Research Weaving: Visualizing the Future of Research Synthesis

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Abstract (120 max)

We propose, and formalize, a new framework for research synthesis of both evidence and influence, named ‘research weaving’. It summarizes and visualizes information content, history, and networks among a collection of diverse publication types on any given topic. Research weaving achieves this feat by combining the power of two methodologies: systematic mapping and bibliometrics. Systematic mapping provides a snapshot of the current state of knowledge, identifying areas needing more research attention and those ready for full synthesis (e.g., using meta-analysis). Bibliometrics enables researchers to see how pieces of evidence are connected, revealing the structure and the evolution of a field. We explain how to become a ‘research weaver’, and discuss how research weaving may change the landscape of research synthesis.

Keywords: meta-research, quantitative synthesis, systematic review, Big Data, data visualization, evidence synthesis (max 6)

A New Framework for Research Synthesis of Evidence and Influence

Research fields are flooded with torrents of publications, and researchers require informative reviews to stay afloat. For many years, researchers sought expert opinions from **narrative reviews** (see Glossary) to obtain and update their knowledge of a research topic or question [1]. These reviews were valuable not just for summarizing ‘facts’ about a particular research field, but also for giving broader insights, such as identifying the origin and development of key theoretical concepts, or drawing attention to ideas that deserved greater research focus. More sophisticated syntheses are now commonly used – **systematic review** and **meta-analysis** [2-8] – which incorporate systematic and often quantitative methods to extract factual information from the literature in a reliable manner. However, both these syntheses have their limitations. They are not practical for broad fields encompassing thousands of publications, and cannot handle a highly heterogeneous literature. A new technique has emerged to deal with these limitations: mapping.

Currently, scientists’ ‘map’ research evidence using two complementary methodologies of different origins: **systematic mapping** and **bibliometrics**. Systematic mapping (sometimes called ‘**evidence mapping**’) is a method derived from systematic reviews, with the goal of classifying the types of research on a broad topic [9-14]. Systematic mapping is still a nascent methodology, with the first systematic maps appearing only in the last decade [9, 10]. In addition to providing a written report, a systematic map typically involves the production of a database of studies and their attributes, which can be provided to users as a searchable database or a series of visualisations [10-12]. In contrast, **bibliometrics** (more specifically '**bibliometric mapping'** [15, 16]) aims to describe the structure of scientific literature using information on authors, citations, or words shared between articles. With such techniques, we can easily visualize a field's origin and development by documenting changes in the networks of publications through time [17]. Both methodologies have also benefitted from recent developments in computational techniques such as (big) data visualization, text mining, and network analysis [15, 16, 18, 19]. Despite their high degree of complementarity, however, bibliometrics has rarely (if ever) been explicitly incorporated within systematic reviews or maps.

Here, we propose a new framework for **research synthesis** that combines the power and utility of both systematic mapping and bibliometrics, which we term **research weaving**. This approach merges rigorous article classification (systematic mapping) with quantification and visualization of the *impact* or *influence* of research, (i.e., bibliometrics; including the influence of individual articles, or authors, on later research). Therefore, we see research weaving as both **evidence synthesis** and **influence synthesis**. Research weaving enables the synthesis of any research topic in an informative and visual manner, and opens up new ways to study critical questions in evidence synthesis. Before describing research weaving in more detail, we will first provide an overview of different types of research synthesis methods.

Alternative Roles of Research Syntheses

Although there are many types of research synthesis [20, 21], they can roughly be divided into two large categories which achieve different goals: deep and broad synthesis (**Figure 1**). A deep synthesis combines studies that have examined the same phenomenon over similar or varying contexts. In ecology and evolution, for example, we often use a systematic review or meta-analysis to understand the effects of a particular process, and to examine how general those effects are. In contrast, a broad synthesis aims to classify what research has been conducted on a topic, and locate clusters and gaps of research activity within that topic. Interweaving deep and broad syntheses is the key idea of research weaving, enabling the development of new questions, concepts, and insights.

Deep Synthesis: Systematic Reviews and Meta-analysis

Synthesizing evidence usually involves four tasks: locating, screening, appraising, and combining scientific information. Currently, the most rigorous way to accomplish these tasks is via some form of 'systematic review', a term that signifies a review's adherence to transparent, reproducible and structured procedures for locating and summarizing information (i.e. **systematic-review approach**). Because a systematic review involves a large number of complex and important stages, current best practice is governed, and frequently updated, via a set of guidelines produced by three major collaborations: Cochrane (www.cochrane.org) [22], the Campbell Collaboration (www.campbellcollaboration.org) and the Collaboration for Environmental Evidence (CEE) (www.environmentalevidence.org). Adherence to these guidelines is usually assessed by authors self-reporting their methodology using a framework such as PRISMA (http://www.prisma-statement.org/)[23, 24] or ROSES (http://www.roses-reporting.com) [25]. A systematic review may use methods for synthesising studies that are qualitative or quantitative, depending on the nature of the data [11, 21, 26], and may also include a meta-analysis of any quantitative findings (see below). Despite 'systematic review' and 'meta-analysis' not being equivalent, these terms are sometimes used synonymously in the field of ecology and evolution [27].

A meta-analysis quantitatively aggregates primary empirical evidence, usually to answer a well-defined question. For example, a meta-analysis can estimate average effect sizes of some experimental treatment on an outcome, or differences in these average effect sizes between different types of experimental approaches [4-6]. Researchers use meta-analyses to answer two main questions: “what works?” and “what’s general?” [4]. The first question asks whether or not certain interventions or experimental manipulations are effective. Many meta-analyses in medical and social sciences are of this kind, and are performed as part of a systematic review. The second question asks how common and robust a phenomenon is. Ecologists and evolutionary biologists often deploy meta-analysis for this purpose; for example, what species or populations are affected by human-induced changes, such as urbanization and global warming. Incidentally, a second order meta-analysis [28] (sometimes referred to as an umbrella review, or an overview of reviews [22, 29]) can been also seen as a type of deep synthesis, but it only deals with secondary research literature (see **Figure 1**).

Broad Synthesis: Systematic and Bibliometric Mapping

Systematic maps answer the question “what’s studied?” (**Figure 1**). They usually probe broad topics or questions, rather than seeking effect-sized based answers [10, 11]. A systematic map can collect relevant primary and secondary research literature of both empirical and theoretical nature (although it can also focus on a single paper type, such as observational studies). The key output of a systematic map is a database of coded features and the contents of each piece of evidence, which can then be visualized as a **content map,** a temporal trend and a spatial map (see **Figure 2**). Although a systematic map will not provide inferential statistics to test a hypothesis, the map can provide plenty of descriptive statistics to visualize attributes of the literature, improving our understanding of research areas. Notably, the value of this mapping process is in identifying *knowledge gaps* (i.e., areas requiring more attention), and *knowledge clusters* (i.e., areas that are ripe for a systematic review) [10, 11]. The use of systematic and evidence mapping approaches has been rapidly growing in the social, medical and environmental sciences in recent years [10-13]. Systematic mapping, however, is not frequently applied to questions that are relevant to ecologists and evolutionary biologists (but see [30]).

