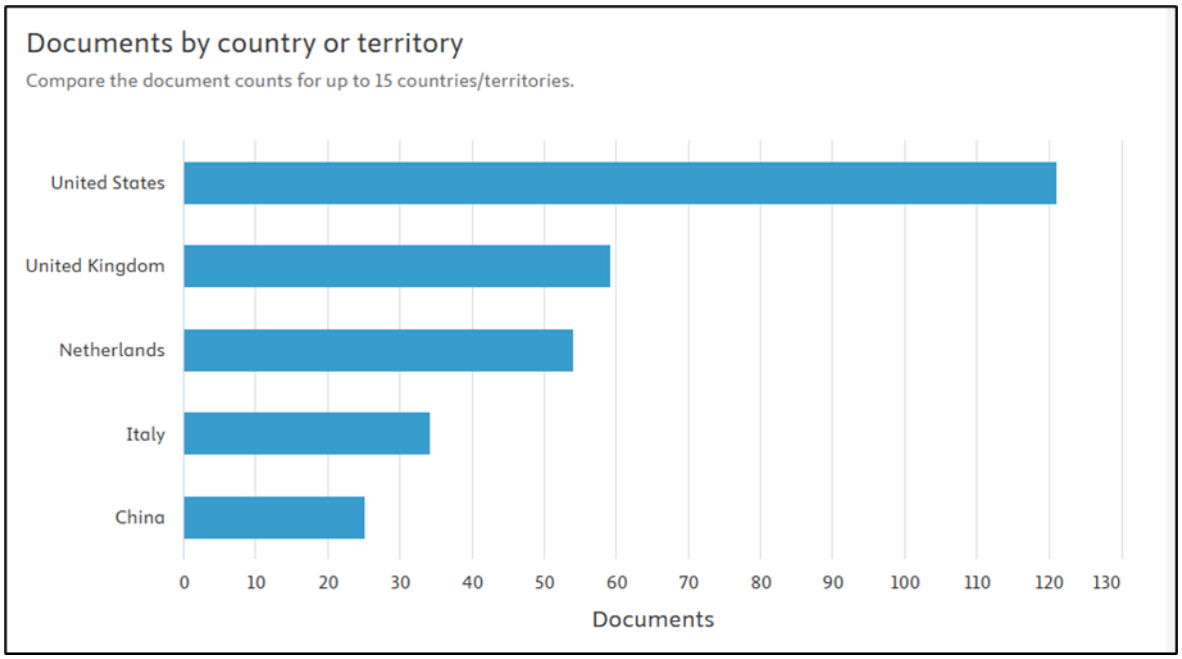

Figure 22. Coastal and marine biogeomorphology-related hub countries

Analysis of co-authorship by country, carried out using VOSviewer, showed the existence of 4 clusters (Figure 23). The first cluster has the United States as its main country, with 121 documents (TSL=53); in the second cluster, the United Kingdom is highlighted, with 58 documents (TLS=46); the third cluster features the Netherlands, with 54 papers (TSL=53), and in the fourth cluster, China stands out, with 25 documents (TSL=23).

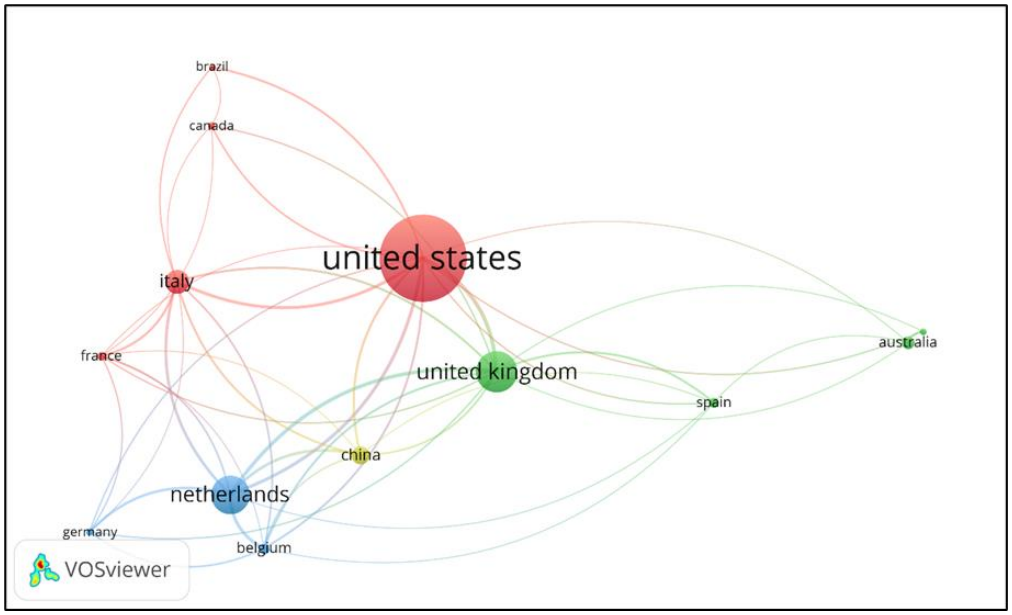

Figure 23. Coastal and marine biogeomorphology-related co-authorship networks by country

In relation to the main research institutions on coastal and marine biogeomorphological environments (Figure 24), the following are cited: Utrecht University, the Netherlands, 35 documents; the Royal Netherlands Institute for Sea Research, the Netherlands, 33 documents; the United States Geological Survey, United States, 18 documents; University of Groningen, the Netherlands, 16 documents, and Deltares, the Netherlands, 16 documents. Dutch research institutions stand out, appearing four times in the institution analysis, representing 80%.

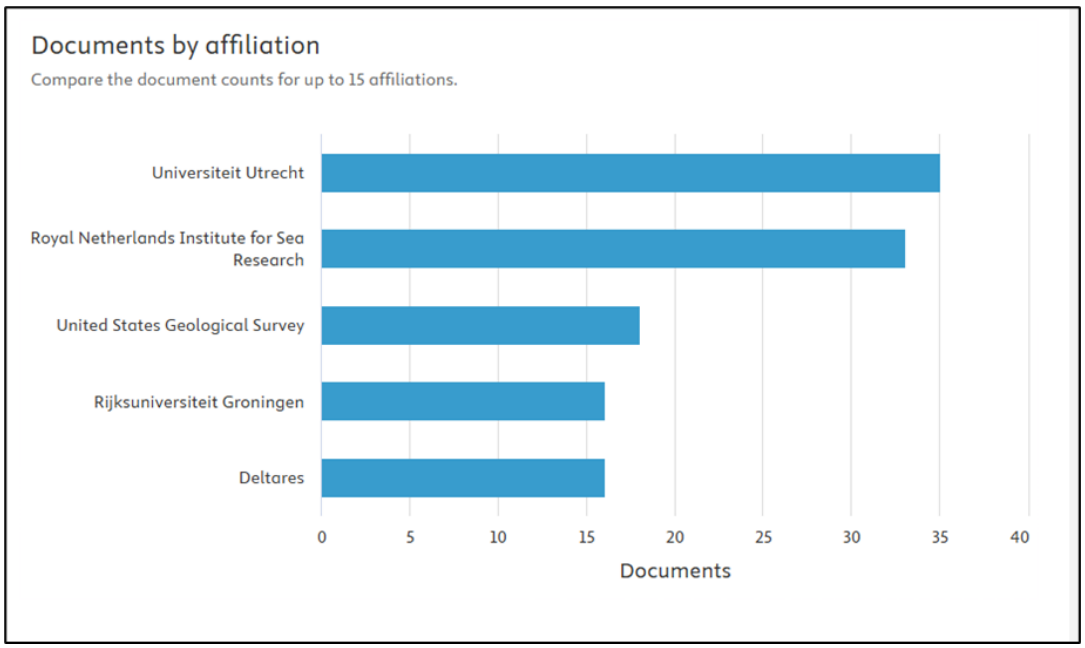

Figure 24. Main research institutions on coastal and marine biogeomorphology

In fluvial biogeomorphology (Figure 25), the following are the main research hubs countries in the area: the United States, 158 documents (44.25%); the United Kingdom, 84 studies (23.52%); France, 53 studies (14.84%); Italy, 32 documents (8.96%), and Canada, 22 studies (6.16%).

