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Mapping Global Research on Ocean Literacy: Implications for Science, Policy, and the Blue Economy

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In recent years, ocean literacy has become a global movement that connects the human dimension to the ocean and intends to be an incentive for positive change in people's behavior. As multiple initiatives on ocean literacy have arisen, a comprehensive understanding of this topic is required to better engage the broader society. In the present study, we applied a combination of bibliometric analysis and science mapping to a dataset of scientific publications on ocean literacy between 2005 and 2019, obtained from Web of Science and Scopus databases. In order to represent the development of the field, analyze the level of collaborations and uncover its thematic areas, we first used bibliometric analyses to describe the field's main features, including indicators of growth and research collaboration. We then used science mapping techniques to build collaboration networks among countries and institutions, and to identify research communities. Lastly, we performed co-word analysis to reveal the underlying thematic areas and their evolution. Our results reveal a slow-growing number of publications and a promising trend for collaboration among authors, countries and institutions. Education and science were identified as the two major thematic areas on ocean literacy showing that, over time, issues related to these themes have gained more attention among researchers. These findings confirm that ocean literacy is gaining more acknowledgment within the scientific community but still faces considerable limitations to its dissemination in sectors like the blue economy and in regions such as Latin America and Africa. Promoting cross-institutional and cross-disciplinary cooperation among research institutions, marine education networks and the industry is critical to support this purposeful movement and represents an urgent challenge.

Keywords: ocean literacy, science mapping, bibliometrics, blue economy, Sustainable Development Goal 14, Ocean Decade

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INTRODUCTION

Maintaining a healthy ocean and moving to a more sustainable use of its resources and services is one of the main challenges of the next decade. The ocean is a critical driver of global climate and maintains life providing many vital functions for our planet. It represents a source of food, raw materials, energy and provides the space for many economic activities (Visbeck, 2018; Jouffray et al., 2020). These rapidly evolving human activities have led to unprecedented pressures such

as overfishing, pollution, habitat degradation and ocean acidification. Yet, the level of public understanding of basic concepts related to the ocean and the threats associated to human activities remains low to moderate (Gelcich et al., 2014; Fauville, 2019).

Ocean literacy (OL) is a relatively new term that connects the human dimension to the ocean and that intends to be an incentive for positive change in people's behavior. It is defined as the understanding of the ocean's influence on us and our influence on the ocean. An ocean-literate person understands the importance of the ocean to humankind, can communicate about the ocean in a meaningful way, and, is able to make informed and responsible decisions regarding the ocean and its resources (Cava et al., 2005).

The campaign for defining and establishing a framework for OL began in the United States of America (United States) as an initiative to identify key ocean concepts that were missing in the American school curricula. After a series of meetings and workshops that began in 2002, participants from ocean science and education communities together with policy makers, came to a consensus on the definition of OL in 2004 (Cava et al., 2005). As a result, a roadmap for marine educators was published, containing the essential principles (**Table 1**) and fundamental concepts as well as the scope and sequence for each grade at school (Schoedinger et al., 2010).

Few years later, the OL concept reached Europe with the establishment of the European Marine Science Education Association (EMSEA) and the First Conference on Ocean literacy in Europe in 2012 (Copejans and Seys, 2012). Similarly, Canada advanced on its efforts to build an ocean literate society by establishing the Canadian Network for Ocean Education[1] (CaNOE). In a joint effort to promote OL initiatives and to encourage its use when communicating about policy, the European Union (EU), Canada and the United States signed the Galway Statement on Atlantic Ocean Cooperation in 2013 (European Commission, 2013). The Galway Statement stands as an example showing that the OL concept and principles are embedded in the European marine policies. These policies include the Blue Growth Strategy, the Marine Strategy Framework Directive, the Marine Spatial Planning Directive, the Common Fisheries Policy, the Birds Directive, the Habitats Directive and most recently, the European Green Deal (French et al., 2015; European Commission, 2019b).

[1]http://oceanliteracy.ca

TABLE 1 | The seven essential principles of Ocean literacy.

1.	Earth has one big ocean with many features.
2.	The ocean and life in the ocean shape the features of Earth.
3.	The ocean is a major influence on weather and climate.
4.	The ocean makes Earth habitable.
5.	The ocean supports a great diversity of life and ecosystems.
6.	The ocean and humans are inextricably interconnected.
7.	The ocean is largely unexplored.

Cava et al. (2005).

In 2018, the United Nations Educational, Scientific and Cultural Organization (UNESCO) launched the Ocean Literacy Portal[2] as part of the actions to progress on the Sustainable Development Goal 14. The portal provides a free-access compilation of OL resources for students, educators, scientists, policy makers and relevant stakeholders from all over the world. Two years later, in 2020, the European Commission launched the European Ocean Literacy Coalition[3] (EU4Ocean) as a platform to connect organizations, projects and people that contribute to OL and the sustainable management of the ocean. The same year, the Global Ocean Literacy Strategy, supported by the United Nations Decade of Ocean Sciences for Sustainable Development (2021–2030; hereafter referred to as the Ocean Decade), was being drafted.

OL has evolved from a national (United States initiative) to a global scale movement. This dynamic has caught the attention of researchers from several disciplines. As an interdisciplinary field, OL integrates knowledge, techniques and tools from marine sciences (e.g., ecology, oceanography, ecosystem modeling), education sciences, social and behavioral sciences (e.g., sociology and psychology), public health, geography, marine policy, science communication, arts and digital technologies (Dupont, 2017; Fauville, 2017; Costa and Caldeira, 2018; European Marine Board, 2020; Kelly et al., 2021). This diversity of research backgrounds has been accompanied by a broad range of approaches and methods that were included in several scientific publications. However, since this information remains sparse, it is necessary to have an updated outlook to investigate how research advancements are developing in structure and what is the relationship between research communities.

