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Opinion

Research Weaving: Visualizing the Future of Research Synthesis

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We propose 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 documents on any given topic. Research weaving achieves this feat by combining the power of two methods: 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. Bibliometrics enables researchers to see how pieces of evidence are connected, revealing the structure and development of a field. We explain how researchers can use some or all of these tools to gain a deeper, more nuanced understanding of the scientific literature.

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 visualize 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.

A New Framework for Research Synthesis of Evidence and Influence

The number of life science publications is increasing exponentially and researchers require informative reviews to stay up to date. 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 are valuable for both summarizing facts about a particular research field and for giving broader insights, such as identifying the origin and development of key theoretical concepts, or highlighting ideas deserving greater research focus. However, other types of syntheses, such as **systematic reviews** and **meta-analyses** [2–8], are increasingly common. These syntheses incorporate systematic methods to reliably extract factual, and quantitative, information from the literature, but are not practical for broad fields (encompassing hundreds or thousands of new publications per year), and cannot handle a highly heterogeneous literature (e.g., not being able to meta-analyze theoretical and simulation articles with empirical studies). A new technique has emerged to deal with these limitations: mapping.

Currently, scientists map research evidence using two complementary methods of different origins: **systematic mapping** and **bibliometrics**. Systematic mapping (sometimes called evidence mapping) is a nascent method derived from systematic reviews, with the goal of classifying the types of research on a broad topic [9–16]. A systematic map typically provides both a written report and a searchable database and often a series of simple visualizations, to catalog the attributes of relevant studies [10–12]. In contrast, bibliometrics (more specifically **bibliometric mapping** [17,18]) describes the structure of scientific literature using information on authors, citations, or words shared between articles; it also shows the impact or influence of a single study on the broader literature, using data on the number and nature of citations that it receives. We can therefore use changes in the networks of publications through time, to document and visualize the development of a field [19]. Both systematic and bibliometric mapping have benefitted from recent advances in (big) data visualization, text mining, and network analysis [17,18,20,21]. Despite their

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high degree of complementarity, however, bibliometrics has rarely (if ever) been explicitly incorporated into 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 informative and visual synthesis of any research topic, and unlocks new ways to study critical questions. Although we describe how to become a research weaver, we argue that learning even part of the research weaving toolbox is not only useful for all researchers, but also improves scientific practice in general. This is because it can help researchers grasp the state of a field better, identify gaps and biases, and become more transparent and rigorous. Before describing research weaving in more detail, we will first provide an overview of the different types of research synthesis methods.

Alternative Roles of Research Syntheses

We can roughly divide the many types of research syntheses [22,23] into deep and broad syntheses (Figure 1). A deep synthesis combines different studies that have examined the same phenomenon. In contrast, a broad synthesis aims to classify what research has been conducted on a topic, and locate clusters and gaps in research activity.

Deep Synthesis: Systematic Reviews and Meta-analyses

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, which follows transparent, reproducible, and structured procedures for locating and summarizing information (i.e., **systematic-review approach**). A systematic review can use qualitative or quantitative methods for synthesizing studies [11,23,24], and meta-analyses of quantitative findings are common (see below). Despite systematic review and meta-analysis not being equivalent, these terms are sometimes used synonymously in the fields of ecology and evolution [25]. A systematic review involves many complex and important stages. Guidelines for best practices are currently provided, and frequently updated, by three major collaborations: Cochrane (www.cochrane.org) [26], Campbell Collaboration (www.campbellcollaboration.org), and Collaboration for Environmental Evidence (CEE) (www.environmentalevidence.org). Adherence to these guidelines is usually assessed using a checklist such as PRISMA (www.prisma-statement.org) [27,28] or ROSES (www.roses-reporting.com) [29].

A meta-analysis – typically a part of a systematic review – quantitatively aggregates primary empirical evidence (both experimental and observational), usually to answer a well-defined question. 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 the 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, and is often asked by ecologists and evolutionary biologists (e.g., what species or populations are affected by urbanization or global warming; what is the relationship between male ornaments and reproductive success in birds?). Incidentally, a meta-analysis of meta-analyses or a second-order meta-analysis [30,31] is a type of deep synthesis, but it only deals with secondary research literature; this type of second-order systematic review is called an overview of reviews or an umbrella review [26,32] (Figure 1).