Bibliometric (science) mapping answers the question "what's published?" and is therefore focussed on the publication itself, rather than the content contained within the publication (**Figure 1**). A bibliometric map displays the connections and networks among authors (collaboration analysis) and among publications, by quantifying citations (citation analysis) and semantic and text similarities (co-word analysis; **Box 1**) [15 , 16, 31]. Bibliometric analysis can objectively identify both 'seminal' (the most cited and/or connected) and disconnected (less well connected or isolated) studies among a population of papers, revealing the development of the field or set of concepts [15 , 16, 17, 32]. Such networks of bibliometric information can be visualised as a 'bibliometric web' (**Figure 2**). Some of these methods have begun to be used in systematic reviews and maps; recent examples include analyses of terminology and semantics within a collection of relevant literature [33, 34]. However, the full toolkit of bibliometric mapping is rarely coupled with a systematic review or mapping approach (i.e. the rigorous screening of included articles in relation to inclusion and exclusion criteria).

Research Weaving: Combining the Power of Maps and Webs

Research weaving marries bibliometrics (influence synthesis) with systematic mapping (evidence synthesis) to minimise bias, maximise rigor, and to provide new insights. Research weaving can combine layers of multifaceted information: types of publications (e.g., primary, secondary), types of research/evidence (experimental, observational, theoretical), author networks (research groups), a tree of life (species information), and mapping of traits and/or methodologies. None of these have previously been combined together under the umbrella of one research synthesis. Importantly, the information required to conduct a bibliometric analysis is often readily available within research article databases (e.g., *Scopus*; see **Box 2**).

So far, we have emphasised differences between systematic maps and bibliometric webs (**Figure 2**), but there is substantial overlap between these two approaches. Here, the *5W1H* questions (*who*, *when*, *where*, *what*, *why* and *how)* are helpful to understand their similarities and differences. Both systematic mapping and bibliometrics provide a *who*, *when* and *where*: *who* conducted the research and *who* wrote the paper (these will usually be the same); *when* the research was conducted and *when* the paper was published (these will usually be similar); *where* the research was conducted and *where* the paper was written (sometimes these are on the opposite sides of the world). Systematic mapping, but not bibliometrics, provides a *what*, *why*, and *how*: *what* scientists study (e.g., species, biome, or system), *why* they study it (i.e., their questions or hypotheses), and *how* they study it (e.g., experimentally, theoretically, comparatively, meta-analytically). However, if systematic mapping borrowed tools from bibliometrics, these questions could be addressed more efficiently.

Co-word analysis, when applied to the full text of papers, can help address key research questions. This may be especially true for *why* questions because, thanks to recent technical advances, text analysis can effectively capture important concepts shared by a group of articles. We do this by creating a **term map** (or term web) [35]. Term mapping (or co-word mapping) assists in setting up a content map, whose construction is the main purpose of systematic mapping (**Figure 2**). These tasks are becoming more straightforward through the widespread availability of topic modelling [19, 36] and, more recently, deep learning [37, 38] (**Box 3**). These tools will soon help researchers semi-automate term mapping as part of a full text analysis, to answer the *what, why*, and *how* questions of research. Mapping terms and clarifying connections among terms can also help identify terminological disagreements and confusion about a topic [19]. Both bibliometrics and systematic maps can be improved by borrowing techniques from each other. This intertwining of different synthesis procedures is what research weaving is really about.

One final advantage of research weaving is to provide a methodological toolbox to support the new field of meta-research (research on research) [39-42], which has emerged in the midst of the current reproducibility crisis [43-45]. The mission of meta-research is to improve scientific methods and practices by understanding and combating biases in science. Meta-research originates in research synthesis, especially meta-analysis [42]. It has already utilized bibliometric mapping [46, 47] and meta-analysis (using systematic-review approaches) [48, 49]. Therefore, research weaving can be used to elucidate not only research biases and biased practices (e.g., by detecting unusual citation patterns, and dominance of certain research groups), but also research clusters and gaps (e.g., a field's focus on one particular taxonomic group or topic, but not other relevant ones). Visualization of content maps and bibliometric webs can truly deliver the "bird's eye view of science", which meta-research seeks [40, 41].

Implementation: How to Become a Research Weaver

Currently, no single software package will serve all aspects of research weaving (**Figure 2**), but do not be deterred. The process of research weaving resembles that of a meta-analysis (or a systematic review), for which many resources and software packages are already available [50-52].

A meta-analysis (more correctly, a systematic review with meta-analysis [8]) involves roughly six steps: i) formulating a question, ii) searching for publications, iii) screening resultant papers, iv) extracting and coding data (including appraising study validity), v) analyzing data (i.e. meta-analysis), and vi) interpreting results [4, 5, 7, 22, 53]. Research weaving deviates from this six-step process in five main ways (**Figure 3**). First, research weaving analyzes full bibliometric data (including bibliographic data), specifically adding to steps iii and iv. Therefore, we need to download all the relevant bibliometric information (e.g., citation data) from bibliographic resources such as the *Web of Science* and *Scopus*. Both resources provide not only the usual reference information and abstracts, but also the number of citations for a paper, and bibliometric information on cited references, keywords, funding bodies, and author affiliations. We can analyze these data before and/or after screening (for a review of types of bibliometric analyses, see [15, 16]). For example, we can create a pre-screening term map to help devise keyword strings for searching, and we can also make a post-screening term map to help code each paper or create a content map (**Box 3**). Second, we can use relevant publications post screening to create a network via bibliometric coupling to identify articles that were not in the post-screened set – this facilitates a process called snowballing (i.e. backward and forward search of articles). Third, we can also code contents, study types, and characteristics of a paper (this process is inherent to systematic mapping), and then merge this content information with bibliometric information. Fourth, we can apply a wide range of visualizations (**Figure 2**) at any stage in the synthesis (cf. **Figure 3**). Visualization is a core step in research weaving. Fifth, and crucially, we integrate and interpret the information of both maps and webs together; we can describe the content of each article and its relationship to other published works in a single analysis.

Available Tools for Research Weaving

There has been a recent surge of 'tools' for systematic reviews and maps. A comprehensive and growing catalogue can be found on the Systematic Review Toolbox website (systematicreviewtools.com). Also, a recent review has compared and contrasted the capabilities of 22 tools for managing a review [52], such as CADIMA (www.cadima.info), Colandr (www.colandrapp.com), and metagear [54]. These tools are put together mainly to support systematic reviews (e.g., planning, screening, documentation, bibliographic management [51]), but none of them actively incorporate features required for the full range of bibliometrics (i.e. **performance analysis** and bibliometric mapping). Therefore, we collated an introductory list of tools for bibliometric analyses, text mining, and associated data visualization (see **Supplemental Information**). We show some examples of these tools in **Figure 3.**

Current Implementation Limitations

Research weaving promises a richer analysis of a research field than is typically provided by systematic mapping and bibliometrics on their own. However, combining these approaches faces some limitations. First, systematic reviews should use multiple databases, because different databases catalogue different literature sources (e.g., overlap between *Web of Science* and *Scopus* can be a low as 40-50% [55]). However, different databases also structure their content differently, which presents technical challenges to smoothly merging overlapping content [16, 56]. Encouragingly, some programs are capable of merging disparate database outputs that may be structured differently (e.g., *bibliometrix,* [31]).