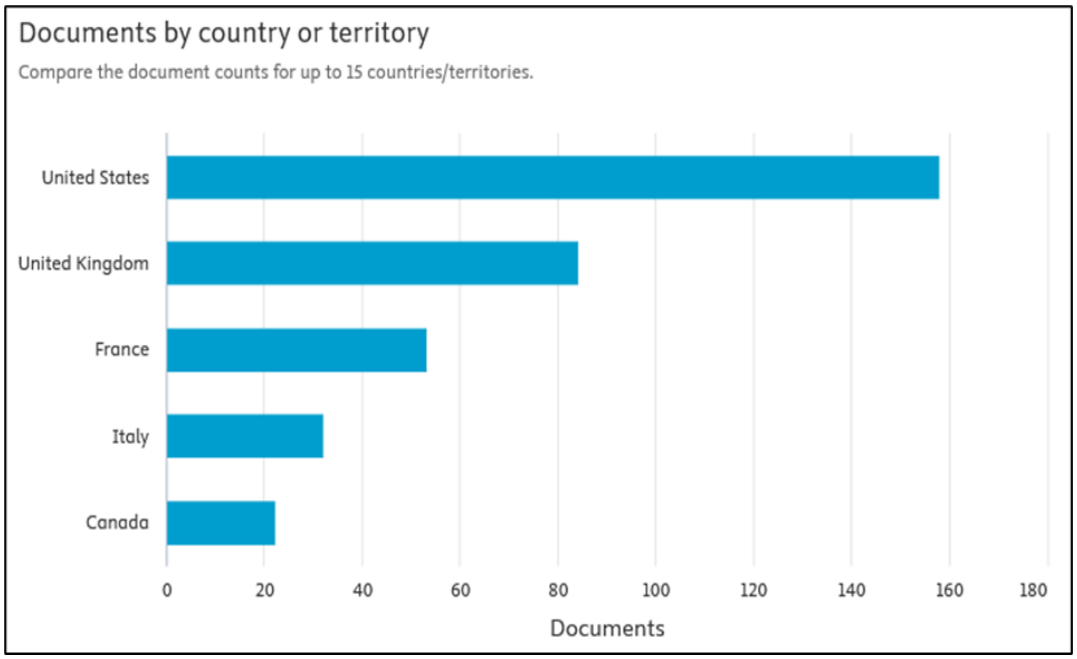

Figure 25. Fluvial biogeomorphology-related hub countries

The analysis of the co-authorship networks showed the following five clusters (Figure 26): the first represents Australia and the Netherlands, which have, respectively, 21 (TSL=11) and 18 papers (TSL=25). The second cluster refers to France, with 53 documents (TSL=70). The third cluster represents the United Kingdom, with 83 papers (TSL=101). The fourth cluster, which stands out, is linked to the United States, with 158 studies (TSL=62). The fifth clusters refers to Sweden, with 10 documents (TSL=12). It is noted that, although the United States published the majority of studies, international co-authorship stands out in countries such as the United Kingdom and France, two biogeomorphological research-related hub countries and whose research institutions are among the most productive in the area.

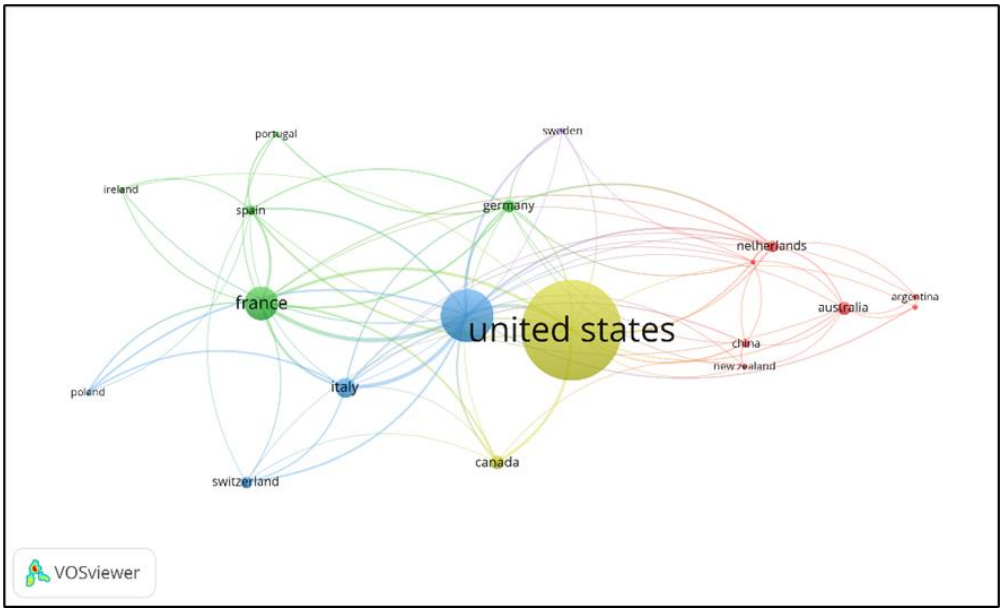

Figure 26. Fluvial biogeomorphology-related co-authorship networks

As for the main research institutions related to fluvial environments (Figure 27), the following stand out: Centre National de la Recherche Scientifique (CNRS), France, 33 papers, (9.24%); Laboratoire de Géographie Physique et Environnementale, Clermont-Ferrand, France, 31 papers (8.68%); Université Clermont Auvergne, France, 30 documents (8.40%); Queen Mary University of London, the United Kingdom, 27 papers (7.56%), and Université Toulouse, 18 studies (5.04%). It is worth noting that although France is 3rd country in volume of studies (53), four out of the five institutions with the majority of papers are in this country. The reason for the French

institutions' leadership is linked to Dov Corenblit (1st most productive author) and Johannes Steiger (2nd most productive author), who conducted research in all the French institutions mentioned above.

