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REVIEW ARTICLE

Four challenges when conducting bibliometric reviews and how to deal with them

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Abstract
The evidence base in environmental sciences is increasing steadily. Environmental researchers have been challenged to handle massive volumes of data to support more comprehensive studies, assess the current status of science, and move research towards future progress. Bibliometrics can provide important insights into the research directions by providing summarized information for several end users. Here, we present an in-depth discussion on the use of bibliometric indicators to evaluate research outputs through four case studies comprising disciplines in environmental sciences. We discuss four big challenges researchers may face when conducting bibliometric reviews and how to deal with them. We also address some primary questions researchers may answer with bibliometric mapping, drawing lessons from the case studies. Lastly, we clarify some misuses of review concepts and suggest methodological principles of systematic reviews and maps to improve the overall quality of bibliometric studies.

Keywords Bibliometric indicators · Case studies · Environmental sciences · Network analysis · Research trends · Bibliometric mapping

Introduction

The scientific literature on environmental sciences endorses crossing boundaries between disciplines, institutions, and countries for environmental studies (Perz et al. 2010). Environmental problems can be so complex to solve that they might require a synthesis of contributions via interdisciplinarity (Lélé and Norgaard 2005; Hirsch et al. 2008), linking science to management through collaboration among universities, governmental organizations, local communities, non-governmental organizations (NGOs), and other stakeholders (Perz et al. 2010). As a consequence, there is diverse and heterogeneous literature across the field, comprising descriptions and assessments, change analysis, the development of environmental solutions (Fortuin et al. 2011; Roudgarmi 2011), and other aspects that integrate natural, social, and applied sciences (Ashley and Boyd 2006; Vincent and Focht 2009; Roudgarmi 2011).

The existing large amount of published environmental research and its constant growth demand from environmental scientists the ability to put each case into context—*what is* published and by *whom*(Fig. 1)—to reveal scientific trends previously unknown (Larsen and von Ins 2010; Lokers et al. 2016; Gibert et al. 2018). Bibliometrics can contribute fundamentally to this purpose, making it possible to examine how disciplines are developing (Romanelli et al. 2018) and how pieces of evidence are connected, revealing the structure of whole fields (Nakagawa et al. 2018). Besides, it provides information on the current knowledge status and supports the

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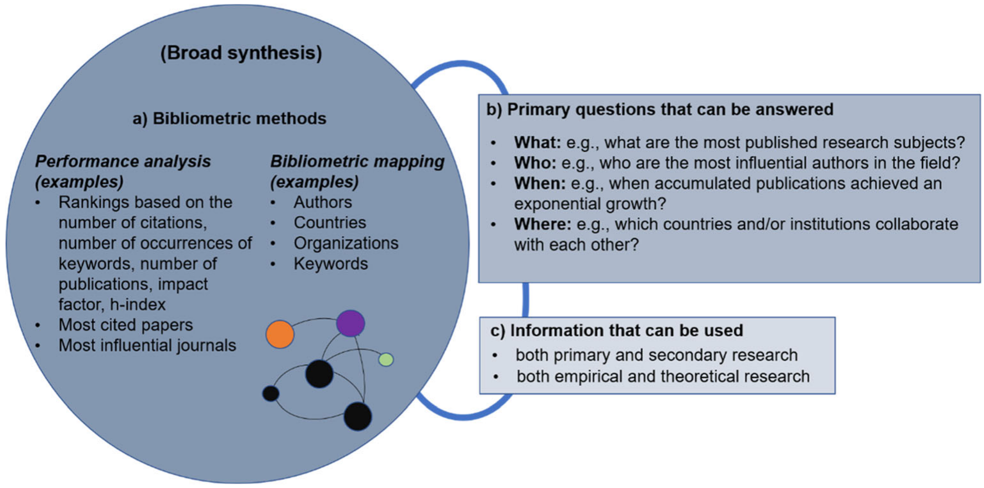

Fig. 1 Bibliometrics as a broad synthesis and its scope. (a) Bibliometric methods and examples from the case studies. (b) Primary questions that can be answered with bibliometrics. (c) Types of data used in bibliometrics

development of future research lines (Pilkington and Chai 2008; Romanelli et al. 2018; Cabeza-Ramírez et al. 2020).

Bibliometrics held a privileged position among the various statistics of science. This is one of the few subfields concerned with measuring the output side of research (Godin 2006). According to most historical references, its initial systematic development is due to D.J.D. Price and Eugene Garfield, as founders (Godin 2006; Huang et al. 2014). Across the scientific literature, bibliometrics is used both to quantify the impact of research and determine the structure of research fields by means of two methods (Fig. 1): (i)*performance analysis*, which quantifies the performance of scientific actors (e.g., rankings of the most influential authors and publishers) through measures of productivity (e.g., publication numbers over time); (ii)*bibliometric networks* (also known as science mapping or bibliometric mapping), which represents structure within the scientific literature by analyzing connections between authors, institutions, and keywords (Nakagawa et al. 2018). We can, for instance, use the analysis of the networks over time to document and visualize the development of a field (van Eck and Waltman 2014).