Second, despite the majority of bibliographic information about an article being reliable within databases, multiple versions of the same publication may result from variants of journal or author names or even different book editions [16, 31]. This may require substantial data cleaning of the article data itself using text-based approaches (e.g., the use of regular expressions or automated duplication identification, if applicable) prior to analysis of a body of work.

Third, content analysis (i.e. extracting information such as species or experimental design from each paper) will be limited by the size and scope of the literature being used (cf. **Figure 1**). Even with some automation, much of a body of work will still need to be processed manually to ensure the content is relevant and has been extracted correctly [16].

A final potential hindrance to research weaving is cultural. The systematic review community has traditionally been weary of making decisions regarding relevance of evidence based on information regarding authorship or even journal titles, to avoid bias towards high-status individuals or publishing venues [54]. It is unclear to what extent research weaving might confound some forms of bias, despite explicitly seeking to quantify and remove it from the synthesis process. Conversely, the bibliometric community has typically focussed on computational methods that differ markedly from the more manual approaches traditionally employed during systematic review. While research weaving provides strong opportunities to both communities, widespread adoption will depend on a culture that prioritizes careful testing and data sharing [51].

Benefits of Research Weaving and Future Opportunities

We see three major benefits of the research weaving framework which go beyond the field of ecology and evolution. First, research weaving involves a more in-depth assessment of a collection of literature than has previously been possible, thus providing a much better understanding of a topic in terms of both research content and people involved (**Figure 2, 3**). This information could help researchers direct primary research efforts and form new groups of collaborators, driving innovations that may increase research efficacy and capacity. Second, research weaving can better identify research biases, gaps, and limitations within a collection of literature, supporting the emerging field of meta-research [39-42]. Finally, the strong emphasis on visualisations within research weaving can greatly aid researchers to rapidly digest the rich information that studies and citations contain. Such visualisations are likely to help not only researchers within and outside the field (thereby facilitating inter-disciplinary collaborations), but also members of the public (where applicable, stakeholders and policymakers), enhancing science communication and the public understanding of science [57].

Furthermore, we see the current limitations discussed above as future opportunities, because the research weaving framework is likely to bring (or is already bringing; evidencesynthesishackathon.com) researchers and developers together to solve these problems. Advances in text mining and machine learning (see **Box 3**) are developing rapidly and are likely to provide creative solutions to some of the aforementioned limitations. We envisage research weaving growing rapidly from cross-fertilization of ideas from many different fields, mirroring what happened to meta-analysis over the last 40 years [3, 4, 6].

Concluding Remarks

Synthesis of scientific information is an essential part of modern research that both enhances the value of existing primary research, and highlights research gaps deserving further research [58]. Research synthesis is growing in importance as a tool for sorting through the ever-increasing amounts of data, and their associated scientific publications. The research weaving framework visualizes research landscapes by utilizing emerging methods of systematic mapping and bibliometrics. Thus, research weaving navigates researchers through a complex research terrain with gaps, clusters, and biases, despite some anticipated difficulties and unknowns (see **Outstanding Questions**). In addition to pulling meta-analysis out of its' 'midlife crisis' (see **Box 2**) [4], research weaving will equip meta-research with a new generation of tools necessary to give an "eagle's-eye view" of the growing scientific literature.

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Box 1: Bibliometrics, Science Maps, and Citation Analysis

Bibliometrics is concerned with the analysis of publications and has been the main focus of library and information sciences [59]. Bibliometrics employs two main approaches: performance analysis and bibliometric mapping (also called science mapping). These approaches can be used at the same time and often overlap with each other [18, 59]. With performance analysis, we quantify citation impacts and productivity using, for example, the *h*-index [60] and Journal Impact Factor [61], which are all too familiar to scientists, and an obsession to some [62]. With bibliometric mapping, we quantify connections and networks among publications, using three types of techniques: 1) collaboration (co-author) analysis, 2) co-word (term) analysis, and 3) citation analysis [15 , 16, 31]. Collaboration analysis explores co-occurrences of authors, countries, and institutions in a collection of publications. In a similar manner, co-word analysis identifies the most frequently used or co-occurring set of terms within a group of documents, which can reveal important concepts in a research field.

Citation analysis examines how often a publication is cited and how such citations are connected. In the field of bibliometrics, however, this ‘direct’ citation analysis is relatively new compared to two other types of analysis [16, 17]: co-citation analysis [63] and bibliographic coupling [64]. Co-citation and bibliographic coupling are both methods of measuring the connection between two papers (see **Figure I**). Co-citation tallies the number of publications that cite both papers, whereas bibliographic coupling measures the overlap in the citations of the papers themselves. Notably, connections (edges) for co-citation dynamically change over time as more papers are published, whereas those of bibliographic coupling and direct citation are static, given a collection of publications [15 , 16, 31]. The idea of bibliographic coupling is closer to collaboration and co-word analysis. All types of citation analyses can be conducted at the level of authors, papers, and journals. The usage of these three types of citation analysis depend on the purpose and scope of research synthesis [15] (see also **Figure 1B**). Direct and co-citation analysis is probably more appropriate when a set is large and consists of papers published over many years, whereas bibliographic coupling is more amendable to a recent set of publications. A spectacular example of a citation network is the Shape of Science project (www.scimagojr.com/shapeofscience/) where the citation network of most scientific journals was constructed by incorporating all three types of citation relationships [65].