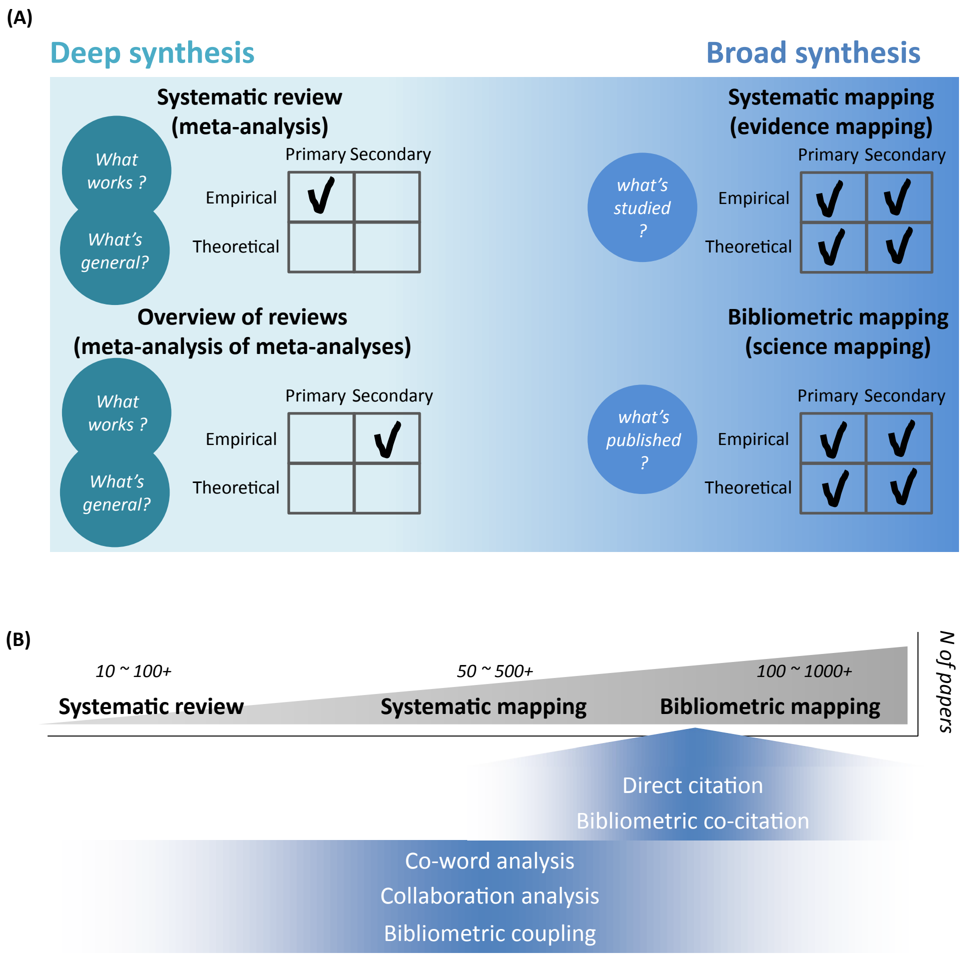

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Figure 1. Types of Research Synthesis and Their Scopes. (A) Research syntheses can be deep or broad (or somewhere in between). The main questions asked (in the circles) and types of data typically used (grids) are shown for the four main types of research syntheses. Systematic reviews and meta-analyses put together evidence from primary empirical studies to infer what works and where/when. Similarly, overviews of reviews (or meta-analyses of meta-analyses) 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 reviews (including meta-analysis) and systematic maps 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.

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 [10,11,15,16]. A systematic map summarizes relevant literature in a database that codes the features and contents of each piece of evidence, which is sometimes visualized as a **content map,** a temporal trend and a spatial map (Figure 2). Any literature type – empirical, theoretical, primary, and secondary – can be included, and descriptive statistics can summarize study