Bibliometric analysis can objectively identify both seminal (the most cited) and less connected (or isolated) studies among a population of articles revealing trends as a set of concepts (Cobo et al. 2011; van Eck and Waltman 2014; Vincenot 2018). Furthermore, being displayed as a map, bibliometric information can be represented as a web (Fig. 3). Some of the bibliometric methods are beginning to be used in other types of reviews, such as those that incorporate principles of systematic reviews and maps (see glossary); a recent example includes an analysis of authors' keywords to describe a population of studies within a collection of relevant literature (e.g., Romanelli et al. 2020a). However, despite their high level of complementarity, bibliometrics is rarely explicitly coupled with systematic approaches (Nakagawa et al. 2018).

Given an outlook between the approaches of systematic maps and bibliometrics, the 5W1H questions (who, when, where, what, why, and how) are helpful to understand their similarities and differences. Both systematic mapping and bibliometrics answer primary questions such as who, when, where, and what; for example, who conducted the research; when the research was performed; where the research was

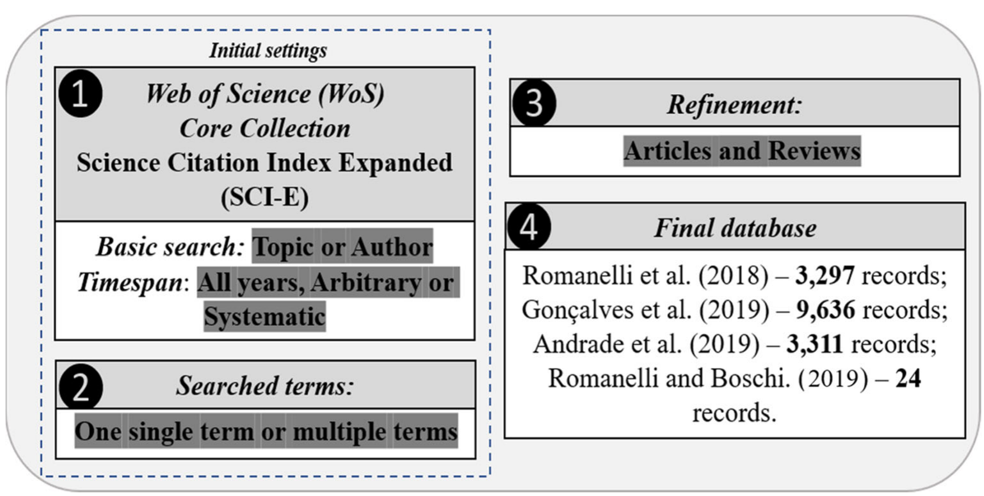

Fig. 2 Summarized methods and results from Romanelli et al. (2018), Gonçalves et al. (2019), Andrade et al. (2019), and Romanelli and Boschi (2019), employing the Web of Science (WoS) platform as a bibliographic source

Table 1 Synthesis of the initial configurations of searches in the Web of Science, and bibliometric indicators explored in each case study. *Abbreviation: NP*, number of publications; *NC*, number of citations; *NO*, number of occurrences; *IF*, impact factor

Science Citation Index Expanded (SCI-EXPANDED)

		Romanelli et al. 2018	**Gonçalves et al. 2019**	**Andrade et al. 2019**	**Romanelli and Boschi 2019**
Initial settings	***Timespan***	Arbitrary (21 years)	Systematic (27, 10, and 5 years)	Arbitrary (20 years)	Systematic (28 years)
	Basic search	Topic	Topic	Topic	Topic and Author
	Searched term(s)	One single term	Multiple terms	Multiple terms	Multiple terms
	Final database	3297 records	9636 records	3311 records	24 records
Bibliometric indicators	***Bibliometric mapping***	Countries, authors, and organizations	Countries, authors, and organizations	Keywords	Keywords
	Geographic distribution (spatial analysis)	-	20 most productive countries	10 most productive countries	-
	WoS categories	Top 5	Top 6	Top 5	-
	Rankings	NP, NC, NO	NP, NC, NO, IF, h-index	NP, NC, IF, h-index	-
	Journals	Top 20	Top 40	Top 10	Top 3
	Keywords	Keywords-plus and author's keywords (40 words)	Keywords-plus and author's keywords (50 words)	Author's keywords (50 words)	Author's keywords (2 occurrences)
	Most cited papers	Top 12 (20 years)	Top 40 (27, 10, and 5 years)	Top 10 (20 and 5 years)	-

conceived (Nakagawa et al. 2018); what are the main research topics published in a research field. Conversely, only systematic mapping answers detailed what, why, and how questions. For example, what researchers study (e.g., biome, or ecosystem); why they study it (i.e., their questions or hypotheses); and how they study it (e.g., experimentally, comparatively) (Nakagawa et al. 2018). Notably, these approaches have been discussed side-by-side in the recent evidence review literature (e.g., Nakagawa et al. 2018), being presented as integrative methods that can provide a detailed synthesis of both evidence and influence.