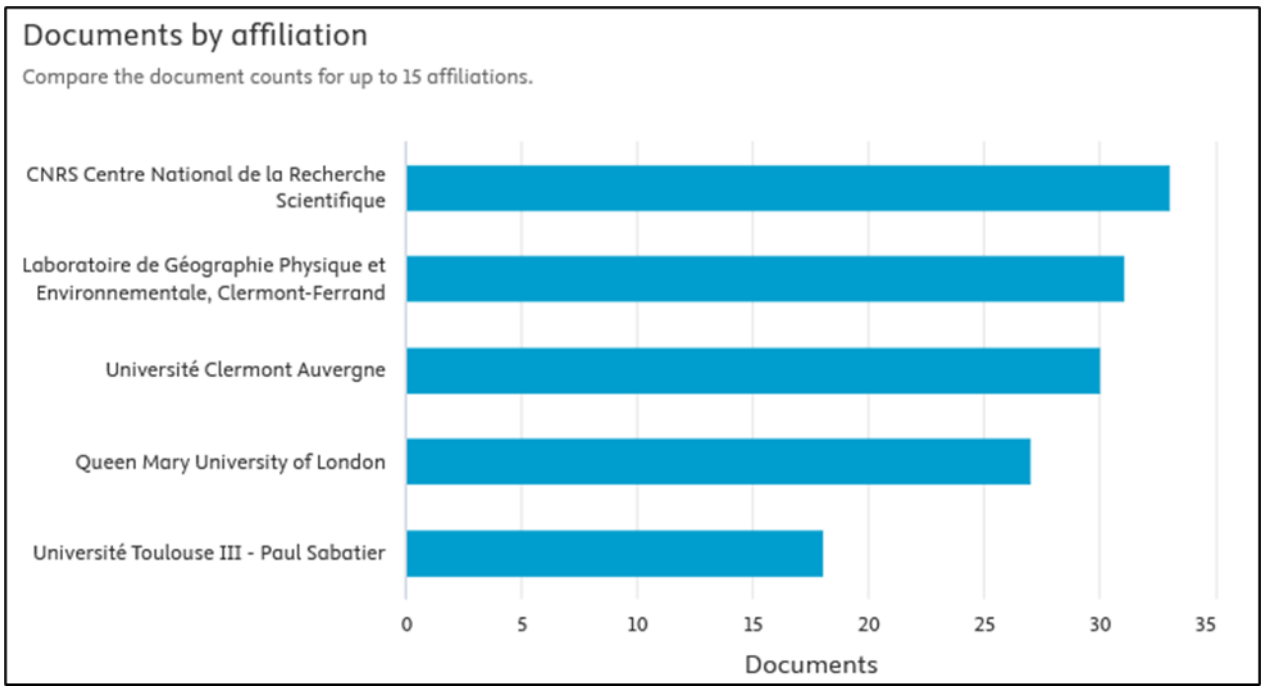

Figure 27. Main research institutions on fluvial biogeomorphology

Regarding biogeomorphological research on hillslope environments, the following countries are highlighted (Figure 28): the United States, 55 publications (52.38%); Czech Republic, 11 publications (10.47%); the United Kingdom, 10 publications (9.52%); Germany, 9 publications (8.57%), and Poland, 8 publications (7.6%).

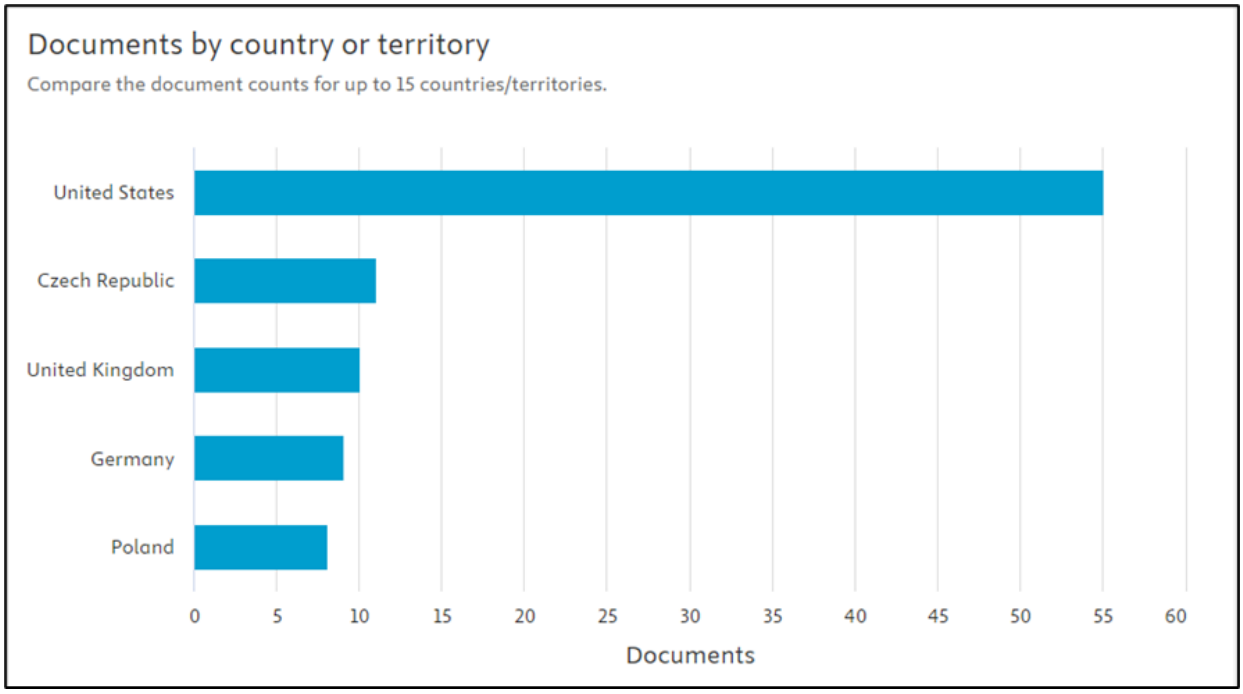

Figure 28. Hillslope biogeomorphology-related hub countries

The analysis of co-authorship networks by country (Figure 29) using VOSviewer showed the existence of three clusters. The first cluster refers to countries such as the United States, with 55 documents (TSL=16), and Czechia, with 11 documents (TSL=14). The second cluster is linked to research developed mainly in Germany, with 9 documents (TSL=6), and the United Kingdom, with 10 papers (TSL=4). The third cluster includes Canada, with 6 documents (TSL=4), and France, with 7 publications (TSL=3).

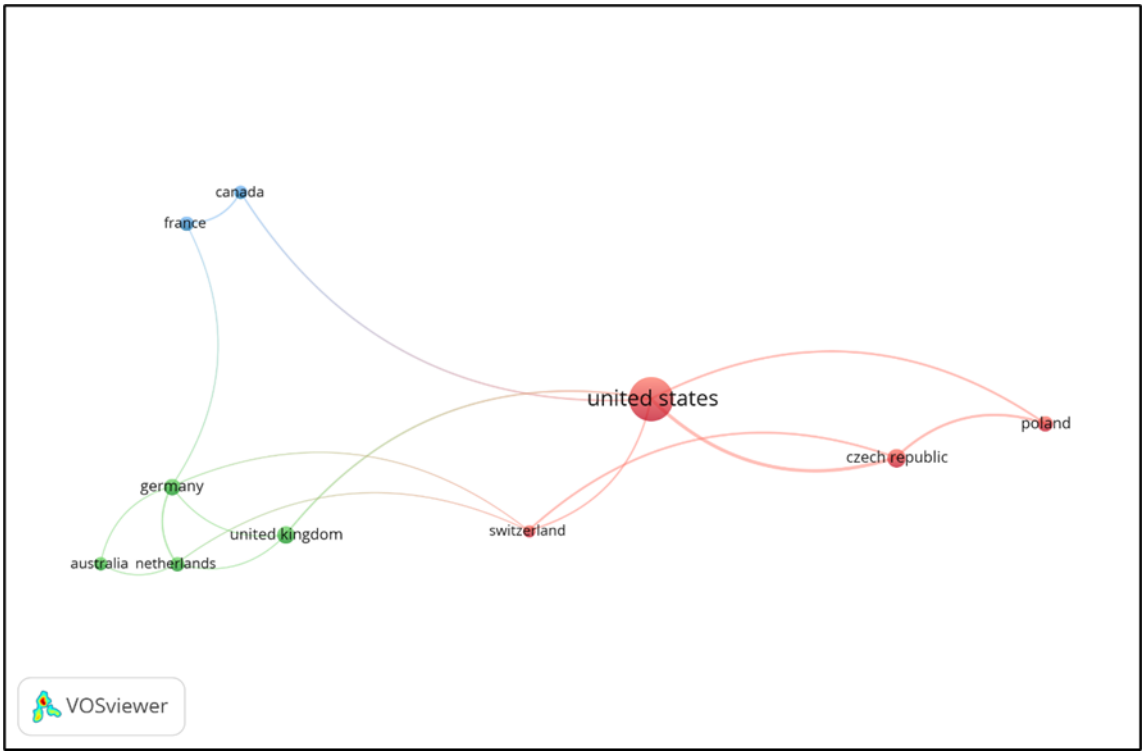

Figure 29. Hillslope biogeomorphology-related co-authorship networks

The main research institutions on hillslope environments (Figure 30) listed were: University of Kentucky (United States), with 9 papers; Masaryk University (Czechia), with 6 documents; Silva Tarouca Research Institute (Czechia), with 5 papers; Mendel University in Brno (Czechia), with 5 papers, and the United States Geological Survey (United States), also with 5 documents.