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: (i) **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 (ii) **bibliometric mapping** (also known as science mapping), which quantifies structure within the scientific literature by analyzing connections between citations, authors, and keywords or phrases.
Citation bias: papers that accrue more citations have more influence, but this authority can be unjustified. Citation bias commonly occurs from positive studies being cited more often than negative studies or it could happen via other means; for example, papers in prestigious journals or from experts in a field are more frequently cited regardless of their content. Citations can also be given, and propagated, for claims not adequately supported by the original source.
Content map: tabulates and visualizes the contents of a collection of research literature; this mapping process is at the heart of a systematic map.
Evidence synthesis: a type of research synthesis, which summarizes research evidence on a given topic (question); it includes systematic reviews and maps.
Gray literature: information found outside of traditional academic publishers. Gray literature includes information from theses and reports from governments and industries, and is typically harder to find and catalog than peer-reviewed published articles.
Influence synthesis: type of research synthesis that summarizes the influence or impact of research articles in terms of citation, connection, and how a particular article contributes to the development of a field or topic (i.e., performance analysis and

attributes. Crucially, mapping can identify knowledge gaps (i.e., areas requiring more attention), and knowledge clusters (i.e., areas that are ripe for a systematic review and meta-analysis) [10,11,15,16]. The use of systematic and evidence mapping approaches has been rapidly growing in the social, medical, and environmental sciences in recent years [10–13,15]. For example, the first systematic map in environmental sciences investigated the effectiveness of different farming practices for preserving biodiversity [33]. Systematic mapping, however, is not frequently applied to 'blue skies' questions that ecologists and evolutionary biologists study. An exception might be a systematic map where the fitness consequences of inbreeding in natural populations are catalogued – this work has clear implications for conservation biology [34] (also see [35]).

Bibliometric (science) mapping answers the question what's published? and is therefore focused 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) [17,18,36]. 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 [17–19,37]. Such networks of bibliometric information can be visualized as a bibliometric web (Figure 2). Some of these methods are beginning to be used in systematic reviews and maps; recent examples include analyses of terminology and semantics within a collection of relevant literature [38,39]. However, the full toolkit of bibliometric mapping has never been 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 minimize bias, maximize rigor, and to provide new insights. Research article databases (e.g., Scopus) make it possible to combine multifaceted information in one research synthesis, including types of publications (e.g., primary and secondary), types of research/evidence (experimental, observational and theoretical), author networks (research groups), phylogeny (species information), and mapping of traits and/or methodologies (Box 2).

So far, we have emphasized 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 (often similar, but sometimes these are on the opposite sides of the world). Systematic mapping, but not bibliometrics, provides a what, why, and how: what researchers 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, and meta-analytically). If systematic mapping borrowed tools from bibliometrics, these questions could be enriched and addressed more efficiently.

Co-word analysis, when applied to the full text of papers, can help find key study information. Text analysis can effectively capture important concepts shared by a group of articles by creating a **term map** (or term web) [40]. Term mapping (or co-word mapping) assists in setting

bibliometric mapping in bibliometrics).
Living systematic review: systematic review that is continually updated with information as it becomes available, which requires regular searches for new evidence and the communication of this updated information and synthesis.
Meta-analysis: quantitative review of research on 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 it is also 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: general term used for the synthesis of research literature, including narrative reviews, meta-analyses, systematic reviews and maps, and bibliometric maps.
Research weaving: 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: 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. Related mapping processes include an evidence map, evidence gap map, and evidence review map.
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).
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.