Considering that the number of environmental science publications is increasing exponentially and researchers require informative and reliable reviews (such as bibliometric reviews) to stay up to date, besides moving science towards progress, this study has two-fold objectives. First, to discuss four big challenges researchers may face when conducting bibliometric studies and how to deal with them. We go forward discussing some primary questions researchers may address with bibliometric mapping, drawing examples from four authorial case studies. Second, we discuss how bibliometric studies can improve in quality by suggesting best practices based on principles of systematic reviews and maps.

Description of the case studies

In order to achieve the two stated objectives, we performed a synthesis of methods and results of four authorial bibliometric studies published by this team (Romanelli et al. 2018; Gonçalves et al. 2019; Andrade et al. 2019; Romanelli and Boschi 2019), which covered varied research topics into the field of environmental sciences. These papers were selected due to (i) presenting different sizes of databases (i.e., different number of publications gathered) (Fig. 2); (ii) addressing different research topics within the environmental sciences; (iii) presenting different strategies to handle bibliometric indicators (Table 1). The Science Citation Index Expanded (SCI-E)-Clarivate Analytics - Web of Science© was used to conduct all the studies. Only articles and reviews were considered for analysis in each paper, considering these documents represent the majority of the complete research results (Fu et al. 2013; Boudry et al. 2018).

In Romanelli et al. (2018), bibliometric analysis was used to assess the global scientific production on *restoration ecology* over 20 years (1997–2017), comprising 3297 publications. From this study, we highlighted the performance of collaboration networks and the analysis of keywords to assess occurrences of research subjects. In Gonçalves et al. (2019), bibliometrics was used to address the research on *enzyme immobilization* in a period of 27 years (from 1991 to 2017), comprising 9636 publications. From this study, we focused on results by the analysis of the temporal dynamics of bibliometric indicators (27, 10, and 5 years). In Andrade et al. (2019), we evaluated the historical and recent trends on *electronic waste* research (1998–2018), based on 3311 publications. From this study, we emphasized the research trends stratified by countries. Finally, in Romanelli and Boschi (2019), we evaluate the research on *common forests*, discussing the performance of bibliometric indicators in a "narrow database" (i.e., a database with few publications gathered), based on 24 publications.

Bibliometric indicators discussed here were chosen because they are accessible for non-bibliometricians to use in scholar assessments, are simple to manipulate, aim at measuring concepts such as quality, quantity, and excellence, besides the impact of the best papers, and also enable cross-field comparisons.

Four challenges when conducting bibliometric reviews

Recognizing the constraints that researchers can sometimes face when attempting to plan, conduct, and publish a high-quality bibliometric review, we discuss here major challenges in conducting this type of synthesis, making use of recent examples (case studies) from across the environmental sciences. Adopting a "critical friend" role of supporting potential bibliometric reviewers, discussion goes on to present what was done in the four case studies and discuss how that impacted our findings. We then highlight existing available tools to support these issues and present other recommendations. For clarity, we use the following terminology: (i) search terms, encompasses individual or compound words used to find relevant documents; (ii) search string, a combination of search terms using Boolean operators; (iii) search strategy, the whole search methodology, including search terms, the bibliographic sources searched, and enough information to ensure the repeatability of the search; (iv) bibliography, articles generally described by authorship, DOI identifiers, title, year of publication, place of publication, editor, and keywords; and (v) search syntax, the set of options provided in the interface of the bibliographic source to achieve searches (Livoreil et al. 2017).

Identifying relevant sources of articles

A primary challenge that authors can face when developing bibliometric reviews relies on which bibliographic source to use since various sources of articles relevant to the study may exist. Understanding the coverage, functions, and limitations of bibliographic sources can be time-consuming. Thus, potential authors are encouraged to involve a librarian or other specialist at this stage. Overall, a bibliographic source allows bibliographies to be organized by providing a search platform and a retrieval interface. There are different options to investigate, for example, individual electronic bibliographic sources such as Biological Abstracts, and also platforms that allow simultaneous searches of several databases (e.g., Web of Science). Furthermore, there are also both subject-based sources (e.g., CAB ebooks; applied life sciences, applied economics, food science, agriculture, environment, nutrition, and veterinary sciences) and multidisciplinary sources such as Scopus and Web of Science (Livoreil et al. 2017). Nevertheless, not all bibliographic sources are completely accessible for all users. This will depend on the institutional subscriptions available to the project team members (Grames and Elphick 2020). So, it is important to check and document in the study which ones were accessed. Echoing recommendations from Glanville (2017), potential authors engaging with reviews should start their searches using a source where the largest number of relevant papers is likely to be found, bearing in mind that the use of a single bibliographic source tends to limit the external validity of the results (i.e., the generalizability of the information obtained). This was extensively discussed in Higgins and Green (2011) and CEE. Collaboration for Environmental Evidence (2018).