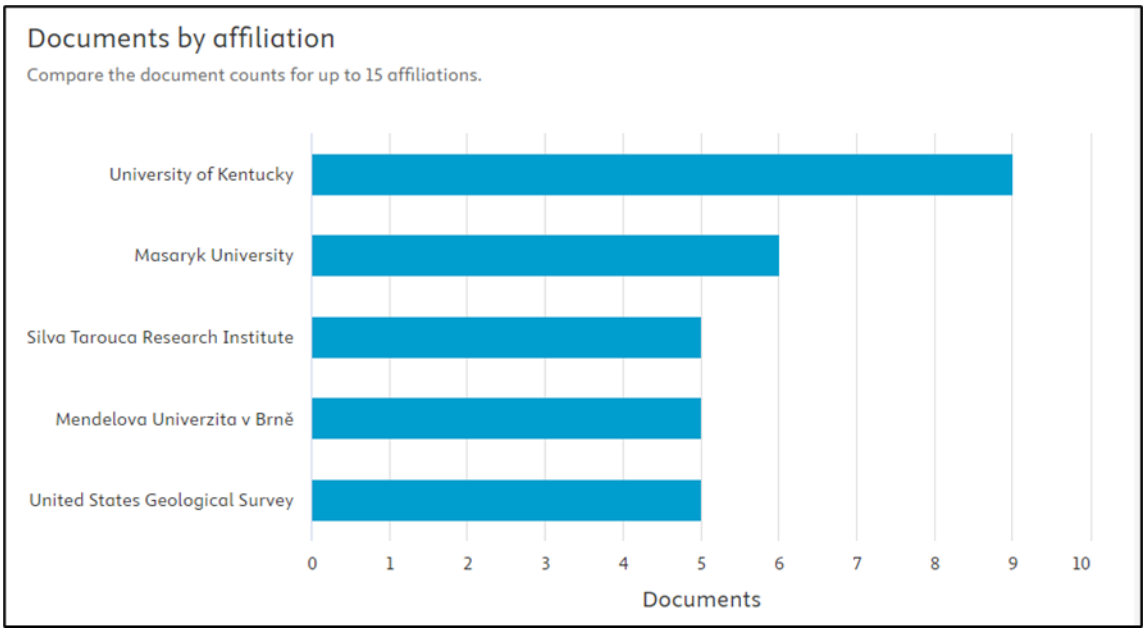

Figure 30. Main research institutions on hillslope biogeomorphology

3.2.5. Main journals and bibliographic sources

The analysis of the main journals and bibliographic sources showed that in coastal and marine biogeomorphology (Figure 31), the journals that stand out are Earth Surface Processes and Landforms, 28 documents (9.62%); Geomorphology, 24 documents (8.24%); Journal of Geophysical Research: Earth Surface, 14 documents (4.81%); Journal of Coastal Research, 13 documents (4.46%), and, Science of Total Environment, 12 works (4.12%).

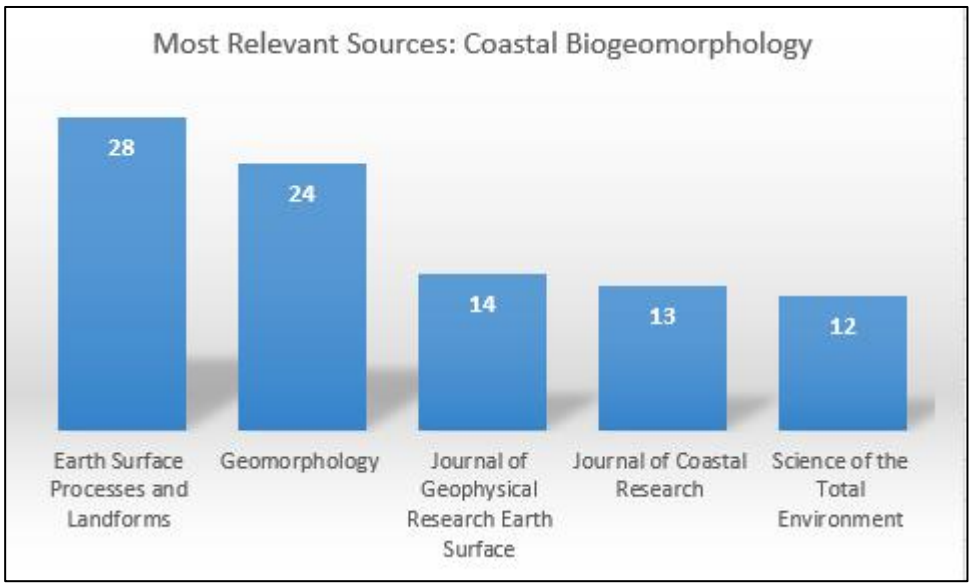

Figure 31. Number of documents in the main coastal and marine biogeomorphology-related periodicals

Analyzing the historical production in these journals (Figure 32), it was found that Geomorphology is the source with the oldest publications, with studies dating back to 1996 and 2002. The source with the majority of studies, Earth Surface Processes And Landforms, started publishing only in 2008, and 2020 was the most productive year, with 5 documents published. Among the sources analyzed, the journals with the most recent

publications are Geomorphology, with 2 papers in 2024, and Science of Total Environment, with 3 documents in 2024.