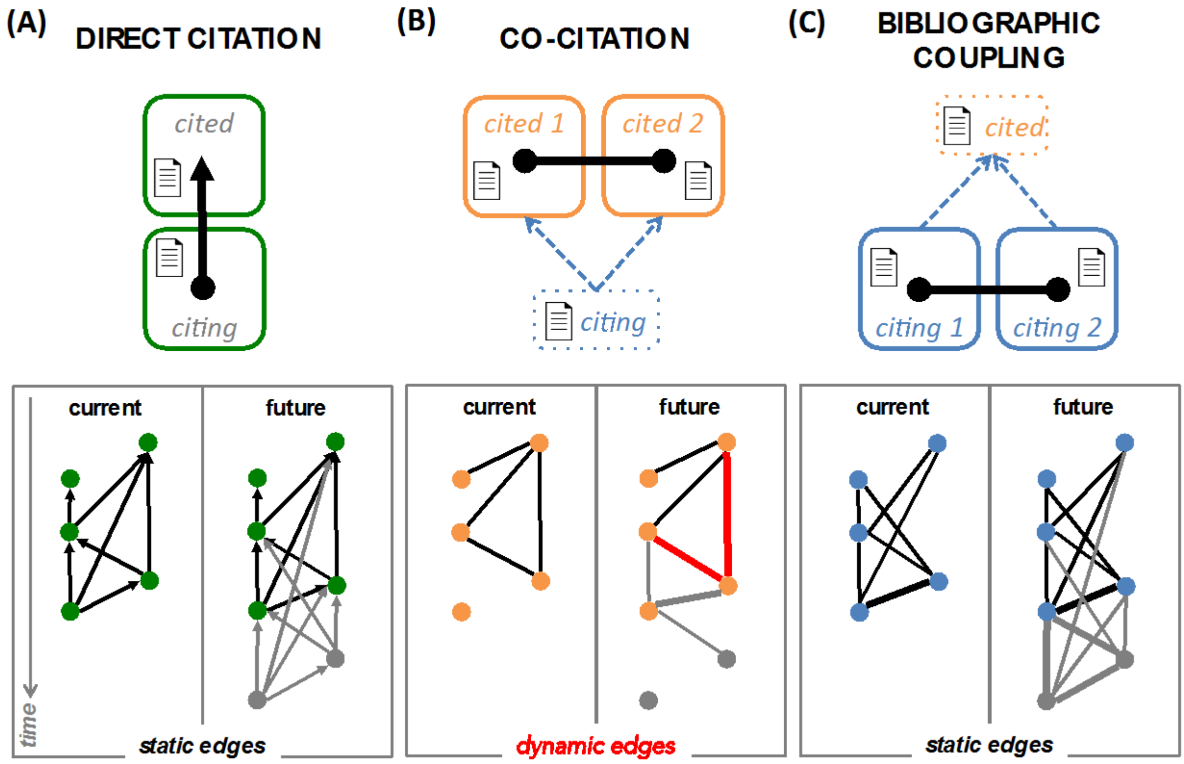

Figure I. Three main types of bibliographic networks.

Papers are represented as nodes/vertices of constant size (i.e. not scaled by number of citations, centrality or any other indices). (A) Direct citations are denoted by arrows (edges) from citing to cited papers. If we create a network for a set of currently existing papers (green nodes/vertices), the edges in this part of the network will not change when new papers (in grey) appear and are added to the network in the future. (B) Co-citations are represented by non-directional connections (edges) between papers that are cited together in other papers (citing). The strength of these connections can change when new papers (in grey) appear and are added to the network in the future, because they can cite existing papers. (C) Bibliographic coupling is shown as non-directional connections (edges) between papers that are citing the same set of papers (cited). The strength of these connections will not change when new papers (in grey) appear and are added to the network in the future, as the reference lists of published papers will not be affected.

Box 2: Research Weaving Helps Meta-analysis

Meta-analysis, now over 40 years old, is said to be going through a 'midlife crisis' [4, 6] with many poor quality meta-analyses being mass-produced (e.g., a meta-analysis without a systematic-review approach) [66]. Research weaving can assist a meta-analysis in divorcing itself from poor practices, because research weaving encourages researchers to use a systematic-review approach. Further, the processes and visualisation techniques of research weaving can be powerful aids for meta-analysts. For example, a meta-analyst would typically only visualise effect sizes via forest and funnel plots [4, 5]. In contrast, given the same dataset, a research weaver would visualise all moderators (i.e. predictors collected to explain variation in effect sizes) and associated information across papers (e.g., taxonomic groups, methodological differences, experimental features, biological information, and publication year) (**Figure 2**). Although such figures would certainly allow readers to see the strengths and weaknesses of a dataset (e.g., confounding effects or overlaps of two variables), few meta-analyses currently present such visualisations. We can see a notable exception in a recent meta-analysis where researchers collated data on the heritability of human traits over the last 40 years [67]. They provide impressive visualisations of the different facets of their dataset via an interactive website (match.ctglab.nl/). We also have a simple web-based example of research weaving associated with our evolutionary/ecological meta-analysis [68] (www.example.researchweaving.com; see **Figure I**).

Further, research weaving, specifically bibliometric analysis, can help meta-analysts during data screening and data collection stages. For example, co-word analysis (and text mining) of key research articles and reviews will help construct a string of keywords for database searches [35, 69]; such analysis could also help detect relevant moderators, once a final dataset is obtained. Co-citation and bibliographic coupling networks from pre-screened ‘hits’ (publications) can facilitate screening by creating clusters of connected and unconnected publications [69]. Collaboration networks will identify key people and laboratories conducting research addressing similar questions. Meta-analysts can then contact these key players or labs to see whether they have unpublished work (e.g., ‘unpublished’ MSc and PhD thesis chapters; we have successfully used this process in several meta-analyses).

