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A retrospective analysis of scientific publications on the deep sea from 1987 to 2016

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Abstract: The deep sea remains the least known biome. Despite this fact, anthropic activities have affected these regions in various ways. The objective of this study was to outline the scientific production scenario based on deep sea research and to analyze trends present in the literature. For this, the bibliographical resources available from the Web of Science (WoS) were surveyed. Between 1987 and 2016, 11,079 articles on the deep sea were published. Growth was over 100% from the first to second decade and 75% from the second to third. The most productive countries were the USA, Germany, France, England and Japan. Of the 404 journals that published articles on the deep sea, 10% accounted for approximately 60% of the total published articles. The keyword with the highest occurrence was "diversity". In the first two decades, the keywords with the greatest "strength" were related to research on mining, especially for hydrocarbons. The description of new species and the analysis of the effects of climate change appear to be emerging trends in deep sea research. Mining continues to be primarily responsible for driving the development of deep sea research.

Key words: Bibliometrics, Databases for scientific publications, Deep sea, Growth rate for science, Information research, Infometrics.

INTRODUCTION

The bathymetric upper limit of the area known as the "deep sea" has historically been considered to be at the break of the continental shelf, approximately 200 m in depth (Sumida 2009). However, this limit has been revised. The Global Open Oceans and Deep Seabed (GOODS) considers a depth of 300 m as the upper limit of the deep sea (UNESCO 2009). A depth of 500 m was adopted by the World Register of Deep-Sea Species (WoRDSS) database for the inclusion of records of pelagic or benthic species, as it is the depth at which the influence of sunlight and the seasonal variation in physical parameters become minimal (Glover et al. 2017).

When considering areas with a depth of more than 200 m, it is estimated that less than 0.0001% of the deep sea has been surveyed, making the deep sea the least studied biome. The surface of the deep sea is less well known than that of the Moon (Danovaro et al. 2017a).

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Despite the lack of knowledge, anthropic activities have affected these regions in various ways, either through pollution, exploitation of their mineral resources or overfishing. These impacts may act cumulatively and synergistically, causing damage, for example, in the cycling of nutrients (Taylor et al. 2016, Danovaro et al. 2017a, b). Of particular concern is the impact on deep sea species, whose bioecology exhibits characteristics such as slow growth and late maturation, which make deep sea species susceptible to human impacts and global change (Danovaro et al. 2017a).

Bibliometric analysis is a field of research that is receiving increased attention from the scientific community and is especially motivated by the rapid development of computers and the internet. Bibliometric analysis is becoming a fundamental method in the field of information science. In the specialized literature, there are several papers that provide complete bibliometric views in many areas of research, including management, economics, health economics, innovation, entrepreneurship and international business research (Merigó and Yang 2017).

Bibliometric techniques are widely used by scholars to analyze a specific topic or journal and provide an overview of existing research trends. Using bibliometric techniques to analyze the publications of a single journal generates a broad picture of the journal, offering a pattern of internal structure. It can reveal the quality, themes and citation scenarios of a journal in any field (Yu et al. 2017).

The objective of this study was to outline the scenario of scientific production publications on the deep sea and to analyze the trends present in the literature from 1987 to 2016. For this purpose, the following indicators were analyzed:

a) Annual number of scientific publications;
b) Countries with the highest number of publications;
c) Journals that published the most articles;
d) Most cited references;
e) Main approaches and emerging issues in investigations research.

MATERIALS AND METHODS

To evaluate the historical evolution of the number of articles published with a focus on aspects of the deep sea, a survey of bibliographic production from 1987 to 2016 was conducted. The Web of Science (WoS) database was used because of its global coverage and because it is recognized for the analysis of data and the production of indicators.

The WoS database was accessed between March 1 and 7, 2017. The "Topic" search field was used to search the title, abstract and keywords of the bibliographic record. The descriptor "deep sea" was used, and the results were limited to the following categories: Oceanography, Marine Freshwater Biology, Ecology, Paleontology, Microbiology, Zoology, Environmental Science, Biology, Evolutionary Biology, Fisheries, Biodiversity Conservation, Cell Biology, Physiology, Parasitology and Behavioral Sciences. The results were refined only to the document type "article".

To delineate the most cited references and main approaches and emerging themes in the investigations indicators, the WoS data were exported (in "txt" format) and then imported into *CiteSpace* software, which allows the visualization and exploration of an area of knowledge (Chen 2014).