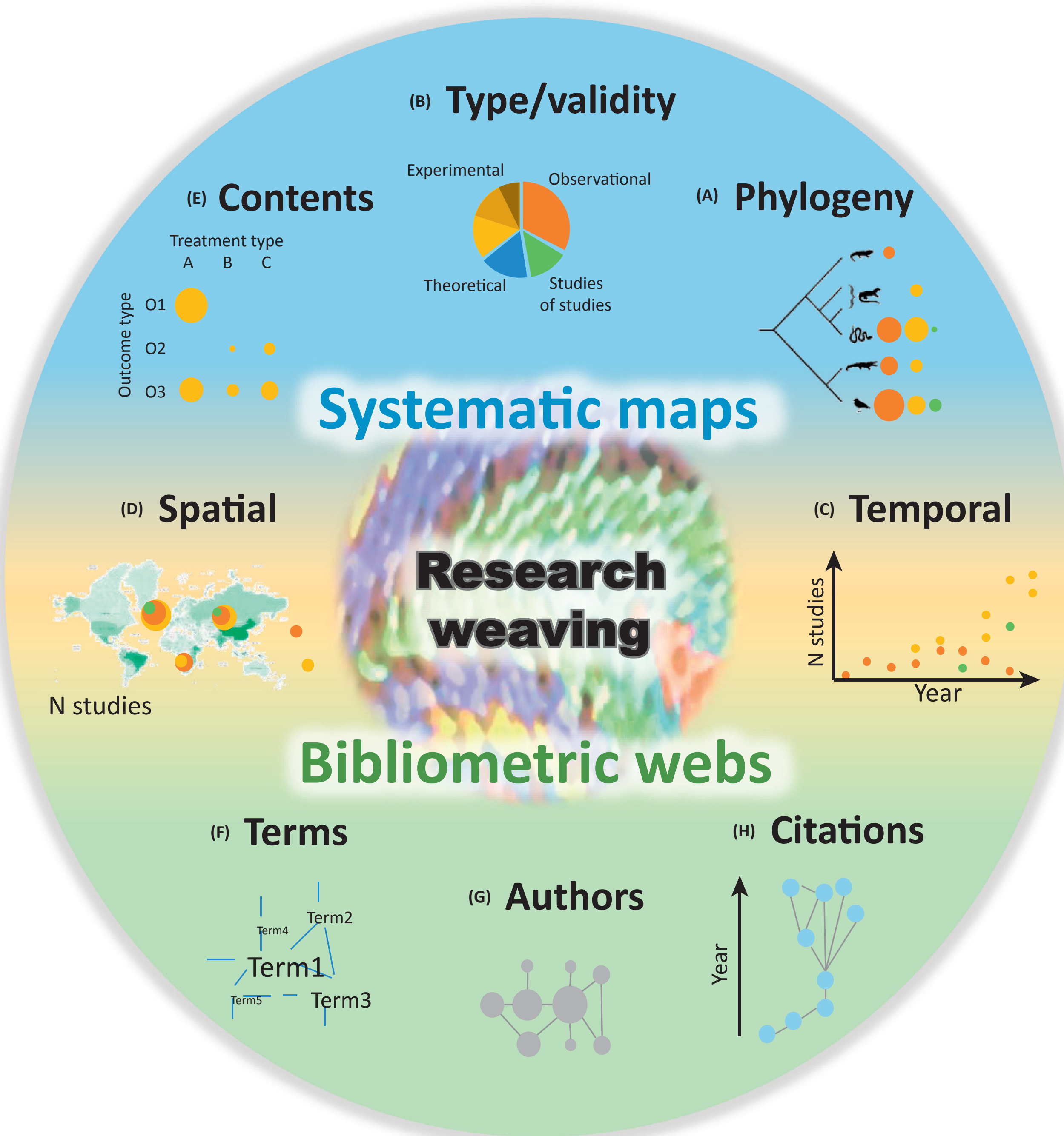

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Figure 2. Research Weaving Encompasses and Joins Systematic Maps and Bibliometric Webs. Pictograms (A–H) illustrate the main types of possible visualizations for interpreting the patterns either in the data extracted from the full text (systematic 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.

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 [81]. Bibliometrics uses 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 [20,81]. With performance analysis, we quantify citation impacts and productivity using, for example, the h-index [82] and Journal Impact Factor [83], which are all too familiar to scientists, and an obsession to some [84]. With bibliometric mapping, we quantify connections and networks among publications, using three types of techniques: (i) collaboration (coauthor) analysis; (ii) co-word (term) analysis; and (iii) citation analysis [17,18,36]. 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 [18,19]: co-citation analysis [85] and bibliographic coupling [86]. Co-citation and bibliographic coupling are both methods of measuring the connection between two papers (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 [17,18,36]. 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 depends on the purpose and scope of research synthesis [17] (see Figure 1B in main text). Direct and co-citation analysis are probably more appropriate when publication databases are large and papers have been 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 [87].