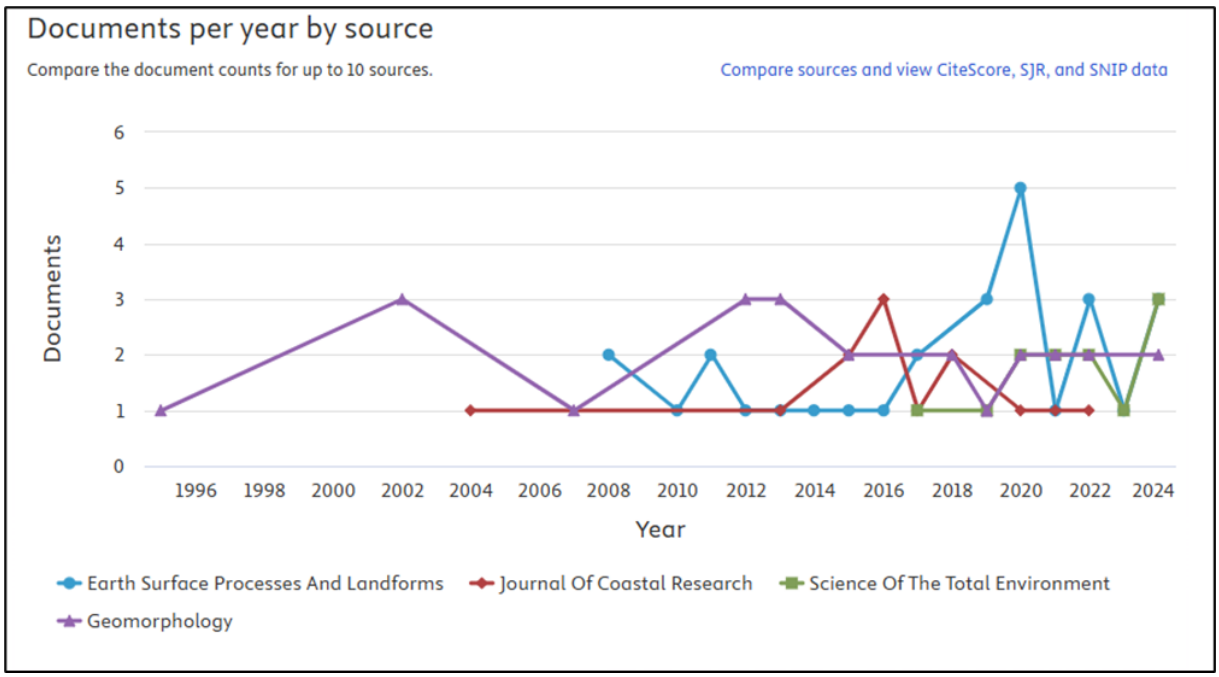

Figure 32. Historical production by coastal and marine biogeomorphology-related periodicals

As for the fluvial biogeomorphology (Figure 33), the top five journals were: Earth Surface Processes and Landforms, 50 papers (14%); Geomorphology, 41 papers (11.48%); River Research and Applications, 32 papers (8.96%); Water Resources Research, 15 papers (4.20%), and Journal of Geophysical Research: Earth Surface, 13 papers (3.64%).

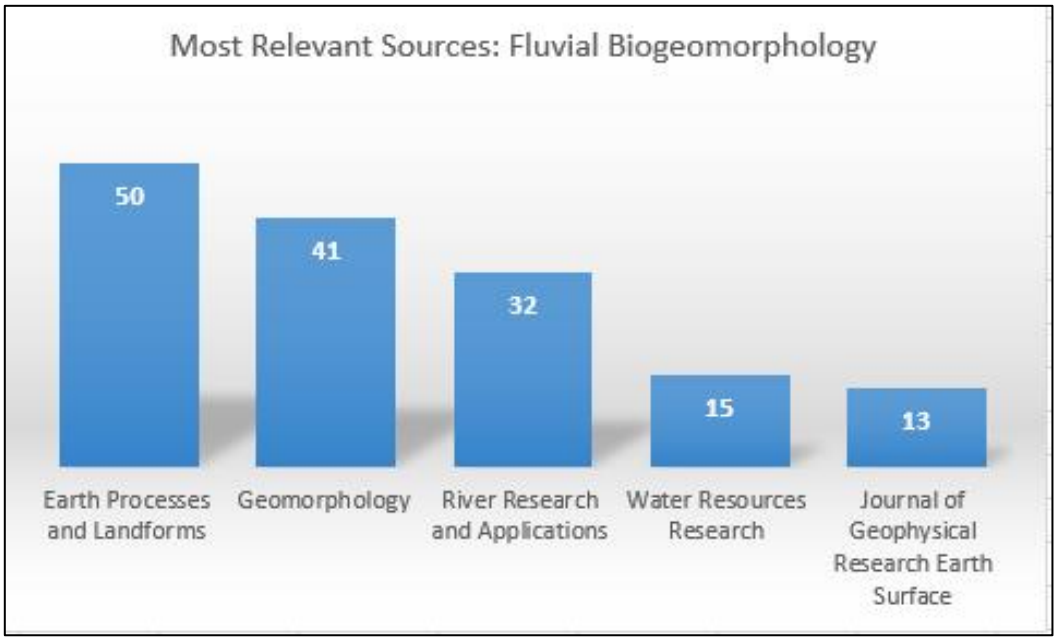

Figure 33. Number of documents in the main fluvial biogeomorphology-related periodicals

A historical analysis of fluvial biogeomorphological production in these journals (Figure 34) showed that the oldest study in the area was published in Earth Surface Processes and Landforms, authored by Trimble (1995). In 1995, Geomorphology published two documents: one by Fetherston et al. (1995), and another by Butler and

Malanson (1995). After that, production in the area ceased, with new publications occurring only in 2003, when Water Resources Research published the study by Statzer et al. (2003). From 2003 onwards, publication has been continuous without long periods between the studies published. Currently, production in the area is mainly found in the two journals with the majority of publications: Earth Surface Processes and Landforms, and Geomorphology.

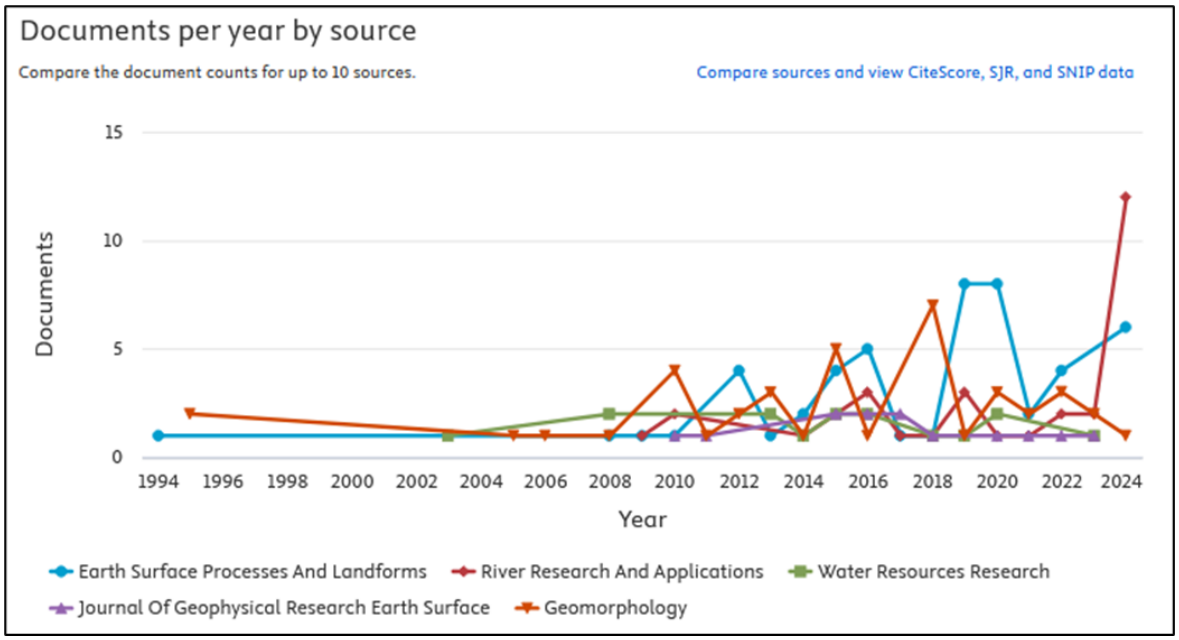

Figure 34. Historical production by fluvial biogeomorphology-related periodicals

Regarding studies on hillslope biogeomorphology (Figure 35), it is possible to mention the following sources: Geomorphology, 22 publications (20.37%); Earth Surface Processes and Landforms, 12 publications (11.11%); Earth-Science Reviews, five publications (4.62%); Journal of Geophysical Research: Earth Surface, 4 publications (3.70%), and Land Degradation and Development, also with 4 publications (3.70%).