RESULTS AND DISCUSSION

The first two studies on the deep sea recorded in the WoS date from 1947, "*Barbourisidae, a new family of deep sea fishes*", authored by A.E. Parr and published in 1945 in the journal Copeia, and "*The Swedish deep-sea expedition*" of H. Pettersson, presented in the Proceedings of the Royal Society of London, Series B - Biological Sciences in 1947.

From 1987 to 2016, 11,079 articles were published, with a constant increase in the number of articles published during the last 30 years (Fig. 1).

During the 30 years analyzed, the average number of articles per year was 186.6 in the first decade and 647.5 per year in the last interval.

Comparing the total number of documents published in the three decades, 1987-1996 (1,658 articles), 1997-2006 (3,422) and 2007-2016 (5,999), the growth is consistent. Growth was 106.3% from the first decade to the second decade (annual average of 8.8%) and 75.3% from the second decade to the third decade (annual average of 6.2%).

In total, authors from 114 countries published on the topic. The data showed a high concentration of publications among a few countries. The five most productive countries were the USA, Germany, France, England and Japan, representing approximately 80% of total world production (Fig. 2). Although the USA accounted for approximately one-third of total production, Germany showed a significant increase in production over the last two decades. In the last decade, China, which was previously not among the ten most productive countries, made a significant contribution (Table I).

Among the ten most productive countries, five were in Europe (Germany, France, England, Spain and Italy), with 48% of the articles, and two were in America (USA and Canada), with 37% of the articles. These 7 countries, therefore, accounted for 85% of the global production.

Articles published during the period were edited by 404 journals. The production was very centralized, with 10% of the journals and 40 publications responsible for 59% of the total production, corresponding to 6,539 articles. This is equivalent to an average of 163 documents per publication, while the other 90% of journals, 364 publications, represented 4,540 documents, with an average of 12 articles per publication. The

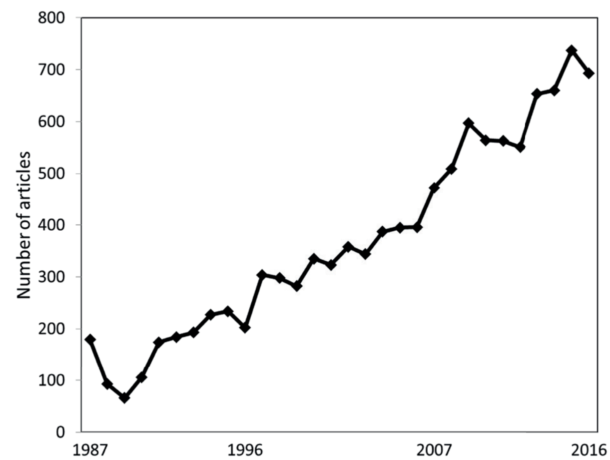

Figure 1 - Number of articles published on the deep sea between 1987 and 2016 from data available from the Web of Science.

most productive journals were Deep Sea Research Part I Oceanographic Research Papers, Deep Sea Research Part II Topical Studies in Oceanography, Marine Geology, Marine Ecology Progress Series and Zootaxa (Table II).

When analyzing the performance of journals over time, we observed the consolidation of main journals during the last 30 years. However, although they continue to publish a substantial number of articles, journals such as Paleoceanography and Marine Geology, which between 1987 and 1996 accounted for approximately 15% of production, accounted for approximately 4.5% in the last decade. In contrast, Zootaxa, created in 2001, published 325 articles in the last decade, which corresponds to 5.5% of the total production. This change in journal dominance is related to the objects of study and the type of result obtained. It is evident in the case of Zootaxa that there was an increase in the number of studies with a taxonomic focus, especially with the description of new species. This trend is in contrast to the still limited knowledge of biota of deep ocean regions (Danovaro et al. 2017a).

In the 11,079 published articles indexed in the WoS, 912 references were cited that were also

TABLE I
Total number and percentage of articles published by the 10 most productive countries in each decade between 1987 and 2016.

	1987-1996				1997-2006				2007-2016		
	Country	**Nº**	**%**		**Country**	**Nº**	**%**		**Country**	**Nº**	**%**
1º	USA	741	44.6	1º	USA	1.142	33.3	1º	USA	1.761	29.3
2º	France	190	11.4	2º	Germany	531	15.5	2º	Germany	906	15.1
3º	England	175	10.5	3º	France	458	13.3	3º	France	689	11.4
4º	Germany	157	9.4	4º	England	385	11.2	4º	England	664	11.0
5º	Japan	97	5.8	5º	Japan	363	10.6	5º	Japan	546	9.1
6º	Canada	63	3.8	6º	Spain	171	4.9	6º	China	538	8.9
7º	Netherlands	54	3.2	7º	Russia	164	4.7	7º	Spain	475	7.9
8º	Scotland	47	2.8	8º	Canada	138	4.0	8º	Italy	379	6.3
9º	Australia	45	2.7	9º	Italy	134	3.9	9º	Australia	311	5.1
10º	Spain	39	2.3	10º	Netherlands	115	3.3	10º	Canada	281	4.6

TABLE II
Number of articles published and percentage of the 10 journals that published the most articles on the topic "deep sea" between 1987 and 2016.