Scientific publications are good indicators of the development of a research field. The quantitative study of scientific publications, citations and journals, is called Bibliometrics (Pritchard, 1969; Broadus, 1987). This technique has been extensively used in a variety of fields ranging from medical sciences (Thompson and Walker, 2015) and cultural evolution (Youngblood and Lahti, 2018) to drug discovery (Agarwal and Searls, 2009) and climate change (Haunschild et al., 2016). In the 1970s and 1980s, bibliometric research was mostly focused on citation analysis to assess the structure of several scientific fields, journal interrelationships, as well as research performance in the humanities and social sciences, citation behavior and interdisciplinary research. In 1990s, powered by the advancements in information technology, international organizations began systematically collecting data to measure and analyze the development of science and technology by means of bibliometrics. Work in the 1990s was focused on the combination of co-citation and word analysis, journal impact measures and the interface of science and technology (van Raan, 2019).

The first decade of the new century was influenced by technological advancements in computer science and the global availability of large bibliographic databases (e.g., Web of Science, previously known as ISI Web of Knowledge) (Chernyi, 2009). Work on bibliometrics addressed new methods for identifying

[2]https://oceanliteracy.unesco.org

[3]www.eu-oceanliteracy.eu

emerging topics, improvements in the visualization of science maps and measures of journal interdisciplinarity, the triple helix model of government–industry–academy interaction, patent citation analysis and the identification of industrially relevant science and text mining. In the last decade, the bibliometric community focused on new indicators of performance and advanced network methods to improve science mapping, university rankings and the comparison between publication-level and journal-level field classifications (van Raan, 2019).

Bibliometrics has undergone a sharp rise since the late 1960s, evolving from a tool to cover library e information center needs, to a powerful field of science with a set of indicators and analytical methods. Over time, this evolution drew the attention of policymakers. Bibliometric research has supported strategic decision making and research funding allocation (Waltman and Noyons, 2018) and has helped to identify the connections between scientific growth and policy changes (Machado et al., 2016). Bibliometric techniques are useful to provide a structured analysis of large datasets, to infer trends over time, identify research themes and shifts in the boundaries of the disciplines. It also enables to detect the most prolific authors and institutions, and to present the "big picture" of a given research area (Aria and Cuccurullo, 2017). In bibliometrics, the two main methods for analyzing a research field are performance analysis and science mapping. While the first method is focused on evaluating the production and impact of publications, science mapping intends to display the conceptual, social and intellectual structure of scientific research, as well as its evolution and dynamical aspects (Gutiérrez-Salcedo et al., 2018).

While OL has captured the attention of diverse research disciplines, previous research has shown that most of the research efforts were focused on educational approaches, particularly at school level (Costa and Caldeira, 2018). Yet, less attention was given to disciplines related to the economic activities happening in the ocean. As the intensity and diversity of these activities continue to grow, the blue economy concept emerges as an approach seeking to promote the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of the ocean (World Bank and United Nations Department of Economic and Social Affairs, 2017). That being said, it becomes essential to understand the implications of OL as a global movement not only for the scientific community but also in the implementation of sustainable ocean practices and marine policy strategies.

Here, we assess the development of global research on OL with relevance to science, policy and the blue economy. We provide a detailed analysis of what happened and what was published during the last 15 years of research on OL from 2005 (the time when the term OL was first used in a publication) to 2019. To this end, we applied bibliometric techniques aiming (a) to identify the main features of OL research, including indicators of growth, most prolific countries, authors, institutions and publishing outlets; (b) to assess the collaborative structure of OL research at the international and inter-institutional levels; (c) to identify the research coupling OL and blue economy; and (d) to uncover the major thematic areas of research and their progressive evolution.

MATERIALS AND METHODS

Data Collection

Publications related to OL were obtained from Web of Science (WoS) and Scopus databases during August 2020. With the aim to analyze OL as a concept, the search criteria was restricted to publications written in English and the keywords used included "ocean literacy," "ocean literate," "ocean and literacy" and "coast* literacy" as search criteria. Publications were retrieved from the databases' custom data from 1950 and 1960 (WoS and Scopus, respectively) to 2019. The documents where search criteria appeared in the title, keywords, and/or abstract were included in the study. Only documents published in peer-reviewed journals such as article, review and conference paper categories were used. Publications retrieved from WoS and Scopus were merged and duplicates were removed. **Supplementary File 1** includes all keywords and steps used to retrieve publications on OL.

Data Analysis

Bibliometric analysis were carried out using *Bibliometrix* R package (version 3.0.2). *Bibliometrix* is an open-source tool that enables a descriptive and quantitative analysis of the bibliographic data as well as data visualization (Aria and Cuccurullo, 2017). The analysis included the identification of the main features, including indicators of growth, such as number of publications per year, number of authors, institutions and publishing outlets. The most prolific authors, institutions and publishing outlets were also identified. We used the collaboration index (CI) as an indicator of research collaboration. The CI was calculated as the average number of authors on multi-authored papers per year (Elango and Rajendran, 2012). In order to identify the most productive countries, each publication was assigned to its corresponding author's country. For a better visualization of the international collaboration among countries, a collaboration world map was plotted. Afterward, publications were categorized as Single Country Publications, to designate records with authors from the same country, and Multiple Country Publications for records with authors from multiple countries.

In order to complement the macro perspective provided by the collaboration world map, a network analysis was performed using the authors' affiliations (hereafter: institutions) as the units of analysis. The institution collaboration network shows how institutions relate to others in OL research and enables to uncover relevant institutions in a specific research theme. In its graphical representation, the network is made up of several clusters. In each cluster, the institutions are represented by nodes (which size is proportional to its occurrence) and the links represent the collaborations (Aria and Cuccurullo, 2017). Subsequently, we selected the largest network and identified its clusters. A label was assigned to each cluster based on the content of the collaborative publication, to be used as a conceptual guide only. With the aim to identify the publications coupling research on both, OL and blue economy, we extracted the publications in which the title, abstract and keywords were related to the blue economy. We then classified them into categories based on the current sectors of the blue economy.