Following the principles of systematic reviews and maps, several sources should be searched to ensure that as many relevant articles as possible are identified (Avenell et al. 2001). However, this is rarely considered in bibliometric reviews (Nakagawa et al. 2018), including those we have written (Romanelli et al. 2018; Gonçalves et al. 2019; Andrade et al. 2019; Romanelli and Boschi 2019). In these four case studies, only the Sci-Expanded Index (Science Citation Index Expanded) within the Web of Science (WoS) as a bibliographic resource was explored. WoS platform is largely used for conducting bibliometric studies and other types of evidence synthesis across the environmental sciences (Wildgaard 2015; Calver et al. 2017; Romanelli et al. 2020a, b). It covers the majority of significant scientific results, as well as other online databases that also contain citation information such as Google Scholar, Scopus, Science Direct, and SciELO. Through extensive evaluation of content, author-diversity, citations, and timeliness, journals are added or removed each year from its databases (Wildgaard 2015). This means that the indexing policies of WoS have a direct effect on the validity of bibliometric indicators (Testa 2009) because of different versions of the WoS permit access to different indexes (Haddaway 2017; Grames and Elphick 2020). As a consequence, bibliometric analysis can result in different pictures of the scholar's performance according to the institutional subscriptions available (Wildgaard 2015; Grames and Elphick 2020).

Accordingly, we argue that a decision on "what" or "how many" bibliographic sources to investigate in bibliometric studies will mostly depend on the disciplines that are being addressed by the research subject (e.g., social sciences, applied sciences) and the identification of sources that may provide the greatest quantity of relevant articles for a limited number of searches (Livoreil et al. 2017).

Selecting search terms

A bibliometric analysis starts with a context of interest, which can be a discipline such as "restoration ecology" (Romanelli et al. 2018), a practice within a research field such as the "enzymatic immobilization" (Gonçalves et al. 2019), and so on. This context is often structured into "building blocks" (concepts or elements) and then used as search terms. Selected search terms need to be combined in a search string to gather as many relevant results as possible (exhaustiveness) while also limiting unwanted results (precision). Importantly, selecting search terms and posteriorly building search strings require review teams to draw upon both their scientific expertise and a certain degree of imagination. Previously analyzing titles, author's keywords and abstracts may represent a viable strategy (Livoreil et al. 2017). Reading published reviews on the subject of interest may also help to identify relevant search terms. Furthermore, experts and stakeholders can also suggest other relevant terms. Other approaches involve the use of bibliometric tools, for example, in the R environment, such as the "litsearchr package" (Grames et al. 2019), which support the selection of search terms using keyword co-occurrence analysis. Similarly, the software VOSviewer©, which was used in the four case studies, also offers this functionality and was expressly designed for the analysis of bibliometric data (van Eck and Waltman 2010). By using VOSviewer, we identified the terms of higher and lower occurrences on the research subject in analysis, supporting the selection of search terms. We recommend starting the search for articles with a general term comprising the research subject, then include variations or synonyms of this term that may appear in this analysis. Defining an effective search string combining relevant search terms is crucial for any bibliometric study since the searching stage lays the foundation of all successive steps of the review (Grames and Elphick 2020; Romanelli et al. 2020a). Lastly, we emphasize that the use of acronyms and abbreviations as search terms may be used carefully because it can recover several non-related publications where different terms/expressions are abbreviated in the same way. For example, the acronym LIBS, which is used to refer to an important subject within the study of Andrade et al. (2019), retrieved articles both referring to the context of "laser-induced breakdown spectroscopy" (LIBS)—a spectroscopic technique, and also "lithium-ion batteries" (LIBs)—a rechargeable battery.

Building the search strategy

To build up the search strategy, the review team should rely primarily on the syntax information that is available in the help pages of the bibliographic sources, including the use of Boolean operators and other important functionalities available to define the population of articles relevant to the synthesis (e.g., the timespan, type of documents) when applicable. Some typical syntax features are discussed below and will vary by interface.