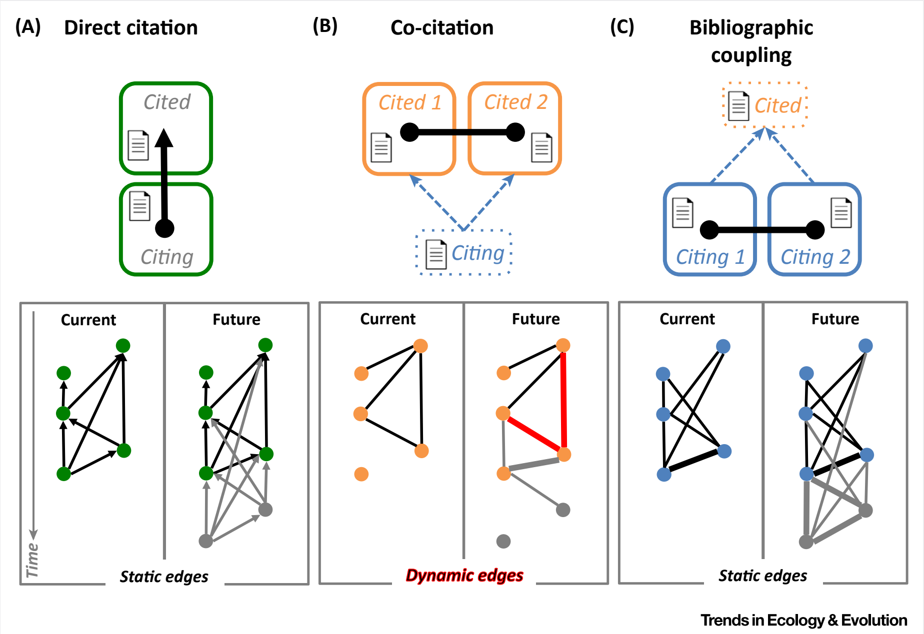

Figure I. Three Main Types of Bibliographic Networks. Papers are represented as nodes/vertices of constant size (i.e., not scaled by number of citations, centrality or any other indices). (A) Direct citations are denoted by arrows (edges) from citing to cited papers. If we create a network for a set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

up a content map – a major goal of systematic mapping (Figure 2). These tasks are becoming more straightforward through the widespread availability of topic modeling [21,41] and, more recently, deep learning [42,43] (Box 3). These tools will soon help researchers semiautomate 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 [21]. Both bibliometrics and systematic maps can be improved by borrowing techniques from each other; intertwining different synthesis procedures is the essence of research weaving.

Why Do We Need Research Weaving?

A major aim of research weaving is to provide an integrated conceptual and methodological toolbox to support the new field of meta-research (research on research) [44–47], which has emerged in the midst of the current reproducibility crisis [48–50]. Meta-research originates from research synthesis, especially meta-analysis [47], and has already utilized both bibliometric mapping [51,52] and meta-analysis (using systematic-review approaches) [53,54]. The mission of meta-research is to improve scientific methods and practices by understanding and combating biases in science.

A key frontier for future meta-research is to understand how individual researchers and their teams contribute to the generation of scientific knowledge. While a traditional view of research synthesis sees articles as collections of facts to be aggregated, meta-research has shown that the scientific literature is strongly affected by the structure of the research teams that create it. We now know, for example, that the size of a scientific team affects their impact on the discipline, with large teams having greater short-term influence and small teams challenging the norm [55]. This finding builds on work showing that invisible colleges – groups of dominant researchers that guide the development of a discipline – strongly influence what information is treated as legitimate within scientific communities [56]. Such biased influence, in turn, affects the nature and quality of published information on that topic. These effects are becoming more important as science continues its trajectory towards larger research teams (particularly in ecology [57]). Therefore, it is no longer sensible to produce reviews that ignore the collaborative networks that generate scientific information.

Box 2. Research Weaving Helps Meta-analysis

Meta-analysis, now >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., meta-analyses without a systematic-review approach) [88–90]. Research weaving might assist a meta-analysis in divorcing itself from poor practices, because research weaving makes more researchers aware of the importance of a systematic-review approach, enforcing transparency in every step of the process. Also, research weaving could identify and mitigate citation biases and other types of biases in a meta-analysis. Furthermore, the processes and visualization techniques of research weaving can be powerful aids for meta-analysts. For example, a meta-analyst would typically only visualize effect sizes via forest and funnel plots [4,5]. In contrast, given the same dataset, a research weaver would visualize 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) (see Figure 2 in main text). 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 visualizations. 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 [73]. They provide impressive visualizations of the different facets of their dataset via an interactive website (match.ctglab.nl). We also have a web-based example of research weaving associated with our evolutionary/ecological meta-analysis [91] (www.example.researchweaving.com; Figure I).

Research weaving with bibliometric data can also help meta-analysts during data screening and collection stages. Along with text mining (Box 3), co-word analysis of key research articles and reviews will help construct a string of keywords for database searches [40,92]. This is because co-word analysis and text mining can identify key terms which connect a collection of papers; this process can, for example, detect synonymous, but also seemingly distinct, terms used among different research groups and (sub)fields [21]. Such analysis could also help detect relevant moderators, once a final dataset is obtained. Co-citation and bibliographic coupling networks from prescreened 'hits' (publications) can facilitate screening by creating clusters of connected and unconnected publications [92]. Collaboration networks will identify both major and minor players and laboratories conducting research addressing similar questions. Meta-analysts can then contact all identified research groups to see whether they have unpublished work (e.g., thesis chapters; we have successfully used this process in several meta-analyses).