In order to identify and visualize the major themes on OL research, we performed co-word analysis using the publication's keywords. This technique enables to illustrate associations between keywords by constructing multiple networks based on their similarities (Krsul, 2002). For this specific analysis, we used *KeyWords Plus*, which are the words that frequently appear in the titles of an article's references, but do not appear in the title of the article itself. *KeyWords Plus* is available for WoS publications only. By applying a clustering algorithm on the keywords network, we obtained a two-dimensional diagram, or thematic map, that highlights the different themes present in scientific publications related to OL. Each theme can be analyzed according to the quadrant in which it is placed. The upper-right quadrant indicates the themes that are well-developed also known as motor themes, the lower-right quadrant indicates the basic themes; the lower-left quadrant indicates the emerging or disappearing themes and the upper-left quadrant indicates the very specialized/niche themes (Cobo et al., 2011; Aria and Cuccurullo, 2017). Each sphere represents a network cluster and the cluster names are the words with the higher occurrence values. The sphere volume is proportional to the cluster word occurrences and its position is set according to the cluster's centrality and density. The cluster's centrality measures the strength of the links from one research theme to other research themes, and is an indicator of the significance of a theme in the development of an entire field. The cluster's density measures the internal strength of the network that make up a theme and provides a good representation of the cluster's development (Muñoz-Leiva et al., 2012). To better understand the conceptual evolution of the most recurring themes, we divided the study period in three smaller periods (2005–2011, 2012–2016, and 2017–2019) following the methodology proposed by Cobo et al. (2011). We set a first period of 7 years (2005–2011) given that during the first years of OL research there were few publications and consequently, low number of keywords.

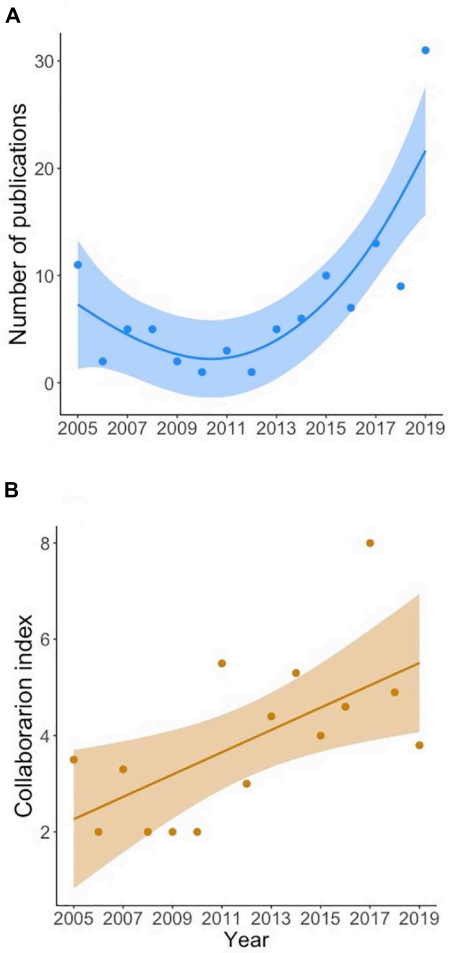

FIGURE 1 | (A) Scatterplot showing the number of publications on Ocean literacy from 2005 to 2019. GAM fitting of the data revealed a positive trend in the number of publications and the appearance of a potential turning point for 2019. **(B)** Scatterplot showing the collaboration index per year. Linear fitting of the data revealed an increase in collaboration among authors.

RESULTS

Development of Global Research on Ocean Literacy

In total, 111 publications were identified suitable for further analysis including 75 articles (67.6%), 30 conference papers (27%) and 6 reviews (5.4%). The development of OL between 2005 and 2019 is shown in the top panel of **Figure 1**. Since 2005, soon after the term OL was formally adopted in the United States, the number of publications has fluctuated over the years, growing by 7.7% on average per year. The overall collaboration index (CI) was 3.8. GAM fitting of the data revealed an increase in the number of publications as from 2012. Linear fitting of CI revealed a positive relationship in the collaborations between 2005 and 2019 (bottom panel of **Figure 1**). In the following years until 2009, publications were dominated by the conference type. The years with less publications were 2010 and 2012 with one article and one conference paper published, respectively. The publication category "review" only appeared in 2017.

A steep noticeable rise in the number of publications was observed in 2019 (n = 31). The number of publishing outlets and authors followed a similar pattern. A total of 368 authors affiliated to 188 institutions have published on OL. Paula Keener-Chavis was identified as the most prolific author with 8 publications (7.2%), other authors included Theodora Boubonari, Mary Carla Curran, Geraldine Fauville and Athanasios Mogias with 4 publications each (3.6%). The majority of authors had an affiliation in the United States (47.7%). The most prolific institutions publishing on OL were led by the National Oceanographic and Atmospheric Administration (NOAA) (14.4%), followed by University of Gothenburg (6.7%), Democritus University of Thrace (5.6%) and National University of Ireland (5.6%). In overall, 57 publishing outlets were identified for the article and review categories (68.4%), and 18 for the conference paper category (31.6%). The most popular journal for publishing on OL was Frontiers in Marine Science (Front.