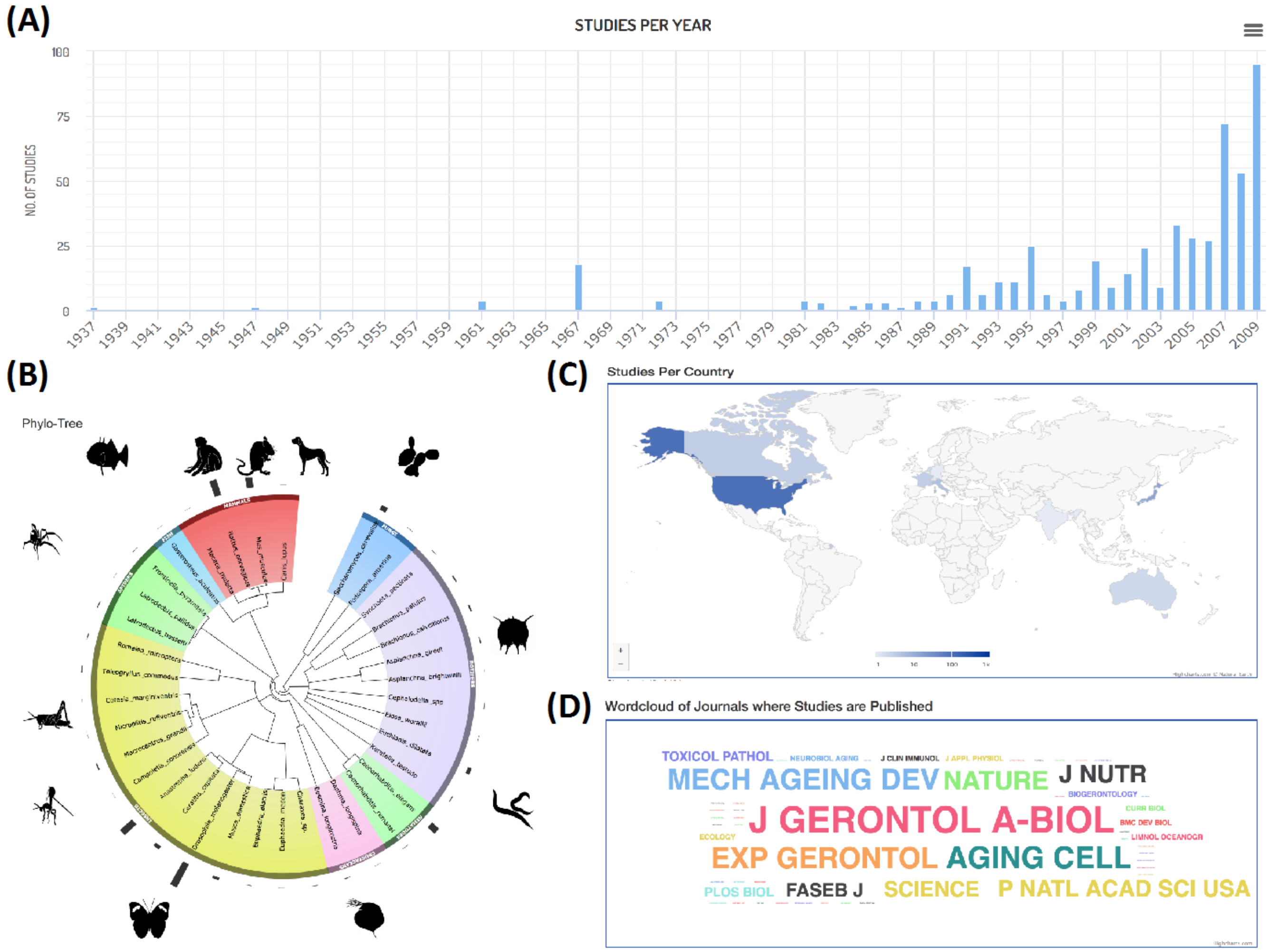

Figure I. Example Visualizations from the Meta-analysis on the Relationship between Dietary Restriction and Longevity.

(A) Distribution of publication dates of included studies, indicating a recent increase in number of published relevant studies. (B) Phylogenetic tree and representation of the main taxonomic groups of the species present in the meta-analytical dataset (bars show relative numbers of individuals of each species included in the analyses). (C) Geographic distribution of the countries of origin of the first author of the included studies. (D) Word cloud of the publication journal names of the included studies.

Box 3: Potential of Text Mining with Deep Learning

Text mining is a collection of methods for extracting information from free text [70]. While it can include tasks such as detecting keywords, synonyms, or named entities (locations, people, species names, etc.), in evidence synthesis projects (e.g., systematic reviews and maps), the term ‘text mining’ more commonly refers to a set of tools for classifying articles on the basis of the words they contain (i.e. content analysis or mapping). Thus, text mining contrasts with the bibliometric analysis of grouping articles by their citation or collaboration networks (see **Box 1**). The function of text mining is virtually the same as co-word analysis, except that co-word analysis usually uses the algorithms developed for network-analysis, whereas text mining uses some form of machine learning to perform the classification [71]. One particularly successful machine-learning approach is ‘deep learning’, which uses artificial neural networks to perform a diverse range of tasks from image classification to natural language processing [37, 38].

Machine learning is typically applied to evidence synthesis in one of two closely related ways. *Unsupervised classification* groups articles into a pre-specified number of related types (e.g., via topic models) [72], providing a broad overview of patterns in the article set (corpus). This is particularly useful during the ‘scoping’ phase of a review project. Alternatively, the user may have some information on what groups are known (or expected) to occur in a corpus and might then perform *supervised classification* to apply that information to a second set of documents. For example, the academic search engine ‘Dimensions’ uses this approach to apply the New Zealand & Australian fields of research codes to the entire body of untagged research in their database [9]. A related approach is to track user classifications of articles during a systematic review, and iteratively update a machine learning algorithm to classify as-yet unchecked articles (e.g., Colandr [72]).

There are several potential benefits of machine learning in research synthesis projects. First, it can make the process more efficient without having to reduce the number of articles that are screened, meaning that time can be reduced without compromising methodological rigor [51]. Second, machine learning allows reviews to be quickly updated as new information becomes available, progressing towards the goal of ‘living systematic reviews’ [73, 74]. Finally, automated approaches are well suited to identifying regions within the academic literature that have been rarely studied and which may benefit from further research [13, 19].

Figure 1

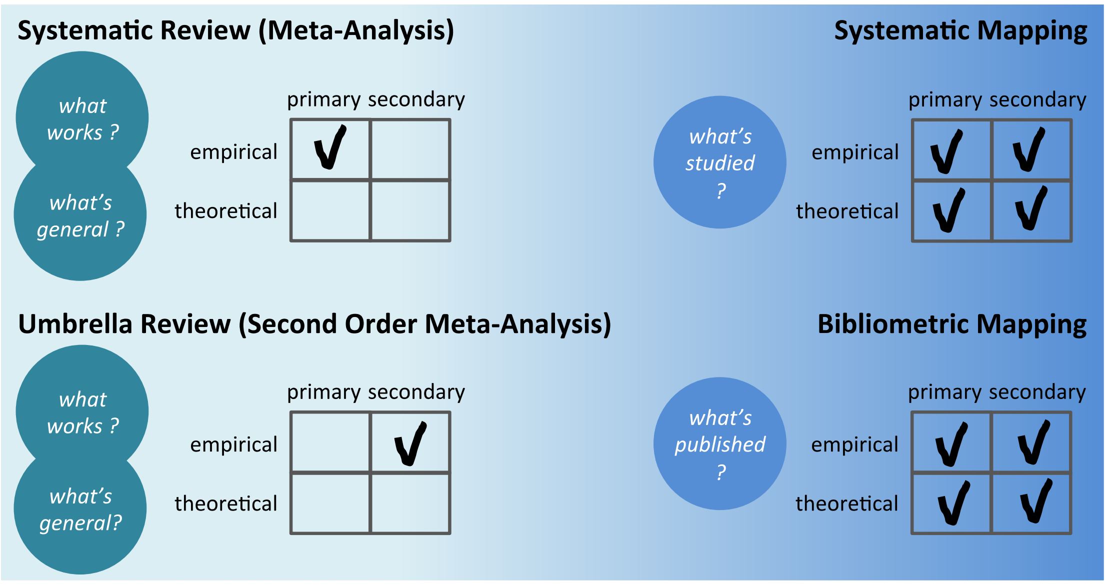

Figure1: Types of Research Synthesis and their Scopes

(A) Research syntheses can be deep or broad (or somewhere in-between). The main questions asked (in the circles) and types of data typically used are shown for the four main types of research syntheses. Systematic reviews and meta-analyses put together evidence from primary empirical studies to infer what works and where/when. Similarly, umbrella reviews deal with secondary empirical studies. Mapping reviews can incorporate many different types of studies to infer what has been done and published and how different pieces (concepts, papers, etc.) are related. (B) The size of the body of literature that the main types of research syntheses typically deal with. Systematic review (including meta-analysis) and systematic mapping are usually restricted to tens or hundreds of papers, due to manual extraction and coding of the data. Bibliometric direct citation and co-citation analyses work best on datasets with hundreds or thousands of papers. Bibliometric coupling, collaboration and co-word analysis can be applied to both small and large collections of papers.