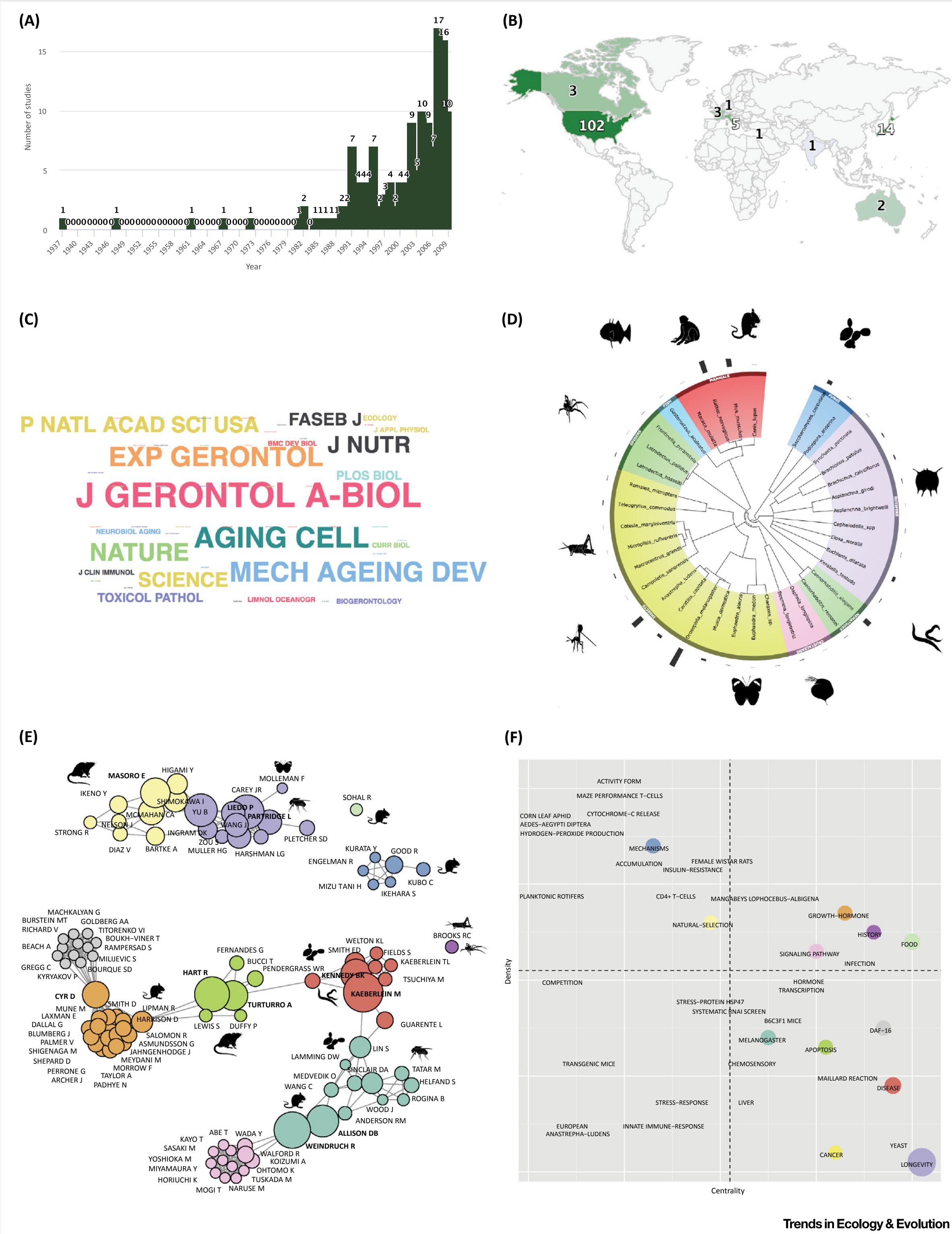

Figure I. Example Visualizations for the Meta-analysis on the Relationship between Dietary Restriction and Longevity. (A) Distribution of publication dates of included studies, indicating a recent increase in number of published relevant studies. (B) Geographic distribution of the countries of origin of the first author

(Figure legend continued on the bottom of the next page.)