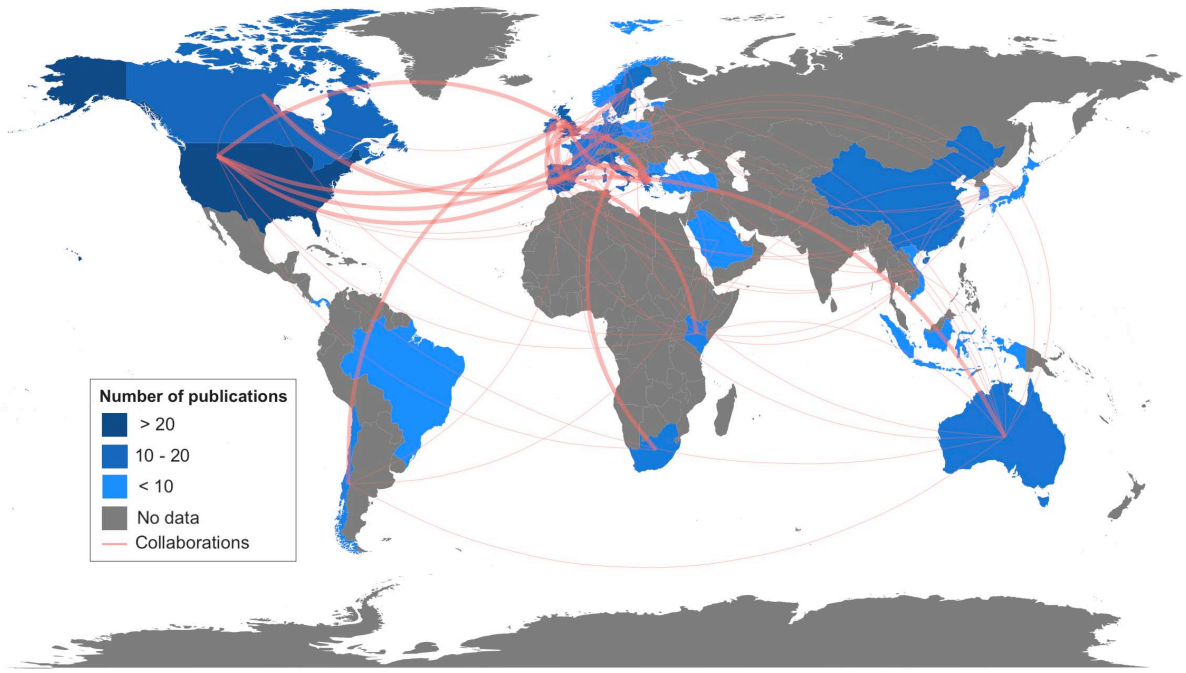

FIGURE 2 | Global collaboration on Ocean literacy research from 2005 to 2019. The blue gradient is proportional to the number of publications by country. Gray color indicates no data and red lines represent collaborations among countries. Line width is proportional to the number of collaborations. World map was created using Biblioshiny app for Bibliometrix R package (version 3.0.2).

Mar. Sci.) with 15 publications, followed by Marine Policy and Sea Technology with 6 and 5 publications, respectively (**Supplementary Figure 1**). Conference papers were published mostly in the Proceedings of OCEANS 05' MTS/IEEE Conference (**Supplementary Figure 2**).

Collaboration Networks

Country Collaboration

A total of 33 countries from five continents have contributed to publishing on OL (**Figure 2**). From the total publications, 20 (18%) were Single Author Publications (SAP) and 91 (82%) were Multiple Author Publications (MAP). The majority of the publications were Single Country Publications (SCP, n = 81; 73%) and a smaller proportion was made by authors affiliated to institutions from different countries (MCP, n = 30; 27%). The United States was identified as the most active country publishing on OL leading with the highest proportion of publications (n = 53; 47.7%) followed distantly by the United Kingdom (n = 10; 9%) and Canada (n = 7; 6.3%) (**Figure 3**). Detailed information regarding country collaboration is shown in **Supplementary Table 1**.

Institution Collaboration

The network analysis of institutions yielded a total of 46 clusters. As most of the clusters were scattered, we extracted the largest network of institutions linked by research on OL resulting in the five clusters portrayed in **Figure 4**. The first group included institutions from the United States and Europe, such as NOAA, College of Exploration, University of California Berkeley, Centro Tecnológico del Mar (CETMAR) and Indigo Med. Based on the content of the collaborative publications, we have chosen to label this group (1) as "ocean exploration and blue economy." Core institutions from group 2 included only European institutions, represented by University of Gothenburg, Democritus University of Thrace, National University of Ireland and the Hellenic Center

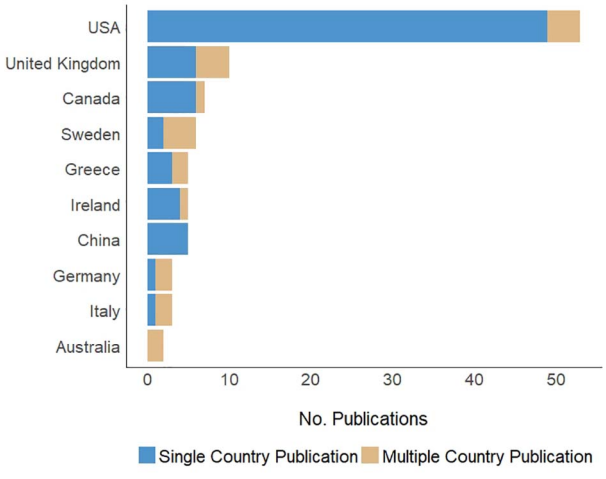

FIGURE 3 | Top 10 publishing countries on Ocean literacy from 2005 to 2019. Multiple Country Publication indicates the number of publications in which there is at least one co-author from a different country. This classification considered the correspondence author's country as the publication's country.