Figure 2

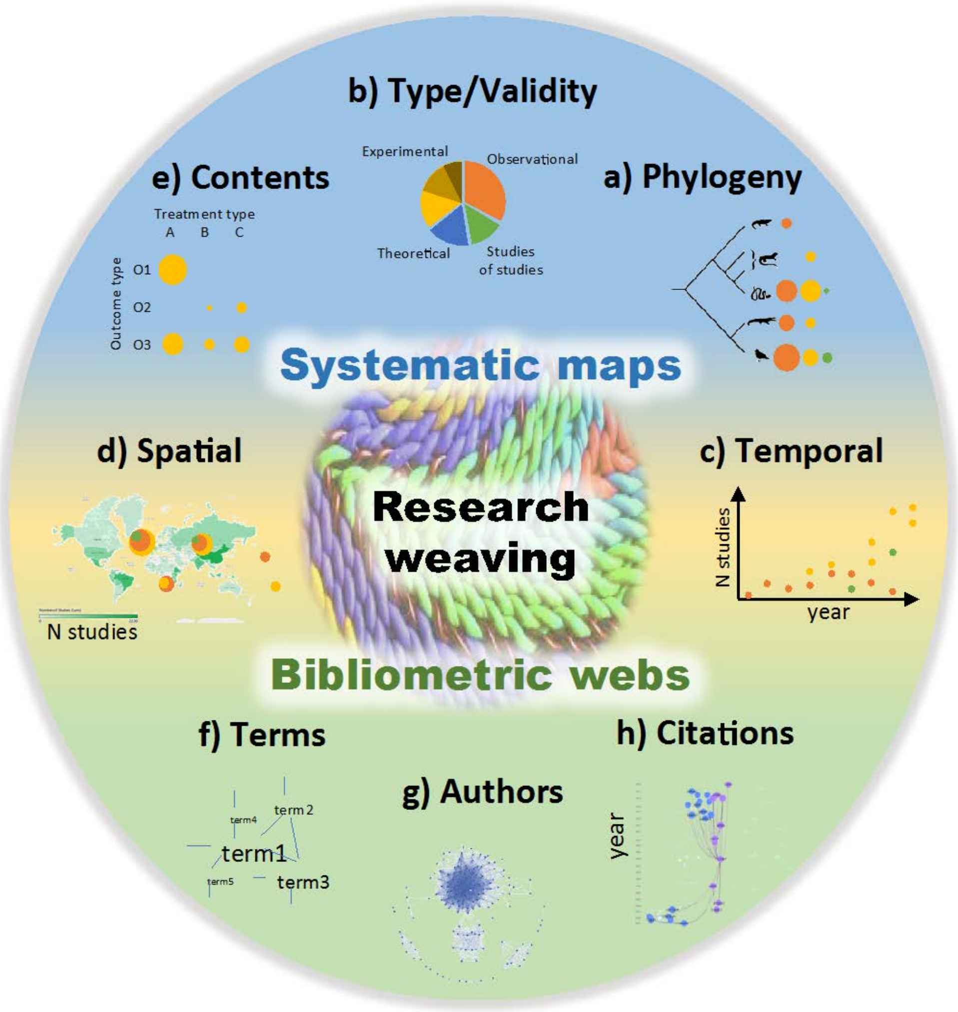

Figure 2

Research weaving encompasses and joins Systematic maps and Bibliometric webs. Pictograms a) to h) illustrate the main types of possible visualisations for interpreting the patterns either in the data extracted from the full text (Systematic maps side) or from paper-level meta-data (Bibliometric webs side). Spatial and temporal graphs (c, d) can be constructed for both (e.g., using study site location or author's address, experiment timing or paper publication date). Note that pictograms a-h also appear in **Figure 3**.

Figure 3

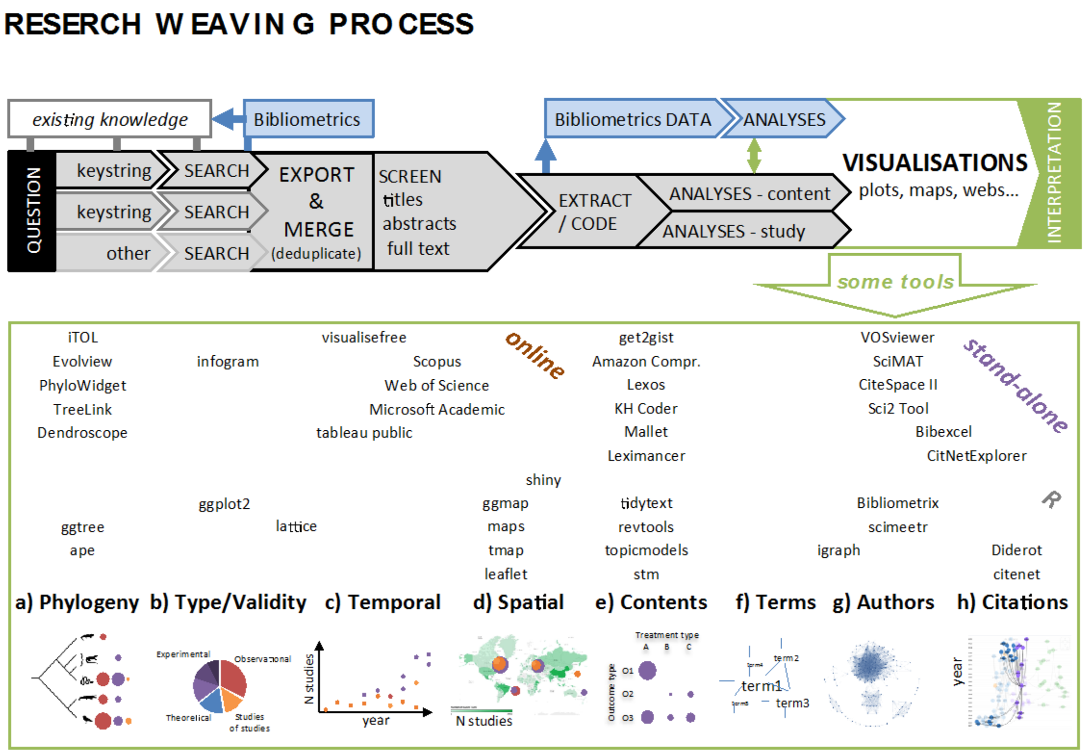

Figure 3. Research Weaving Processes and Implementation Tools

Research weaving uses tools and processes from bibliometrics (blue boxes on top) and systematic mapping process (grey boxes). Bibliometric tools can help identify relevant literature and knowledge at the early stages of the systematic mapping process. Later, for the included papers, visualisations of bibliometric indices and relationships can be added and blended with the visualisations of the papers' contents. Examples of visualisations are given at the bottom (pictograms a-h); for more details see legend of **Figure 2**). The table above the pictograms shows examples of software and platforms (grouped by background colours into online, stand-alone software and *R* packages) that could be used to produce a given type of visualisation. For content visualisations (e), we picked examples of text-mining software representing the tech-savvy end of the continuum of approaches to extract and represent content data – at the other end of the continuum, manually-coded data on the details of the study methods/design/results can be visualised using any basic graphing software.

Highlights

An exponential increase in scientific publications requires informative and integrative reviews to provide a detailed synthesis of a particular research field and this has resulted in the emergence of novel methods for synthesizing heterogeneous research.

Research weaving provides a novel framework that combines bibliometrics and systematic mapping to inform the development of a field, the influence of research papers and their interconnections, and to visualise content across and within publications.