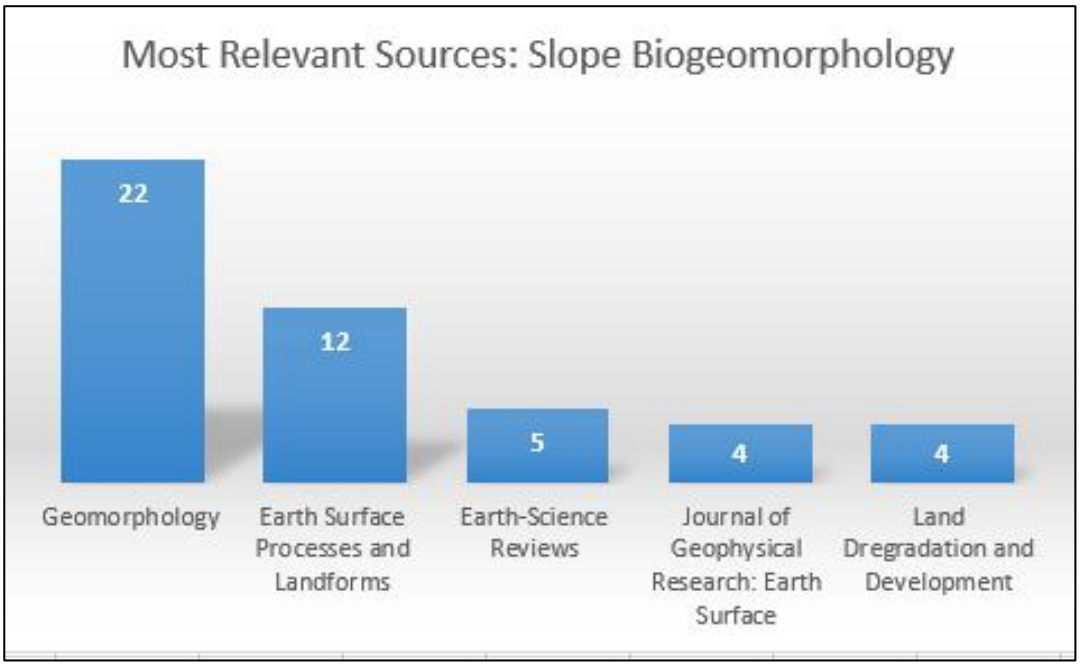

Figure 35. Number of documents in the main hillslope biogeomorphology-related periodicals

According to the historical analysis (Figure 36), the oldest study in the area of hillslopes was published in Geomorphology, authored by Fetherston et al. (1995). In 1998, Land Degradation and Development published, after a three-year hiatus, the work by Lavee et al. (1998). Unlike Geomorphology, which remains the pioneering journal, still publishing the highest number of papers in the field, Land Degradation, also a pioneer, publishes more sporadically. The journal with the second highest volume in published papers, Earth Surface Processes And Landforms, published its first paper in the middle of the first decade of the century, in 2008, a theoretical paper by Viles et al. (2008). It is also clear that only the Geomorphology, Earth Surface Processes and Landforms, and Earth Science Reviews journals publish papers on a recurring basis.

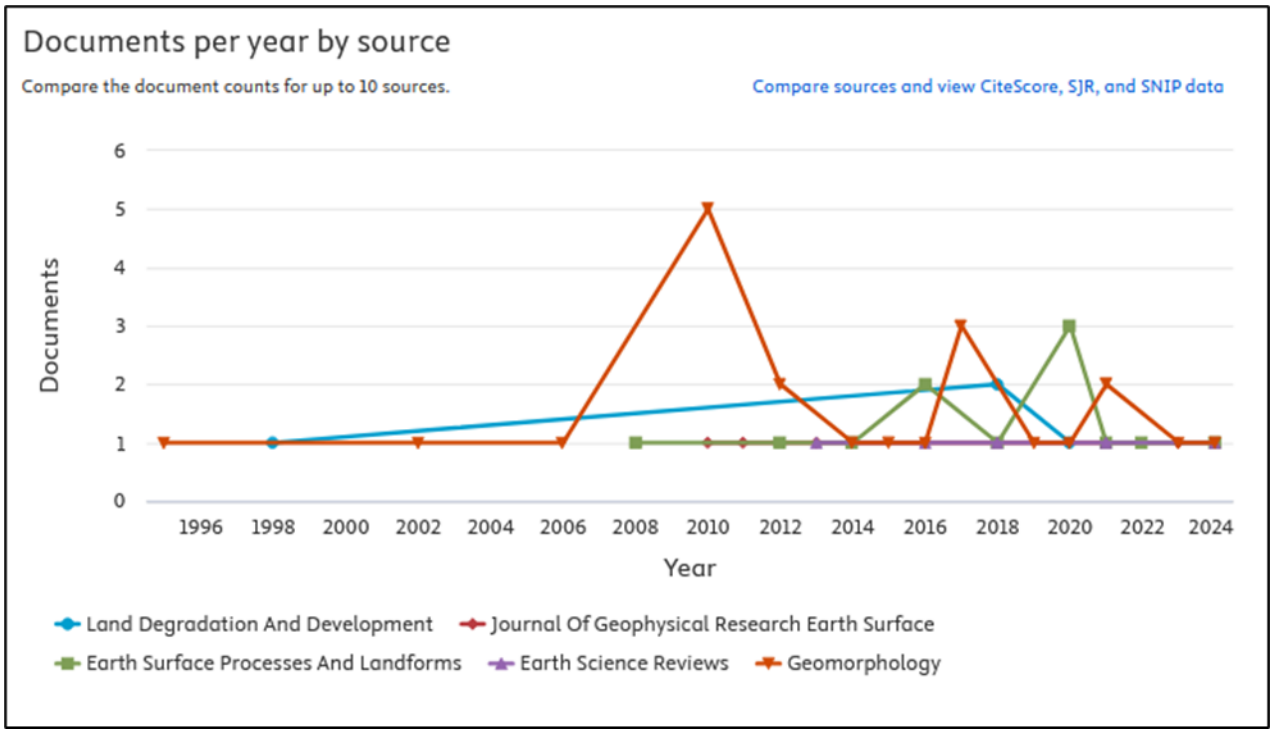

Figure 36. Historical production by hillslope biogeomorphology-related periodicals

3.2.6 Co-occurrence of keywords

Using VOSviewer, one performed the analysis of the co-occurrence of keywords used in the studies listed. For coastal and marine biogeomorphology, and limited to keywords that occurred at least 10 times, the analysis showed a map with five clusters and the five most used keywords in each of them (Figure 37). In the first cluster, they were *geomorphology*, 81 occurrences; *vegetation*, 61 occurrences; *sediment transport*, 42 occurrences; *coastal morphology*, 38 occurrences, and *dune*, with 28 occurrences. In the second cluster, *wetlands*, 44 occurrences; *climate change*, 41 occurrences; *saltmarsh*, 39 occurrences; *sea level change*, 30 occurrences, and *sea level*, with 25 occurrences.

In the third cluster, *biogeomorphology*, 83 occurrences; *ecosystems*, 30 occurrences; *erosion*, 25 occurrences; *intertidal environment*, 20 occurrences, and *ecosystem engineering*, 19 occurrences. In the fourth cluster, *United States*, 38 occurrences; *ecogeomorphology*, 39 occurrences; *morphodynamics*, 18 occurrences; *remote sensing*, 18 occurrences, and *Atlantic Ocean*, 15 occurrences. In the fifth cluster, the analysis found *saltmarsh*, 31 occurrences; *wetland*, 25 occurrences; *ecosystem*, 25 occurrences; *article*, 22 occurrences, and *nonhuman*, 15 occurrences.