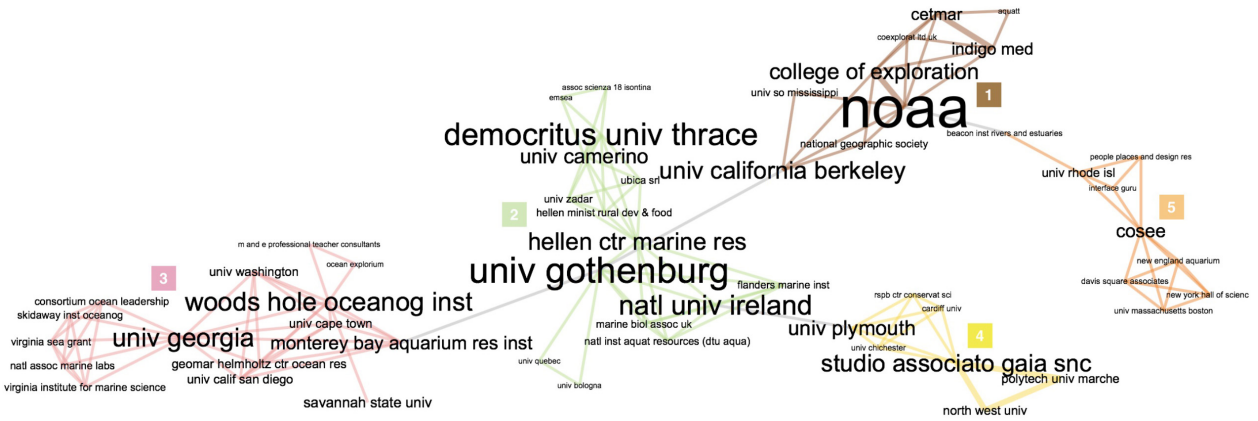

FIGURE 4 | The largest connected institution network in Ocean literacy research between 2005 and 2019 analyzed using collaboration network techniques. Brown corresponds to group 1 ("ocean exploration and blue economy"), green corresponds to group 2 ("marine education and learning technologies"), pink corresponds to group 3 ("oceanography and geosciences"), yellow corresponds to group 4 ("conservation") and orange corresponds to group 5 ("public outreach"). Name size is proportional to the number of publications.

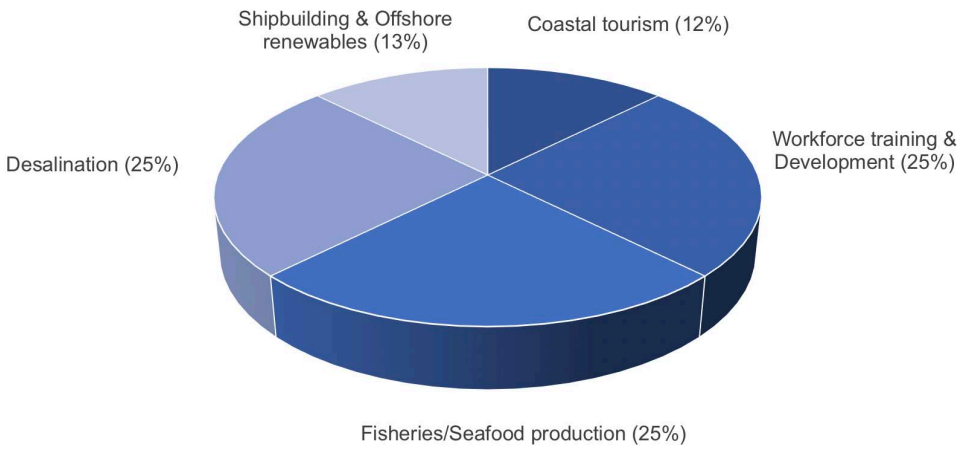

FIGURE 5 | Blue economy topics identified from publications on Ocean literacy for the period 2005–2019 (n = 8).

for Marine Research. The label chosen for this group (2) was "marine education and learning technologies." Core institutions in group 3 where mostly from the United States, including University of Georgia, Woods Hole Oceanography Institute and Monterey Bay Aquarium Research Institute. We have chosen to label this group (3) as "oceanography and geosciences." Core institutions in group 4 included the European institutions Studio Associate Gaia SNC and University of Plymouth. The label chosen for this group (4) was "conservation." Core institutions in group 5 belonged to the United States and included the Center for Ocean Sciences Education Excellence (COSEE) and University of Rhode Island. We have chosen to label this group (5) as "public outreach." The aforementioned group labels should be taken as subjective and only used as indicators of research communities rather than referential thematic definitions.

From the five groups, only group (1) consisted of institutions publishing on blue economy, while only 8 publications (7.2%) from our dataset had a focus on the blue economy. The majority of these publications belonged to the article category (75%), followed by conference papers (25%). A total of 28 authors were identified, belonging to 11 institutions from six countries (United States, United Kingdom, Ireland, Spain, Greece and Turkey). All publications had more than one author ranging from 2 to 8 authors, with 3.5 authors per publication on average. Overall, the publications focused on topics related to workforce development and training as well as industrial sectors such as shipbuilding, offshore renewables, coastal tourism, desalination, fisheries and seafood production (**Figure 5**).

Research Themes

According to their location in the thematic map (upper-right quadrant), the themes Education and Science were identified as motor themes on OL research. The themes Management, Attitudes, Knowledge and Climate Change were the most general or basic themes (lower-right quadrant). The themes Hydrothermal Vent, Decision Making and North Atlantic were