First, the establishment of the timespans (i.e., the period of analysis) is a fundamental step to define the set of publications that will be analyzed in bibliometric studies, and different strategies can be used according to the objective of the study. For instance, in Romanelli et al. (2018) and Andrade et al. (2019), we established arbitrary timespans (two decades) to limit the population of articles. This strategy is feasible to employ when the objective of the study is to show recent trends in the literature, considering that old publications would be excluded from the analysis and just recent research outputs will be present. Limiting timespans is also an alternative to decrease the number of available publications to make efforts of literature review viable. Nonetheless, by following the principles of systematic reviews and maps (Haddaway et al. 2015; CEE. Collaboration for Environmental Evidence 2018), it is recommended that the searching process be as comprehensive as possible, avoiding so-called temporal bias (Leimu and Koricheva 2004; Bayliss and Beyer 2014). Strongly positive studies are more likely to be published sooner and this may influence temporal trends as well as the magnitude and direction of the effect being investigated (Leimu and Koricheva 2004). We understand that in bibliometric studies determining effects is not a real concern, due to the nature of bibliometric data. However, research trends tend to substantially change depending on the timespan considered, as demonstrated in Gonçalves et al. (2019) and Andrade et al. (2019). For example, in these studies, we explored different types of information in rankings to perform a temporal analysis of bibliometric indicators such as (i) the number of citations and the number of accumulated publications (primary values), and (ii) index values and scientific coefficients like the impact factor (used to evaluate journals) and the *h*-index (used to evaluate journals and authors). These analyses revealed that (i) there may be significant positioning changes in the rankings of the most influential journals when considering different timespans, which may be associated with changes in the authors' preferences by other publishing sources or even the emergence of new journals; the number of citations and the *h*-index also tend to follow this trend, showing significant changes according to the period of analysis; (ii) rankings of the most productive authors may (or may not) change significantly over time; even so, new authors may stand out in rankings from shorter and more recent periods when compared to the rankings of longer periods; (iii) rankings of the most cited publications may also remain more or less stable in the temporal analysis, since the number of citations tends to increase over time and older publications tend to be the most cited ones. However, recent studies with a high number of citations may emerge, indicating, for example, new perspectives and/or new research interests (Okubo 1997; Romanelli et al. 2018).

Moreover, in Gonçalves et al. (2019), we defined the timespan after a prior assessment of the body of literature was retrieved. In the beginning, the entire period available in the WoS at the time (1945 – 2019 (current year)) was considered, then relevant landmarks across the database were used to define the period of the bibliometric analysis (e.g., the starting year when the research subject achieved a specific number of accumulated publications). This strategy was also used by other authors in environmental sciences (e.g., Boanares and Azevedo 2014). Differently, in Romanelli and Boschi (2019), we used the year of the publication of the seminal book of Elinor Ostrom (Ostrom 1990) as a landmark to define the period of the bibliometric analysis. Summarily, potential authors of bibliometric reviews should realize that limiting the timespan may represent a way to "shape" the analysis and make it more operational/feasible; nonetheless, this tends to reduce the external validity of the results, which should be considered before starting the study and subsequently reported in the resulting review.

Second, authors of bibliometric reviews may also face the challenge of choosing which field of search to use (i.e., the form to enter search terms in the platforms and/or databases) for retrieving articles across bibliographic sources. This is an important concern because the strategy employed will also influence the comprehensiveness of the searches, the number of articles retrieved, and consequently the types of metrics that will be feasible to be analyzed in bibliometrics. Different options are available, for example, searching by *topic*, *source name* (journal titles), *authors*, *digital object identifier* (DOI), among others. In WoS, although setting the search for articles by *topic* is the most comprehensive way to retrieve articles, this option can also return lots of non-related publications, as it retrieves entered search terms from the title, abstract, authors' keywords, and keywords-plus. *Keywords-plus,* in particular, are generated in WoS by the most frequent keywords that occurred in the titles of the references cited in each study, and they are not always associated with the main context of the study but are retrieved even so. Therefore, when using the search by *topic* in WoS, we recommend screening by relevance to the synthesis all publications gathered, mainly those retrieved by the keywords-plus. A viable alternative to solve this problem is to screen publications by relevance to the synthesis using specialized (e.g., EPPI-reviewer-http://eppi.ioe.ac.uk/cms/) or multifunctional (e.g., Microsoft Office Excel) software, by adding filters and removing unrelated publications. Except for Romanelli and Boschi (2019), which we used the strategy of searching by *authors* to retrieve publications of the main author of the research subject being investigated, all other studies used the *topic* option. Accordingly, a decision needs to be made as to which field of search will be the most appropriate for attending the objective of the study.

Third, authors may also face a critical challenge when combining selected search terms to build up the search string. How individual or compound words perform as search terms, and how to use special characters (e.g., quote notes or asterisks) and Boolean operators are issues not always well-understood by authors of reviews in environmental sciences (Romanelli et al. 2020a). Nevertheless, this is a crucial issue because only providing a poorly structured search string is not enough for achieving a high-quality bibliometric study, and any change in the search string can lead to different results, so nuances over review conclusions may emerge (Grames and Elphick 2020). We summarize below important insights on using different strategies to establish the search string.