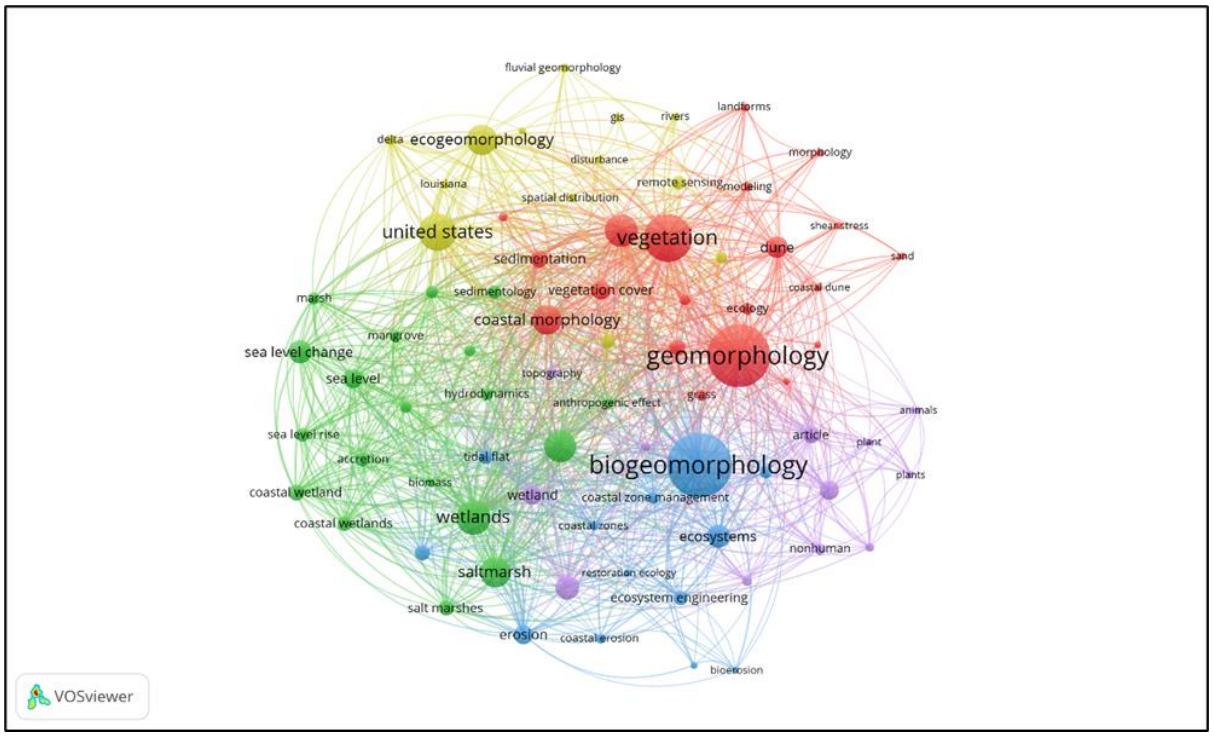

Figure 37. Co-occurrence of keywords in coastal and marine biogeomorphology

For fluvial biogeomorphology (Figure 38), limited to a minimum of 10 occurrences, the analysis found six clusters. In the first cluster, the five most used keywords were *rivers*, 86 occurrences; *riparian vegetation*, 82 occurrences; *floodplain*, 51 occurrences; floods, 48 occurrences, and *channel morphology*, 35 occurrences.

In the second cluster: *biogeomorphology*, 122 occurrences; *fluvial geomorphology*, 108 occurrences; *geomorphology*, 100 occurrences; *sediment transport*, 70 occurrences, and *ecosystems*, 36 occurrences. In the third cluster: *ecogeomorphology*, 122 occurrences; *vegetation*, 91 occurrences; *United States*, 67 occurrences; *sedimentation*, 28 occurrences, and *vegetation cover*, 27 occurrences.

In the fourth cluster: *vegetation dynamics*, 31 occurrences; *sediment*, 23 occurrences; *forestry*, 18 occurrences; *deposition*, 17 occurrences, and *ecosystem engineer*, 16 occurrences. The fifth and sixth clusters are sets of a single keyword, respectively: *biogeomorphic feedbacks*, 11 occurrences, and *dams*, 10 occurrences.

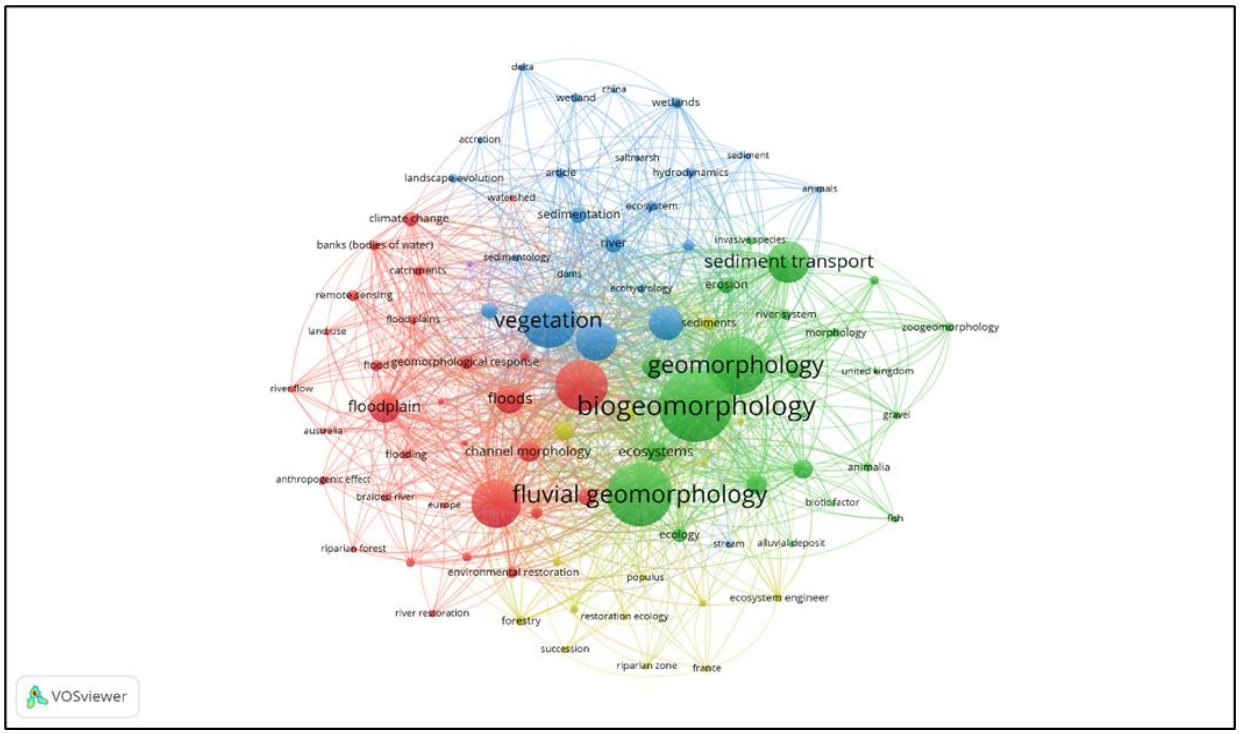

Figure 38. Co-occurrence of keywords in fluvial biogeomorphology

For the biogeomorphological studies on hillslope environments, three clusters were found (Figure 39). Selecting the five most used keywords from each cluster, the first cluster had: *hillslope*, 30 occurrences; *vegetation*, 24 occurrences; *ecosystem*, 13 occurrences; *erosion*, 12 occurrences, and *soils*, 11 occurrences. In the second cluster, there were only 4 keywords, namely: *United States*, 28 occurrences; *ecogeomorphology*, 14 occurrences; *sediment transport*, 14 occurrences, and *fluvial geomorphology*, 11 occurrences. The third cluster also presented four keywords: *biogeomorphology*, 46 occurrences; *geomorphology*, 44 occurrences; *landscape evolution*, 14 occurrences, and *vegetation dynamics*, 10 occurrences.