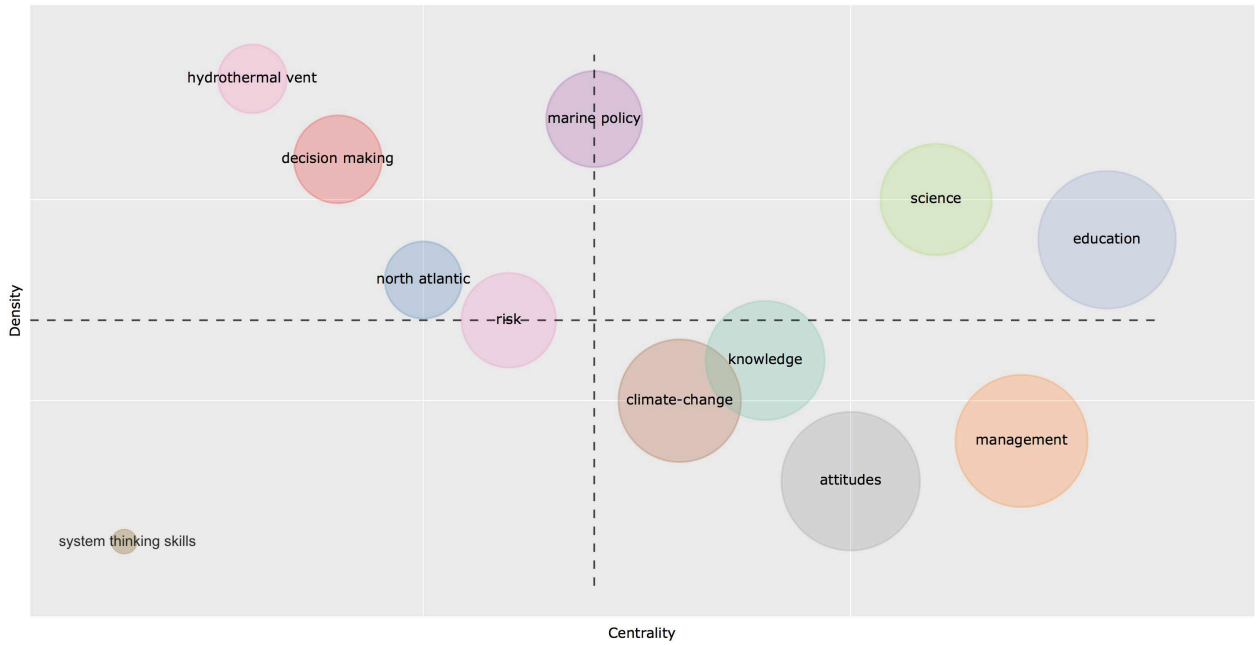

FIGURE 6 | Thematic map on Ocean literacy research for the period 2005–2019 obtained from co-word analysis. The upper-right quadrant indicates the motor themes, the lower-right quadrant indicates the basic themes; the lower-left quadrant indicates the emerging or disappearing themes and the upper-left quadrant indicates the very specialized/niche themes. The volume of the spheres is proportional to the number of publications corresponding to each keyword.

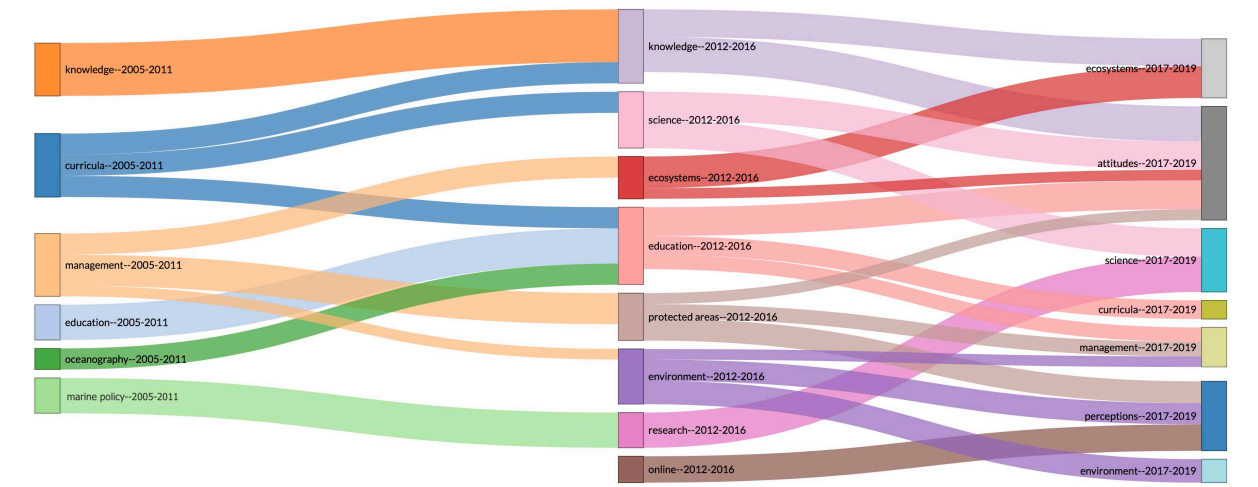

FIGURE 7 | Evolution of Ocean literacy research themes for the periods 2005–2011, 2012–2016, and 2017–2019. Each color represents a research theme and the width of the branches is proportional to the number of publications corresponding to each theme.

three very specialized themes and peripheral in character (upper-left quadrant). The theme System Thinking Skills was presumed to be an emerging theme (lower-left quadrant). The theme Marine Policy was in the transition from motor theme to specialized theme and the theme Risk was in the transition from emerging to specialized theme (**Figure 6**).

Figure 7 illustrates the evolution of the most recurring themes during the periods 2005–2011, 2012–2016, and 2017–2019. Through the analyzed time span, the basic theme Knowledge has unified with Curricula to later become part of the themes Ecosystems and Attitudes. The theme Curricula has diverged into three themes to later reappear in the period 2017–2019. The basic theme Management has diverged into three themes and then has reappeared for the period 2017–2019. The motor theme Education has diverged into three themes, namely Attitudes, Curricula and Management. The theme Oceanography has integrated into the theme Education. Over time, the theme Marine Policy has integrated into Research, which was later integrated into Science. The theme Online has emerged in the period 2012–2016 to be later integrated into the theme

Perceptions. Notably for the period 2017–2019, the theme Attitudes has integrated the motor and basic themes Knowledge, Science and Education.