In some cases, using a single search term or a composite search term (between quotes) may be broad enough to retrieve most publications on a given research topic. For instance, in Romanelli et al. (2018), we used the term 'ecological restoration' (enclosed by quotes) in the search. The quotes were used to fix the order of the words, forming an expression to describe the practice of the discipline restoration ecology, setting the search to retrieve only publications that presented this exact order of terms. This strategy can be seen as restrictive; however, the probability of recovering non-related studies is reduced due to the specificity of the term, but it still exists. The more words are combined in the quotes, the more restrictive the search becomes. Consequently, fewer publications tend to be retrieved. Conversely, the use of the asterisk (wildcard character) at the end of the word broadens a search by finding variations of a term starting with the same letters (e.g., plural variation, different verb tenses). For example, the search by 'mammal*' will retrieve variations of keywords such as mammals or mammalian (Palencia et al. 2009; Ponce and Lozano 2010).

Regarding Boolean operators, we focused our discussion not only on the use of *OR* and *AND* because they were extensively used in our case studies, but also on the use of the Boolean *NOT*, due to its important function of excluding unwanted articles, thus supporting the definition of the dataset. Boolean operators group terms into blocks, structuring the search to be reproduced (CEE. Collaboration for Environmental Evidence 2018). Each operator has a specific search function that must be thoroughly understood to be used correctly. The operator *OR*, in particular, retrieves articles with at least one of the terms, making it possible to search for a term and its synonyms simultaneously, broadening the search results. This strategy was used in Gonçalves et al. (2019) and Andrade et al. (2019), where multiple search terms (synonyms) were combined with *OR* to account for most variations of terms related to the topic being investigated. Conversely, the operator *AND* is used to retrieve only articles containing all the input terms, resulting in a more limited result. For instance, in Romanelli and Boschi (2019), the Boolean *AND* was used to associate different research subjects within the same context (e.g., governance *AND* forest). Lastly, the operator *NOT* is used to exclude terms from a search, eliminating from the results any publication that contains a certain term. Yet, it is important to use the operator *NOT* carefully to avoid excluding relevant papers accidentally. For example, searching for ("mammal*" NOT "fish") might omit a paper that is on both mammals and fish which contains relevant mammal data. The term has been properly excluded, but a relevant paper may be omitted (CEE. Collaboration for Environmental Evidence 2018; Romanelli et al. 2018).

Developing bibliometric networks (science mapping)

Bibliometric mapping has been widely used to evaluate the social and intellectual roots of disciplines (Koseoglu 2016; Viana et al. 2017). Generally, this analysis is performed through the criteria of co-authorship, co-occurrence, co-citation, or bibliographic coupling (Abbasi et al. 2011; Zupic and Cater et al. 2014; Leydesdorff et al. 2016). A bibliometric map can incorporate different data and displays networks and connections among (i) authors, based on the number of documents they share (co-authorship analysis); (ii) publications, by quantifying the number of documents in which terms and text similarities occurs (co-occurrence/co-word analysis); (iii) citations, based on the number of times they are cited together (co-citation analysis) or the references that articles share (bibliographic coupling) (van Eck and Waltman 2010; Cobo et al. 2011; Zupic and Cater 2015).

By analyzing networks, several aspects of scientific collaboration can be traced (Glanzel and Schubert 2004) and the four types of 4W primary questions (Fig. 1) can be investigated (Nakagawa et al. 2018). For example, in Romanelli and Boschi (2019) and Andrade et al. (2019), we showed "what" was published (although not as detailed as in systematic maps) by analyzing the co-occurrence of authors' keywords, revealing the hot topics among research subjects (Fig. 3a). In Romanelli et al. (2018) and Gonçalves et al. (2019), we displayed in bibliometric maps "who" developed the research and "where," showing which authors, institutions, and countries established an international research collaboration (Fig. 3b). Although the "when" question was not explored in the four case studies, it is possible to join different types of information to address this question (e.g., authors' keywords or countries) with a tool that provides an "overlay visualization" functionality (e.g., in the VOSviewer software), making possible the combination of bibliometric data over time (Fig. 3c).

All bibliometric maps presented in the four case studies were generated with VOSviewer© software, considering the co-authorship criterion to evaluate collaborations among authors, organizations, and countries (Romanelli et al. 2018; Gonçalves et al. 2019), and the co-occurrence criterion to evaluate trends across authors' keywords (Romanelli et al. 2018; Gonçalves et al. 2019; Andrade et al. 2019; Romanelli and Boschi 2019). In general, we noticed that the network analyses involving collaborations between countries or authors are more appropriate for large databases because there is sufficient information to characterize the networks, whereas the network analysis based on the co-occurrence of keywords may provide valuable and detailed information for both types of databases (i.e., with a small or large number of publications) (e.g., see Romanelli and Boschi 2019).