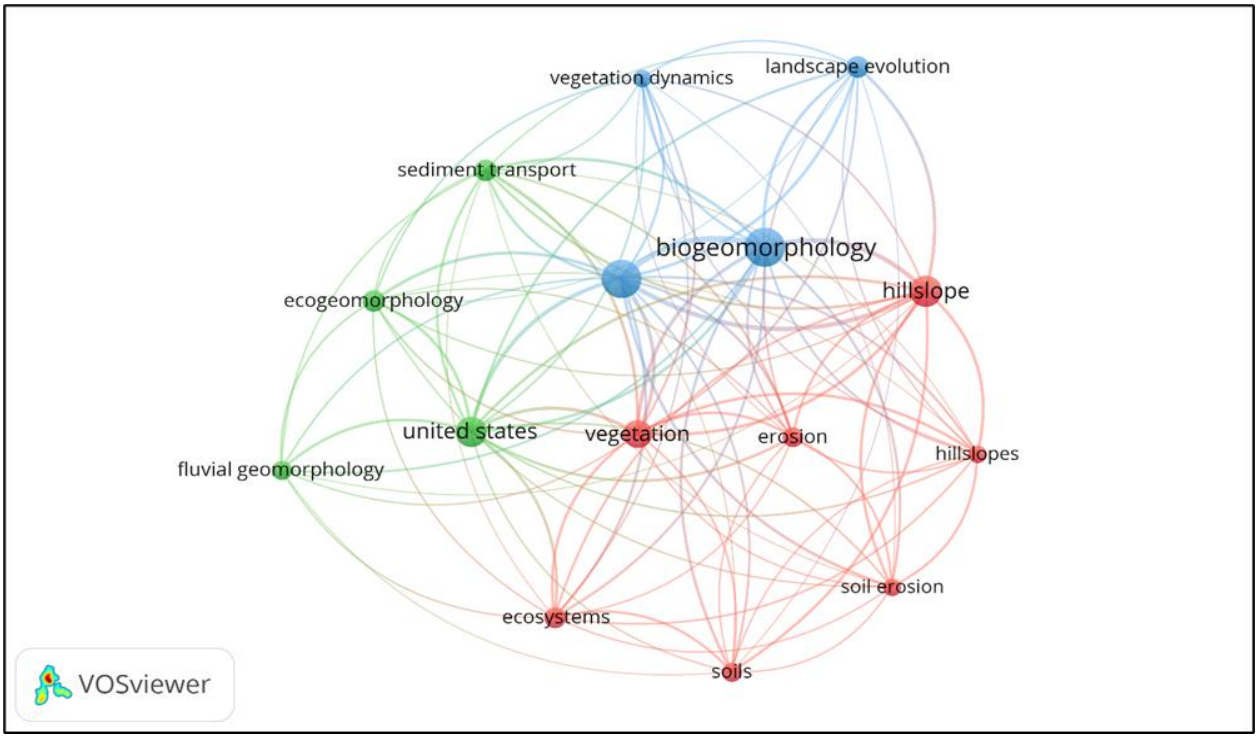

Figure 39. Co-occurrence of keywords in hillslope biogeomorphology

By analyzing the co-occurrence of keywords, it is clear that biogeomorphological studies are more often focused on understanding the dynamic interrelationships between the various biotic and abiotic elements in the same system in different geomorphological environments. For the sub-areas considered in this study, the frequency of the following keywords stands out, with positive occurrence in all environments considered: *sediment transport*; *ecosystems*; *ecosystem engineer* or *ecosystem engineering*, and *vegetation*.

It can be seen, therefore, that the great contribution of biogeomorphic studies is to bring the ecosystemic perspective to geomorphological discussions in such environments, especially highlighting the function of biotic factors, through concepts such as *ecosystem engineering*. It is also worth noting the emphasis of the studies on the fundamental role of related *vegetation cover* in the *sediment transport* and *deposition* system in *geomorphological* systems, terms that are recurrent in all sub-areas considered.

Clearly, a more detailed study is necessary to characterize such research areas. However, the list of terms serves as a preamble to meta-analysis research and review articles where such scientific questions can be clarified. The authors, therefore, suggest a meta-analysis, where the subject of biogeomorphological research can be better characterized in its fundamental questions.

The results obtained demonstrate that biogeomorphology is a growing research field, with significant growth in academic production over the last decades. In addition, the data indicate that academic production is concentrated in countries such as the United States, the United Kingdom, the Netherlands, and France, which concentrate the most productive institutions and researchers in the area. The analysis of co-authorship networks highlighted significant international collaboration, which reinforces the interdisciplinary nature of biogeomorphology and its potential for the development of applied research in environmental management and landscape conservation.

5.0 Conclusions

Biogeomorphology has established itself as an essential discipline for understanding the interactions between geomorphological and biological processes, with significant growth in scientific production in recent decades. This study aimed to characterize biogeomorphology and its thematic areas through a bibliometric analysis, allowing the identification of its historical evolution, its main authors, co-authorship networks, and the geographic distribution of research.

The results indicate that biogeomorphology is a well-established specialty of Geomorphology (Naylor; Viles, 2002; Viles, 2020) and that academic production is predominantly organized around coastal, fluvial and hillslope environments, reflecting the diversity of processes and interrelationships between physical systems and biosystems in such environments. Nevertheless, the potential of the discipline in geoscientific research is highlighted, since there are still gaps in certain geomorphological environments, where, according to Larsen et al. (2020), methodological and theoretical advances are still necessary.

Biogeomorphological research grew in the timespan analyzed, but at a different pace: among the sub-areas of the discipline, biogeomorphological studies on fluvial environments (38.72%) prevail in relation to those on coastal environments (31.56%) and hillslope environments (11.71%). But, one mentions that it is necessary to expand the scope of research, considering karst or glacial geomorphological environments, areas in which biogeomorphological research has also been conducted at an increasing pace.

With regard to national production, Brazil still does not stand out in the databases consulted. Although the Brazilian presence was not significant in this bibliometric analysis, 10 relevant studies by national authors or institutions were identified (Carvalho, T.M.; Carvalho, C.S., 2012; Ielpi et al., 2018; Kim et al., 2015; Nascimento et al., 2021; Nascimento et al., 2024; Rovai et al., 2018; Santos et al., 2019; Soares et al., 2011; Twilley et al., 2019; Zoffoli et al., 2022). For a more comprehensive assessment of national scientific production, a systematic survey on databases such as Google Scholar and the Capes Journal Portal is suggested, covering articles, reviews, dissertations, and theses, in order to map more precisely Brazilian contributions to the biogeomorphology development.

The conclusion is therefore that biogeomorphological research varies according to the biotic groups (kingdoms) of research, but mainly due to the geomorphological environments where the interrelations develop. It is noted that it is mainly from biogeomorphological studies that concepts such as *bioerosion*, *bioprotection* and *bioconstruction* are formulated; these concepts fit within the characterization of the functionalities of biotic elements in geomorphological systems (biogeocomplexity). In this way, one highlights the importance of biogeomorphology for understanding the correlations between abiotic diversity (geodiversity) and biotic diversity (biodiversity), or simply biogeodiversity.

Authors' contribution: J.V.: Conception, Methodology, Investigation, Resources, Data curation, Final version writing, review and editing, Supervision, Project administration, Funding acquisition. P.C.R.S.: Formal analysis, Investigation, Data curation, Final version writing, review and editing, Visualization.

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Conflict of interest: The authors have no conflict of interest to declare.

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