Research weaving has the potential to provide a more efficient, in-depth, and broad synthesis of a research field, to identify research biases, gaps, and limitations. Such insights have the potential to inform ecological and environmental policy and communicate research findings to the general public in more effective ways then are typically done in current research syntheses.

Glossary

Bibliometrics

methods to track the dissemination of written communication. For the scientific literature bibliometrics is used to quantify the impact of research on the rest of the discipline, and identify how research fields are structured, through two methods: (1) performance analysis, which quantifies the performance of scientific actors, such as authors and publishers, through measures of productivity such as citation numbers over time, and (2) bibliometric mapping (also known as science mapping), which quantifies structure within the scientific literature by analyzing connections between citations, authors, and keywords or phrases.

Content map

tabulates and visualizes the contents of a collection of research literature; this mapping process is the heart of a systematic map.

Evidence synthesis

a type of research synthesis, which summaries research evidence in a given topic (question); it includes systematic reviews and maps.

Influence synthesis

a type of research synthesis which summaries the influence or impact of research articles in terms of citation, connection and how a particular article contributed to a development of a field or topic (i.e. performance analysis and bibliometric mapping in bibliometrics).

Meta-analysis

quantitative review of research in a given topic. Statistical analysis of combined results from different primary empirical research to provide a quantitative answer to a research question, and identify sources of heterogeneity to explain differences between studies. The term is often used to indicate the whole process of research synthesis but, also it is used to mean only the statistical analysis part of synthesis.

Narrative reviews

traditional approaches to literature reviewing of research in a given field, which has not been conducted in a systematic way

Research synthesis

a general term used for the synthesis of research literature, including narrative reviews, meta-analyses, and systematic reviews and maps, and bibliometric maps.

Research weaving

a holistic form of research synthesis that combines bibliometrics with systematic mapping (but also possible with systematic reviews and meta-analyses) to provide a quantitative, qualitative, and visual description of a research field.

Systematic map

has been 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. Relating mapping processes include an **evidence map**, evidence gap map and evidence review map.

Systematic review

a 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 which uses approaches involved in a systematic review (i.e., systematic review approach)

Term map

also known as a co-word map, visualizes the relatedness of a set of co-occurring terms. The distance between terms represents the number of co-occurrences between them.

Outstanding Questions

- Will research weaving successfully merge three different areas of methodologies: research synthesis (interdisciplinary), bibliometrics (library and information sciences) and text-mining (computer sciences)?
- How successful are machine learning algorithms in content classification using bibliometric information and/or full text information?
- What are effective approaches for narrowing down a body of work to relevant research articles in a field, and how much can research weaving help the process?
- How can data and methods for research weaving studies be most easily and effectively disseminated such that research fields in ecology and evolution can be updated with new research in the future?
- How effective will research waving be in developing ecological and environmental policy and communicating a fields research findings to the politicians and the general public?

Supplemental Materials

SI Table 1. Visual mapping and weaving software tools summary

References

1. Jennions, M.D. et al. (2013) Role of meta-analysis in interpreting the scientific literature. In The handbook of meta-analysis in ecology and evolution (Koricheva, J. et al. eds), pp. 364-380, Princeton University Press.
2. Arnqvist, G. and Wooster, D. (1995) Meta-analysis: synthesizing research findings in ecology and evolution. Trends Ecol Evol 10 (6), 236-40.
3. Shadish, W.R. and Lecy, J.D. (2015) The meta-analytic big bang. Res Synth Methods 6 (3), 246-64.
4. Gurevitch, J. et al. (2018) Meta-analysis and the science of research synthesis. Nature 555 (7695), 175-182.
5. Nakagawa, S. et al. (2017) Meta-evaluation of meta-analysis: ten appraisal questions for biologists. BMC Biology 15, 18.
6. Glass, G.V. (2015) Meta-analysis at middle age: a personal history. Res Synth Methods, n/a-n/a.
7. Koricheva, J. et al. (2013) The handbook of meta-analysis in ecology and evolution, Princeton University Press.
8. Vetter, D. et al. (2013) Meta-analysis: A need for well-defined usage in ecology and conservation biology. Ecosphere 4 (6).
9. Bates, S. et al. (2007) Systematic maps to support the evidence base in social care. Evid Policy 3 (4), 539-551.
10. Haddaway, N.R. et al. (2016) The benefits of systematic mapping to evidence-based environmental management. Ambio 45 (5), 613-620.
11. James, K.L. et al. (2016) A methodology for systematic mapping in environmental sciences. Environ Evid 5 (1), 7.
12. Miake-Lye, I.M. et al. (2016) What is an evidence map? A systematic review of published evidence maps and their definitions, methods, and products. Syst Rev 5, 28.
13. McKinnon, M.C. et al. (2015) Sustainability: Map the evidence. Nature 528 (7581), 185-7.
14. O'Leary, B.C. et al. (2017) Evidence maps and evidence gaps: evidence review mapping as a method for collating and appraising evidence reviews to inform research and policy. Environ Evid 6 (1), 19.
15. Cobo, M.J. et al. (2011) Science Mapping Software Tools: Review, Analysis, and Cooperative Study Among Tools. J Am Soc Inf Sci Tec 62 (7), 1382-1402.
16. Zupic, I. and Cater, T. (2015) Bibliometric Methods in Management and Organization. Organ Res Methods 18 (3), 429-472.
17. van Eck, N.J. and Waltman, L. (2014) CitNetExplorer: A new software tool for analyzing and visualizing citation networks. J Informetr 8 (4), 802-823.
18. Ding, Y. et al., eds. (2014) Measuring scholarly impact: methods and practice, Springer.
19. Westgate, M.J. et al. (2015) Text analysis tools for identification of emerging topics and research gaps in conservation science. Conserv Biol 29 (6), 1606-1614.
20. Booth, A. et al. (2012) Systematic approaches to a successful literature review, SAGE.
21. Gough, D. et al. (2017) An introduction to systematic reviews, 2nd edition. edn., SAGE.