Box 3. Potential of Text Mining with Deep Learning

Text mining is a collection of methods for extracting information from free text [93]. While it can include tasks from the field of natural language processing such as detecting keywords, synonyms, or named entities (locations, people, species names, etc.), the term text mining more commonly refers to a set of tools for classifying documents 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 (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 [94]. 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 [42,43].

Machine learning is typically applied to evidence synthesis in one of two closely related ways. Unsupervised classification groups articles into a prespecified number of related types (e.g., via topic models) [95], 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 might have some information on which 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 [95]).

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 [69]. Second, machine learning allows reviews to be quickly updated as new information becomes available, progressing towards the goal of living systematic reviews [74,75]. Finally, automated approaches are well suited to identifying regions within the academic literature that have been rarely studied and which can benefit from further research [13,21].

Research weaving provides powerful new tools to assess the influence of individual researchers and teams on the production of scientific information. To date, the evidence synthesis community has sought to negate the influence of dominant researchers or groups by anonymizing articles during screening, and by using multiple reviewers to screen each article to ensure consistency. We argue that this approach risks ignoring the problem; recognizing bias, as well as minimizing bias, is an essential part of evidence synthesis [58]. Research weaving faces the problem head on, by mapping the structure of a corpus in terms of shared authorship or citation among articles via bibliometrics (Figure 2). It is possible, for example, to quantify (and then to control for) the influence of dominant researchers on the evidence base. Bibliometrics also provides information on the degree of interdependence among articles in terms of shared authors or citations, which can act as a proxy for uniqueness of the data that a paper provides. With such information, we could account for nonindependence of data in any resulting meta-analyses, using methods built to account for pseudoreplication, or spatial or phylogenetic dependence [59]. In a similar manner, characteristics of highly cited papers, or **citation bias** [60–62] can be subject to analysis (e.g., an unusually large effect size). Therefore, research weaving could recognize and deal with research biases associated with citation or influence [48,63]. Notably, these types of biases are distinct from well-known biased practices – the focus of a field on one particular taxonomic group, geographical place, or question, but not other relevant ones [64–66], which can also be elucidated through research weaving.

of the included studies. (C) Word cloud of the publication journal names of the included studies. (D) 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). (E) Author collaboration network, where nodes represent top 100 authors in terms of the numbers of authored papers in the data set; links are co-authorships; author clusters are manually annotated with the respective main study organisms. (F) Thematic map based on co-word network analysis and clustering of keywords of the included studies (more examples available at www.example.researchweaving.com).

In addition to revealing citation bias and biased practices, research weaving involves a more in-depth assessment of a collection of literature than was previously possible. By providing a better understanding of a topic in terms of both research content and people involved (Figure 2), this information could help researchers direct primary research efforts and form new collaborations, thus driving innovations and increasing research efficacy and capacity.

Finally, research weaving places a strong emphasis on visualizations – rapidly and efficiently conveying the rich information contained in studies and citations (Figure 2). Such visualizations are likely to help, not only researchers within and outside the field (thereby facilitating interdisciplinary collaborations), but also members of the public (where applicable, stakeholders and policymakers), enhancing science communication and the public understanding of science [67]. Visualization of content maps and bibliometric webs can truly deliver a 'bird's eye view' of science, which meta-research seeks [45,46].

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 [68–70].

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 [4,5,7,26,71]. Research weaving deviates from this six-step process in five main ways (Figure 3). First, research weaving analyzes full bibliometric data, which requires all relevant bibliometric information (e.g., citation data) from bibliographic resources such as the Web of Science or Scopus. Both resources provide the usual reference information and abstracts, as well as 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 or after screening (for a review of types of bibliometric analyses, see [17,18]). For example, we can create a prescreening term map to help devise keyword strings for further searching; and we can also make a postscreening term map to help code each paper or create a content map (Box 3). Second, we can use relevant publications postscreening to create a network via bibliometric coupling to identify articles that were not in the postscreened 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 (Figure 3). Visualization is a core step in research weaving. Fifth, and crucially, we can 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.