The number of retrieved publications (the database) in each case study varied substantially, resulting in different strategies for analyzing networks. In Romanelli et al. (2018), Gonçalves et al. (2019), and Andrade et al. (2019), the strategy of minimum counting of keywords was used to generate the maps, limited to display 40, 50, and 50 words, respectively (Table 1). Importantly, in these studies, we eliminated meaningless words (also called stop words) and/or synonyms for improving the robustness of the analysis. Alternatively, in Romanelli and Boschi (2019), we used the strategy of considering a minimum number of occurrences of keywords to set the analysis instead of establishing a specific number of words, considering that this database has low occurrences of terms overall.

Furthermore, in Gonçalves et al. (2019) and Andrade et al. (2019), we investigated the collaboration networks in association with the geographic distribution of publications through spatial analysis (Fig. 3d). Both papers explored geographic maps to display bibliometric data stratified by countries. Through this analysis, it was possible to formulate other questions that may be opportunities for future research in the field of environmental sciences, such as (i) does the proximity between countries favor the research collaboration networks?; (ii) is there a scientific focus in a certain region or continent? (Fig. 3d).

Towards high-quality bibliometric reviews in environmental sciences

Here, we present some important final insights for potential bibliometric users in the field of environmental sciences:

(i) It is difficult to infer when a body of literature is sufficiently comprehensive to deliver reliable results (outputs) on a given topic, but bibliometric practitioners should guarantee that the search string is sensible enough to gather as many as possible related publications, whereas avoiding unwanted ones.