DISCUSSION

When mapping global research on OL, two main observations regarding its development were identified. First, while the number of publications covering OL showed a slow-growing pattern especially over the first years, the collaboration among researchers seemed more rapidly growing with more authors, countries and institutions involved in publishing. The second observation refers to the identification of research themes underlying in this multidisciplinary topic. Despite its increasing acceptance, the low number of publications on OL indicates that this term has not been widely used in scientific publishing. Previous studies have suggested that research on "environmental literacy" has been more successful than OL research in terms of number of publications (Uyarra and Borja, 2016). Environmental literacy research has produced 292 publications indexed in WoS until 2019, more than twice the amount of publications from OL research. This difference in productivity is understandable given the fact that the OL concept emerged 33 years after the first incorporation of environmental literacy in the scientific literature (Anonymous, 1971). Likewise, Uyarra and Borja (2016) suggested that the interdisciplinary field of "citizen science" was more successful than both OL and environmental literacy. Since 2006 until 2019, citizen science's output has reached 3962 peer-reviewed publications, exceeding by far the other two fields' production (Bautista-Puig et al., 2019). However, "climate literacy," a concept that was adopted in 2006 and that is analogous in structure to the OL concept (USGCRP, 2009), seems to be less successful than OL with only 81 publications indexed in Scopus for the same time span. Additionally, a search of OL in Google gave 155,000 results, suggesting that the term OL is mostly used beyond the scientific domain. We suggest that further research should analyze OL data on websites (web scraping).

Notably, the use of two databases enabled to conduct a comprehensive interdisciplinary search and broaden the field of investigation, minimizing the risk of not capturing the full extent of research on OL. However, the search term "ocean literacy" excludes work by researchers that use different terminology or do not explicitly mention OL. Whereas including other terms in our query such as "marine education" and "ocean awareness" would have expanded our results, we chose to limit our search to one term to avoid over-representing particular themes.

In particular for 2019, the rapid increase reported, with almost five times the average publication rate, may mark a turning point in the OL development with a positive trend that may follow. This increment was, in part, a result of *Frontiers in Marine Sciences* special issue on OL[4]. Considering the new and ongoing initiatives with focus on OL, we should expect them to boost OL publications in the near future. By the time our analysis were done for 2015–2019, there were already 12 publications indexed in WoS and Scopus for 2020, and the Mediterranean Marine Science journal[5] announced a special issue on OL for 2022.

OL research is published in an irregularly distributed manner across publishing outlets. According to our data, the journal with the highest use by OL researchers (Front. Mar. Sci.) accounts for only 13.5% of the publications. Since this topic brings together researchers and ideas from a broad spectrum of academic fields, the journals' scopes are very diverse ranging from computational intelligence and tourism geographies to education and marine policy. Our results indicate the absence of a dedicated journal for OL research, which could be mainly due to the recent origin of the term.

Science mapping enables to reveal hidden patterns in the social structure of a given field, that is, how authors, institutions and countries interact with each other (Aria and Cuccurullo, 2017). Our analysis revealed that authorship is collaborative, with most authors publishing in association with other authors. The positive trend for the collaboration index is particularly promising, suggesting the increase of larger teams and interdisciplinary research that may translate into higher scientific impact (Wu et al., 2019) and productivity (Parish et al., 2018; Murić et al., 2019). In our study, the average level of scientific collaboration on OL research stays aligned to other topics such as biodiversity (Liu et al., 2011), marine sciences (Elango and Rajendran, 2012) and coastal flooding (Gao and Ruan, 2018).

The large number of clusters obtained from the network analysis of institutions, in relation to the total number of institutions, suggests that a cohesive research team has not yet formed. Our results indicate that the international cooperation teams on OL research are gathering but the majority of them are still scattered, with limited cooperation among different institutions. The five research groups represented in **Figure 4** differ in their activity, topics of study and connectivity. The group 2, labeled as "marine education and learning technologies," has the greatest connectivity to other research groups and closeness to the center of the network, suggesting that it is one of the most influential and central research community. Similarly, members of group 1 "ocean exploration and blue economy" and group 3 "oceanography and geosciences" also have high connectivity. This is unsurprising given the fact that several of these institutions have played crucial roles in setting the basis for the foundation of the field and its further dissemination. Institutions from group 4 "conservation" and group 5 "public outreach" are the only non-adjacent groups identified and the furthest from the center of the network. This approach seems very useful to assess the interactions among research communities and has been applied to other interdisciplinary fields such as circular economy (Alnajem et al., 2020) and cultural evolution (Youngblood and Lahti, 2018). However, this approach raises the challenge of labeling the resulting groups in a subjective manner. Hence, we suggest to use our proposed group labels as indicators of research communities rather than thematic areas.

[4]https://oceanliteracy.unesco.org/special-issue-in-frontiers-in-marine-science-on-ocean-literacy/

[5]https://ejournals.epublishing.ekt.gr/index.php/hcmr-med-mar-sc/announcement/view/223

Publications with focus on the blue economy represent a small proportion of the global research on OL (7.2%), indicating that the coupling of these two fields is still developing. OL research has been predominantly pursued within the educational domain, particularly at school level (Williams, 2017; Fauville et al., 2019; Fernández Otero et al., 2019; Mogias et al., 2019), despite its potential to reach citizens in their professional careers and industrial activities across different sectors, including the blue economy (Fernández Otero et al., 2019). As an example of an initiative to reach the maritime sector, the EU-funded MATES[6] project capitalizes the synergies between its partnership integrated by the industry, academia and OL practitioners, to integrate OL as a transversal component in its overall strategy to foster the European shipbuilding and offshore renewable energy sectors (Fernández Otero et al., 2019). Promoting OL research with focus on the blue economy is necessary and of special relevance given that maritime stakeholders, decision-makers and the workforce in general, are not sufficiently aware of the full extent of the environmental, economic, social and political importance of the ocean for their daily lives (Uyarra and Borja, 2016).