	Journals	**Nº**	**%**
1º	Deep Sea Research Part I Oceanographic Research Papers	640	5.7
2º	Deep Sea Research Part II Topical Studies in Oceanography	577	5.2
3º	Marine Geology	451	4.0
4º	Marine Ecology Progress Series	389	3.5
5º	Zootaxa	366	3.3
6º	Paleoceanography	363	3.2
7º	Palaeogeography Palaeoclimatology Palaeoecology	342	3.0
8º	Marine Biology	236	2.1
9°	International Journal of Systematic and Evolutionary Microbiology	224	2.0
10°	Marine Micropaleontology	187	1.6

indexed in the WoS. Among the 10 most cited articles, nine were published in the last 10 years, six of which are nonexclusive analytical tools for research in deep areas. In particular, molecular biology and mathematical models were combined with the development of computational analysis instruments.

The most cited article dealing with deep water biota was published by Sogin et al. in 2006 and addressed the microbial diversity of these regions (Table III).

The graphical analysis of the network of the most cited references in the period from 1987 to 2016 shows references clustered by thematic proximity of the articles. Groups were formed based on the central theme and related themes, and they were connected to authors who published on the theme; in this way, the references were related.

Twenty-six clusters were identified, of which the main ones are "trophic level", "seamount" and "South China Sea".

The "trophic level" presented 87 associated topics: Cape Blanc; Goban; ecological evidence; benthic foraminifer accumulation rate; Pliocene Caribbean Sea; benthic foraminiferal succession; live-dead comparison; north-east Atlantic; benthic response; and late Quaternary Mediterranean sapropel. This cluster had only two of the twenty most cited references: Gage and Tyler (1991) and Pfannkuche (1993).

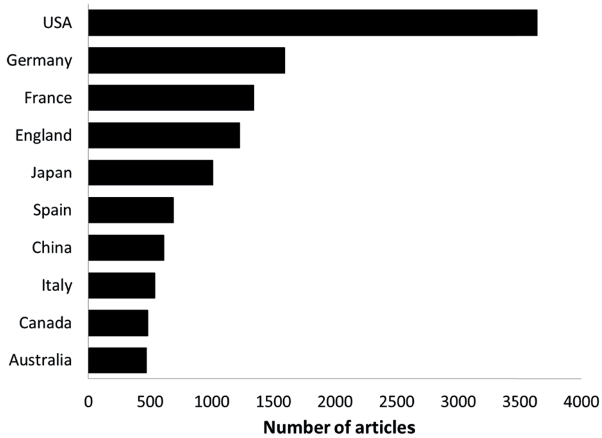

Figure 2 - Number of articles published between 1987 and 2016 by the 10 most productive countries. The sum of the number of articles published by the countries will be higher than the total number of articles because many articles are published by authors from different countries.

The cluster "seamount" was formed by 70 members with the following associated topics: spill; coral; Porcupine Seabight; adjacent slope; habitat heterogeneity; and ecosystem functioning. This cluster contains four of the ten most cited references: Clarke and Gorley (2006), Roberts et al. (2006), Canals et al. (2006) and Anderson et al. (2008).

The cluster "South China Sea", was formed by 69 members with the following associated topics: archaea; Antarctic polar front; biogeochemistry; archaeal; genomic; spill; China Sea; and Atlantic Ocean. This cluster contains five of the ten most cited references: Tamura et al. (2011), Sogin et al. (2006), Schloss et al. (2009), Ludwig et al. (2004) and Pruesse et al. (2007).

Another cluster was formed by the "Deep Sea Drilling Project" (DSDP), an initiative that began in the 1960s and carried out drilling operations in deep areas in the Atlantic, Pacific and Indian Oceans, as well as in the Mediterranean and Red Seas. This initiative was succeeded by the International Ocean Discovery Program, an international collaborative research network of the history and dynamics of Earth from sediment and rock seabed data (DSDP 2017 and IODP 2017). This project is related to

TABLE III
Number of citations and keywords of the 10 most cited articles between 1987 and 2016.