22. Higgins, J.P.T. and Green, S. (2011) Cochrane Handbook for Systematic Reviews of Interventions, Version 5.1.0., Wiley.
23. Liberati, A. et al. (2009) The PRISMA Statement for Reporting Systematic Reviews and Meta-Analyses of Studies That Evaluate Health Care Interventions: Explanation and Elaboration. Plos Med 6 (7), e1000100.
24. Moher, D. et al. (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Ann Intern Med 151.
25. Haddaway, N.R. et al. (2018) ROSES RepOrting standards for Systematic Evidence Syntheses: pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps. Environ Evid 7 (1), 7.
26. Gough, D. et al. (2012) Clarifying differences between review designs and methods. Syst Rev 1 (1), 28.
27. Nakagawa, S. and Poulin, R. (2012) Meta-analytic insights into evolutionary ecology: an introduction and synthesis. Evol Ecol 26 (5), 1085-1099.
28. Schmidt, F.L. and Oh, I.-S. (2013) Methods for second order meta-analysis and illustrative applications. Organ Behav Hum Decis Process 121 (2), 204-218.
29. Ioannidis, J.P.A. (2009) Integration of evidence from multiple meta-analyses: a primer on umbrella reviews, treatment networks and multiple treatments meta-analyses. Can Med Assoc J 181 (8), 488-493.
30. Neaves, L.E. et al. (2015) The fitness consequences of inbreeding in natural populations and their implications for species conservation–a systematic map. Environ Evid 4 (1), 5.
31. Aria, M. and Cuccurullo, C. (2017) bibliometrix: An R-tool for comprehensive science mapping analysis. J Informetr 11 (4), 959-975.
32. Vincenot, C.E. (2018) How new concepts become universal scientific approaches: insights from citation network analysis of agent-based complex systems science. Proc Roy Soc B - Biol Sci 285.
33. Haddaway, N. et al. (in press) How is the term ‘ecotechnology’ used in the research literature? A systematic review with thematic synthesis. Ecohydrol Hydrobiol.
34. Haddaway, N. et al. (in press) The multifunctional roles of vegetated strips around and within agricultural fields. A systematic map. Environ Evid.
35. van Eck, N.J. et al. (2010) Automatic term identification for bibliometric mapping. Scientometrics 82 (3), 581-596.
36. Nunez-Mir, G.C. et al. (2016) Automated content analysis: addressing the big literature challenge in ecology and evolution. Methods Ecol Evol 7 (11), 1262-1272.
37. LeCun, Y. et al. (2015) Deep learning. Nature 521 (7553), 436-444.
38. Schmidhuber, J. (2015) Deep learning in neural networks: An overview. Neural Netw 61, 85-117.
39. Fidler, F. et al. (2017) Metaresearch for Evaluating Reproducibility in Ecology and Evolution. Bioscience 67 (3), 282-289.
40. Ioannidis, J.P.A. (2018) Meta-research: Why research on research matters. Plos Biology 16 (3).
41. Ioannidis, J.P.A. et al. (2015) Meta-research: Evaluation and Improvement of Research Methods and Practices. Plos Biol 13 (10).
42. Ioannidis, J.P.A. (2010) Meta-research: The art of getting it wrong. Res Synth Methods 1 (3-4), 169-184.

43. Parker, T.H. et al. (2016) Transparency in Ecology and Evolution: Real Problems, Real Solutions. Trends Ecol Evol 31 (9), 711-9.
44. Nosek, B.A. et al. (2015) Promoting an open research culture. Science 348 (6242), 1422-5.
45. Nakagawa, S. and Parker, T.H. (2015) Replicating research in ecology and evolution: feasibility, incentives, and the cost-benefit conundrum. BMC Biology 13, 88.
46. Chavalarias, D. and Ioannidis, J.P.A. (2010) Science mapping analysis characterizes 235 biases in biomedical research. J Clin Epidemiol 63 (11), 1205-1215.
47. Fanelli, D. and Glanzel, W. (2013) Bibliometric Evidence for a Hierarchy of the Sciences. Plos One 8 (6).
48. Fanelli, D. et al. (2017) Meta-assessment of bias in science. Proc Natl Acad Sci U S A 114 (14), 3714-3719.
49. Fanelli, D. and Ioannidis, J.P.A. (2013) US studies may overestimate effect sizes in softer research. Proc Natl Acad Sci U S A 110 (37), 15031-15036.
50. Tsafnat, G. et al. (2014) Systematic review automation technologies. Syst Rev 3, 74.
51. Westgate, M.J. et al. (2018) Software support for environmental evidence synthesis. Nat Ecol Evol 2 (4), 588.
52. Kohl, C. et al. (2018) Online tools supporting the conduct and reporting of systematic reviews and systematic maps: a case study on CADIMA and review of existing tools. Environ Evid 7 (1), 8.
53. Pullin, A.S. and Stewart, G.B. (2006) Guidelines for systematic review in conservation and environmental management. Conserv Biol 20.
54. Lajeunesse, M.J. (2016) Facilitating systematic reviews, data extraction and meta-analysis with the metagear package for r. Methods Ecol Evol 7 (3), 323-330.
55. Mongeon, P. and Paul-Hus, A. (2016) The journal coverage of Web of Science and Scopus: a comparative analysis. Scientometrics 106 (1), 213-228.
56. Waltman, L. (2016) A review of the literature on citation impact indicators. J Informetr 10 (2), 365-391.
57. Allen, W.L. (2018) Visual brokerage: Communicating data and research through visualisation. Public Underst Sci, 0963662518756853.
58. Hampton, S.E. and Parker, J.N. (2011) Collaboration and Productivity in Scientific Synthesis. Bioscience 61 (11), 900-910.
59. De Bellis, N. (2009) Bibliometrics and citation analysis: from the Science citation index to cybermetrics, Scarecrow Press.
60. Hirsch, J.E. (2005) An index to quantify an individual's scientific research output. Proc Natl Acad Sci U S A 102 (46), 16569-16572.
61. Garfield, E. (1955) Citation indexes to science: a new dimension in documentation through association of ideas. Science 22 (3159), 108-111.
62. Kelly, C.D. and Jennions, M.D. (2006) The h index and career assessment by numbers. Trends Ecol Evol 21 (4), 167-170.
63. Small, H. (1973) Co-citation in the scientific literature: A new measure of the relationship between two documents. J Assoc Inf Sci Tec 24 (4), 265-269.
64. Martyn, J. (1964) Bibliographic coupling. J Docum 20 (4), 236-236.
65. Hassan-Montero, Y. et al. (2014) Graphical interface of the Scimago journal and country rank: an interactuve appriach to accessing bibliometric information. Prof inf 23 (3).

66. Ioannidis, J.P.A. (2016) The mass production of redundant, misleading, and conflicted systematic reviews and meta-analyses. Milbank Q 94 (5), 485-514.
67. Polderman, T.J.C. et al. (2015) Meta-analysis of the heritability of human traits based on fifty years of twin studies. Nat Genet 47 (7), 702-+.
68. Nakagawa, S. et al. (2012) Comparative and meta-analytic insights into life extension via dietary restriction. Aging Cell 11 (3), 401-409.
69. Janssens, A.C.J.W. and Gwinn, M. (2015) Novel citation-based search method for scientific literature: application to meta-analyses. BMC Med Res Methodol 15.
70. Manning, C.D. et al. (2008) An introduction to information retrieval, Cambridge University Press.
71. Leydesdorff, L. and Nerghes, A. (2017) Co-word Maps and Topic Modeling: A Comparison Using Small and Medium-Sized Corpora (N < 1,000). J Assoc Inf Sci Tec 68 (4), 1024-1035.
72. Cheng, S. et al. (2018) Using machine learning to advance synthesis and use of conservation and environmental evidence. Conserv Biol.
73. Elliott, J.H. et al. (2014) Living Systematic Reviews: An Emerging Opportunity to Narrow the Evidence-Practice Gap. Plos Med 11 (2).
74. Elliott, J.H. et al. (2017) Living systematic review: 1. Introduction-the why, what, when, and how. J Clin Epidemiol 91, 23-30.