International collaboration on OL research is promising. This can be partially attributed to the efforts done by the marine education networks such as the USA-based National Marine Educators Association (NMEA), the Canadian Network for Ocean Education (CaNOE), the International Pacific Marine Educators Network (IPMEN), the European Marine Science Education Association (EMSEA) and the Australian Association for Environmental Education (AAEE) (Marrero et al., 2019). Particularly, the collaboration among European countries is very dense, reflecting high publication activity in a collaborative basis. An example of this are the EU-funded projects Sea Change and ResponSEAble, which have gathered several EU countries and non-EU external experts into partnerships to collectively work in three main societal groups: the general public, formal educators, and policy makers (European Commission, 2018, 2019a). Likewise, the Marine CoLAboration initiative (CoLAB) used a multi-sectorial and values based approach to connect people to the ocean in the United Kingdom (Chambers et al., 2019). Conversely, no research collaborations were found in our dataset within Latin America and Africa. Both regions seem to lack a larger cross-national network to promote OL initiatives in a consistent and culturally relevant way. Nevertheless, the recently created Latin American Marine Educators Association[7] (RELATO) seeks to promote OL in Latin America and the Caribbean, by connecting local initiatives, improving practices and sharing educational material. Additionally, there are several local initiatives on marine education in African countries (SAAMBR, 2019; University of Namibia, 2019; Open Ocean Project, 2020), however, to the best of our knowledge, there is no African network as such. Facilitating the synergies among marine education networks is of particular interest, as this can accelerate the sharing and dissemination of knowledge and attract more attention to OL research, especially in low and middle income countries. Particularly, programs fostering international collaboration for Latin American and African research communities might help to level the playing field.

Education and Science were identified as the most heavily studied themes on OL research, being both well-developed and important for the structuring of this field. This is consistent with previous work that highlighted the emphasis placed on educational approaches on OL research (Costa and Caldeira, 2018). These themes were strategically located in the upper-right quadrant of the thematic map, indicating that they were also related externally to concepts applicable to other themes, such as management and climate change. Our results are well aligned to the current trends in OL research and are supported by previous work done in education (school and higher education) (Schaffner et al., 2016; Mogias et al., 2019) and marine science (Cava et al., 2005; Schoedinger et al., 2005; Visbeck, 2018). Other important themes were management, climate change, attitudes and knowledge, which notably, include strong social aspects and public perceptions (Potts et al., 2016; Ashley et al., 2019; Stoll-Kleemann, 2019). **Figure 7** revealed that most thematic areas evolve in a discontinuous but compact way from their beginning. This suggest that over the time, they attract the interest of the research community, characterized by a progressive growth in the publications on these themes. These findings support the potential advantages of using bibliometric analysis to uncover the intellectual structure and evolution of research themes. Overall, this approach has shown to be effective to analyze the evolution of fields such as climate change (Sharifi et al., 2020), sustainable tourism (Della Corte et al., 2019) and circular economy (Alnajem et al., 2020). One of the limitations of this analysis is that the use of *KeyWords Plus* excludes the publications indexed by Scopus, which does not provide this metadata. However, *KeyWords Plus* was chosen based on its suitability as the best content field for performing analysis on thematic areas and in order to avoid the lack of standardization reported for author's keywords (Ugolini et al., 2001).

Implications for Science, Policy, and the Blue Economy

Our results suggesting that OL is an emerging field of science are not just bibliometric indicators but also powerful evaluation tools for science policy-makers, research managers, and individual researchers. It provides a strategic overview that synthesizes 15 years of research and validates the inclusion of OL as one of the priority areas of research and technology development of the Ocean Decade (R&D 7; Ryabinin et al., 2019). As such, OL should be recognized as a research field and should be allocated adequate funding support for long-term projects and placement in organizational work programs (Eparkhina et al., 2021).

Effective strategies to eliminate the reported disparities in OL research between the Global North and the Global South, are likely to require joint efforts by researchers, practitioners, policy-makers and the industry, with a rapid exchange of knowledge among them (Eparkhina et al., 2021). While research capacity on OL needs to grow globally, particular attention should be given to regions and groups from Small Island Developing

[6]https://www.projectmates.eu

[7]https://relatoceano.org

States, Least Developed Countries and Landlocked Developing Countries (Ryabinin et al., 2019). In addition, training aimed to improve research capacity should be powered by web-based tools, such as MOOCs and virtual reality, to increase information flow and knowledge exchange (Waite et al., 2017; Fauville et al., 2021; Jacobs et al., 2021). To be most effective, OL research will need a solid foundation across the science-policy interface and international cooperation within and across ocean basins, as stated in the Ocean Decade's mission (UNESCO/IOC, 2020a).

OL research with focus on the blue economy seems to be scarce and sector-specific, and will increasingly need to follow an interdisciplinary approach across the marine, maritime, education, social and economic sciences (Bavinck and Verrips, 2020; ten Brink et al., 2020). Managing the blue economy requires managing people, which calls for efforts to better understand their knowledge, attitudes, behavior and needs (Ashley et al., 2019; Cavallo et al., 2020). Such efforts require strategies across multiple sectors, from high-level policy-makers to individual-level behavioral changes (Cisneros-Montemayor et al., 2021). Benchmarking and continued monitoring of OL levels are necessary to evaluate the effectiveness of programs and initiatives (Eparkhina et al., 2021), not only for students but for all actors of society (Kelly et al., 2021), like those directly linked to the ocean, such as maritime workers. This need is well-aligned with the ultimate goal of the Ocean Decade, aiming to connect ocean science with the needs of society and effectively support sustainable development (Claudet et al., 2020; UNESCO/IOC, 2020b).

Overall, this study provides a global perspective on OL research. Our findings evidence the development of the field between 2005 and 2019 using the information contained in scientific publications. Based on our findings, we point out the need to foster coordinated and interdisciplinary collaboration by integrating the scientific community, decision-makers, the industry and relevant practitioners, which can result in stronger and more consistent partnerships. We hope that experts and decision makers could use the results provided by this study to gain a better understanding of the current state of the art in OL research and to orient future research.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

EP-C and TD contributed to conception and design of the study. MM and AV discussed initial ideas. EP-C organized the database, performed the statistical analysis, and wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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