Nº of citations	References	Keywords
174	Tamura et al. 2011	Neighbor-Joining Method; Model Selection; Phylogenetic Inference; Mitochondrial-DNA; Protein Sequences; Clock; Trees; Nucleotide; Software; Substitution.
154	Sogin et al. 2006	Biodiversity; Low abundance; Marine; Microbes; Rarefaction.
134	Schloss et al. 2009	Microbial Communities; software analyze community sequence data; Operational taxonomic units.
128	Brandt et al. 2007	Marine benthic communities – Antarctica.
121	Ludwig et al. 2004	ARB – project interdisciplinary bioinformatics; Ribonucleic acid – RNA.
18	Tamura et al. 2007	Neighbor-Joining Method; Model Selection; Phylogenetic Inference; Mitochondrial-DNA; Protein Sequences; Clock; Trees; Nucleotide; Software; Substitution.
112	Clarke and Gorley 2006	Multivariat statistic.
97	Roberts et al. 2006	Coral reefs tropical seas; Deep-ocean exploration; Coral ecosystems in deep waters; Impacts of deep-water trawling.
95	Canals et al. 2006	Submarine canyon – Gulf of Lions Margin; Dense Shelf Water Cascading – DSWC; Deep-sea ecosystems.
94	Pruesse et al. 2007	Ribonucleic acid – RNA; SILVA rRNA database Project.

efforts to map new areas for mining, which is an emerging source of impact on deep ocean regions (Danovaro et al. 2017b, Van Dover et al. 2017).

Among the 10 most frequent keywords in the 11,079 papers published in the analyzed period, the one with the highest occurrence was diversity, with 734 mentions (6.6% of all papers). The frequency of occurrence of the keywords is representative of the themes of the deep sea studies in the period studied. Table IV indicates the keyword frequency, the year of the first registration of the keyword and the cluster to which it belongs.

The word “diversity” was in cluster # 1, which had 54 members. The word “Harpacticoida” was at the center and was associated with the terms Copepoda, Cletodes, Paramesochridae, Peracarida, new species, Crustacea, Japan and bank (Fig. 3).

The term “diversity” is closely related to the identification of new species of crustaceans. Although diversity was a theme since 1992 (Table IV), it was only intensely quoted since 2012.

Significantly, “sediment” occurred 644 times (5.8% of all papers). This word was in cluster # 5, which had 28 members. The term “microbial communities” was at the center and was associated with the terms deep-sea hydrothermal vent, hydrothermal, nov (new species), hyperthermophilic archaeon and ammonia-oxidizing bacteria.

The word “sediment” is related to the study of microbial communities that thrive in deepwater hydrothermal vents. This theme was most present in the first decade analyzed (1987-1996) (Table V).

The term “deep sea sediment” occurred 600 times (5.4% of all papers). This term was in cluster # 6, which had 20 members. The term “extraterrestrial component” was at the center and was associated with the terms CaCO3 preservation, central equatorial Pacific Ocean, bathymetric reconstruction and China (Fig. 3).

The temporal order of research themes from 1987 to 2016 emphasizes the emergence and termination of trends that involve the theme “deep sea” (Table V).

TABLE IV
The 10 keywords most used by articles published between 1987-2016, their frequency, the year of their first registration and the cluster to which the keywords belong.

Keywords	Frequency	Year	Cluster #
Diversity	734	1992	1
Sediment	644	1987	5
Deep sea sediment	600	1988	6
Atlantic	530	1990	1
Marine sediment	497	1990	3
Hydrothermal vent	497	1992	5
Community	461	1991	1
Evolution	440	1992	1
Water	435	1990	3
North Atlantic	432	1988	0