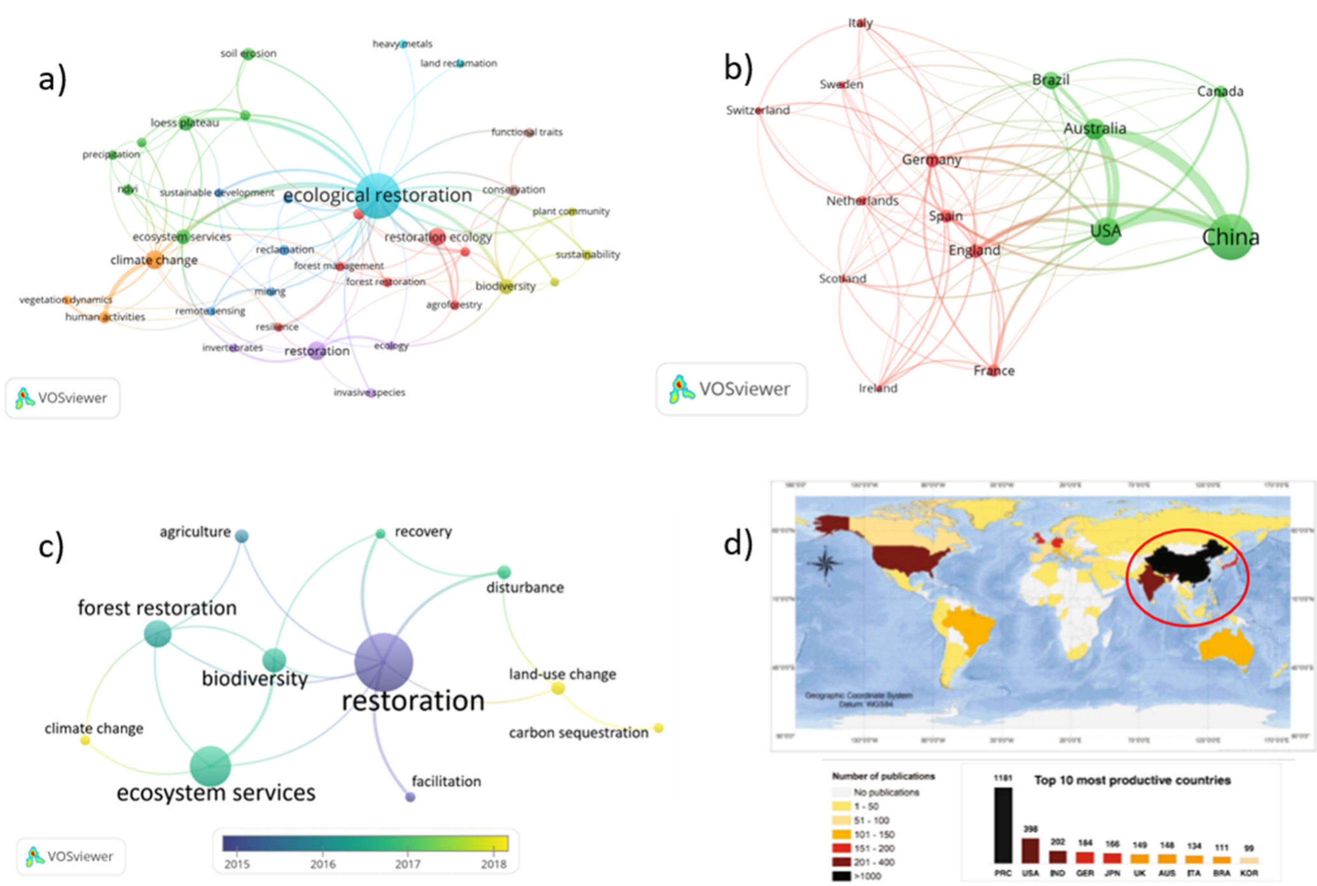

Fig. 3 Types of bibliometric networks and their scope (a, b, c) and spatial analysis of bibliometric data (d). (a) Authors' keywords used to display in networks *what* was published as research subjects. (b) Country collaboration map displaying in networks *where* the research was developed. (c) Main research topics (authors' keywords) displayed over time addressing the *when* question. (d) Geographic distribution of publications (number of publications) through spatial analysis (Andrade et al. 2019)

(ii) There is still no unique bibliographic resource covering all the available literature in environmental sciences and each one provides different search functionalities and has its specific journal indexing policies. Therefore, comprehensive searches demand searching for multiple bibliographic sources.

(iii) Bibliometric readers and users should be aware that the results expressed through bibliometric indicators can vary substantially depending on the bibliographic source used, and thus do not represent the whole academic activity.

(iv) The WoS platform is the main source of scientific information used by environmental researchers (Calver et al. 2017; Lázaro-Lobo and Ervin 2019; Romanelli et al. 2020b); however, there is a generalized conceptual misunderstanding about its functionalities. The WoS is not a single "database" as many authors claim. WoS is a platform on which many databases can be interrogated (Haddaway 2017).

(v) In the four case studies (Table 1), we explored only the Science Citation Index Expanded (SCI-EXPANDED) as a bibliographic resource within WoS. Nevertheless, the Social Sciences Citation Index (SSCI) may also be an important source of information for conducting bibliometric studies in environmental sciences, since this research field also comprises the social sciences (Guan et al. 2018). Additionally, the Emerging Sources Citation Index (ESCI) also contains complete records of papers indexed by journals not yet covered by SCI-EXPANDED or SSCI. Journals indexed in ESCI reach the minimum standards of editorial quality, but as they are relatively new, they are still under evaluation to be indexed in these citation indexes. So, relevant scientific results may also be found in the ESCI, which can influence the bibliometric metrics.

(vi) Bibliometric indicators should not be considered a real measure of research quality. The impact factor (IF), for example, is the main metric used worldwide to assess the importance of scientific journals when accounting for citations received in respective areas (Garfield 1972; Glanzel and Moed 2002). Nonetheless, a measure of the quality and impact of a paper, based on the number of citations, is not entirely reliable, since different journals have their own indexing policies. Furthermore, well-founded articles may have few citations, which can be explained by "preferences" on research subjects by the academic community.

(vii) Although bibliometric analysis aims to prospect and collate most publications related to a given topic, it should be seen as a sample of the literature.

(viii) Bibliometric approach is quite different from systematic approaches, such as systematic reviews and maps (see "Glossary"). Systematic approaches include greater methodological robustness in terms of scope, transparency, and objectivity. For further details, see Pullin and Stewart (2006), CEE. Collaboration for Environmental Evidence (2018), and Nakagawa et al. (2018).

(ix) To conduct more robust, reliable bibliometric reviews, it is necessary that authors document and ensure greater methodological transparency in all steps, including the inclusion/exclusion of studies, effectively documenting the screening process, and detailing any activity for delimiting and analyzing data. Moreover, counting for duplicates of publications when searching in multiple bibliographic sources is also crucial to increase the reliability of outputs in bibliometric studies.

(x) Finally, a key frontier for future meta-research (i.e., research on research) is to understand how individual researchers and their respective teams can contribute to the generation of scientific knowledge. In this regard, the concept and framework for research synthesis named *research weaving* have emerged in the environmental field. Research weaving goes towards synthesizing both evidence and influence, combining systematic mapping and bibliometric methods. For an extensive discussion on research weaving, we recommend Nakagawa et al. (2018).

Glossary *Systematic review,* "rigorous summary of research literature on a given topic that has been conducted using structured, transparent, and reproducible methods. The term could be used to indicate any review that uses approaches involved in a systematic review (i.e., systematic review approach)" (Nakagawa et al. 2018); *Systematic map,* "literature summary conducted using strict, systematic standards. It summarizes the characteristics of studies from a broad research field in a database, figure, or graph. Can identify knowledge gaps and knowledge clusters". (Nakagawa et al. 2018)

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