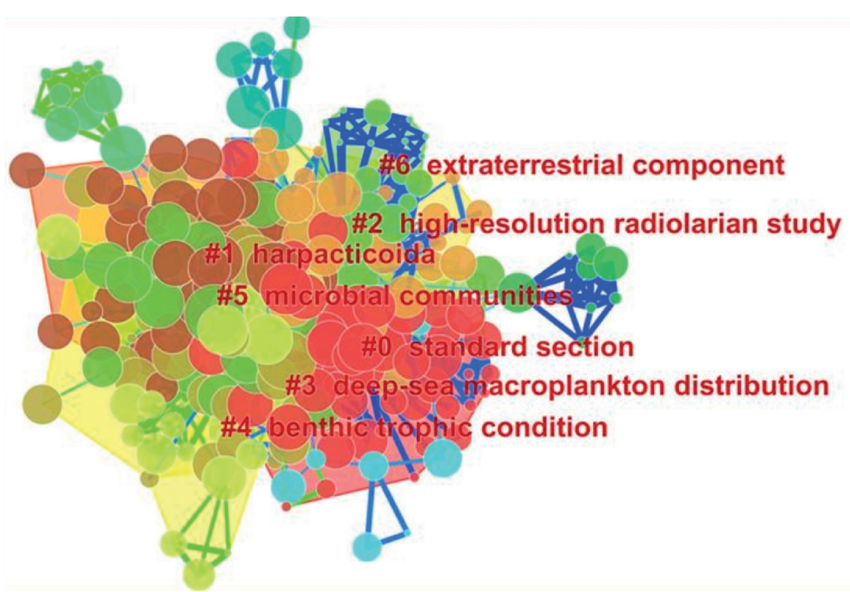

Figure 3 - Keyword clusters of deep sea publications between 1987 and 2016.

TABLE V
Emerging themes on the "deep sea" between 1987 and 2016.
"Strength" represents the strength or vigor of a keyword's appearance during the period.

Keywords	Strength	Start	End	1987 - 2016
Sediment	6.4635	1987	1993	
Stratigraphy	6.9432	1988	1999	
Fluxe	13.2227	1990	2001	
Oxigen	13.6801	1991	2003	
Diagenesis	9.9676	1991	2004	
Seasonal deposition	11.4481	1992	1998	
Phytodetritus	22.3174	1992	2001	
Calcium carbonate	4.8741	1994	2000	
Early diagenesis	6.5347	1996	2001	
Productivity	11.5196	1997	2002	
Organic carbon	4.6955	1997	2003	
Sediment trap	4.2316	1998	2002	
Paleoceanography	6.9591	1999	2005	
Planktonic foraminifera	5.6223	2002	2005	
Northeast Pacific	4.3001	2003	2006	
Angola basin	7.1924	2005	2009	
Antarctica	6.1619	2007	2008	
Mid Atlantic ridge	4.6578	2008	2009	
Deep sea coral	12.8526	2009	2014	
Methane seep	7.8892	2010	2012	
New Zealand	8.105	2010	2013	
Fishery	5.6179	2011	2014	
Sp. nov.	11.2063	2012	2016	
Climate change	11.3402	2012	2016	
Submarine canyon	12.1358	2013	2014	
Maximum likelihood	22.6808	2013	2016	
Taxonomy	8.0903	2014	2016	
Gulf of Mexico	17.9417	2014	2016	
Mediterranean Sea	10.2609	2014	2016	

During the first two decades, the keywords with the greatest strength were related to research on mineral prospecting, especially hydrocarbons (e.g., stratigraphy, diagenesis, early diagenesis and Angola basin).

In the last decade, topics such as "deep sea coral" and "fishery" were registered, evidencing the advance of fishing activity in deep areas.

Species caught by deep sea fisheries generally have common biological characteristics, such as maturity at a relatively advanced age, slow growth, a long life expectancy, a low natural mortality rate, intermittent recruitment, and the possibility that spawning does not occur every year. All these characteristics result in low productivity (FAO 2009). For this reason, fisheries targeting deep sea species often exhibit a rapid expansion pattern followed by an abrupt decline of the captured biomass, reaching exhaustion. This exhaustion is mainly due to the inefficient management of these resources (Rogers et al. 2008, Clark et al. 2016).

The description of new species and the analysis of the effects of climate change were also research trends. According to the data collected, the sites of these surveys were the Gulf of Mexico and the Mediterranean Sea (Table V).

In addition to the mortality caused by fishing activity in deep areas, another threat is the increasing accumulation of plastic debris (Van Cauwenberghe et al. 2013, Woodall et al. 2014, Taylor et al. 2016). This concern, however, up to the present study, did not appear as an emerging theme. Similarly, initiatives that seek to mitigate impacts and define conservation strategies for the deep sea, such as the implementation of “Deep-Sea Ecosystem Monitoring Networks,” which are focused on the monitoring of organisms and ecosystems (Danovaro et al. 2017b), seem to be far away.

It can be concluded that despite the growing scientific publication on the deep sea, mining continues to be the main motivation for boosting the development of research. However, even if still incipient, the increase in the knowledge of the biota of these regions is remarkable.

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AUTHOR CONTRIBUTIONS

Harry Boos and Charles Rodrigues are responsible for the study conception and sampling design, performed data analysis and wrote the manuscript. Paula Beatriz Araujo is responsible for the supervision of the project and contributed to the data analysis and to the writing of the manuscript.

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