Available Tools for Research Weaving

There has been a recent surge of tools for systematic reviews and maps. A comprehensive and growing catalog 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 [70], such as CADIMA (www.cadima.info), Colandr (www.colandrapp.com), and metagear [72]. These tools are created mainly to support systematic reviews (e.g., planning, screening, documentation, and bibliographic management [69]), but none of them

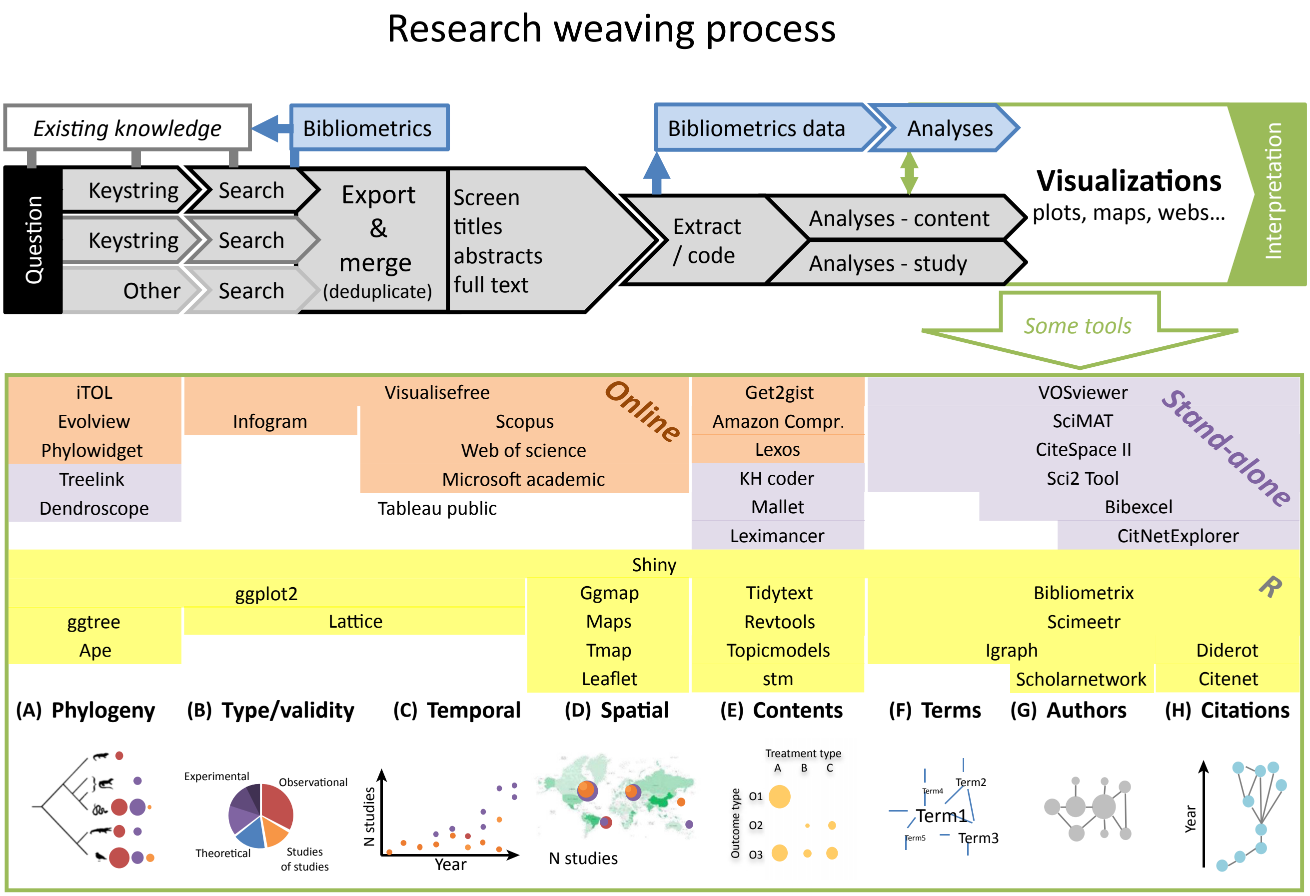

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Figure 3. Research Weaving Processes and Implementation Tools. Research weaving uses tools and processes from bibliometrics (blue boxes on top) and systematic mapping process (gray boxes). Bibliometric tools can help identify relevant literature and knowledge at the early stages of the systematic mapping process. Later, for the included papers, visualizations of bibliometric indices and relationships can be added and blended with the visualizations of the contents of the papers. Examples of visualizations 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 colors into online, stand-alone software and R packages) that could be used to produce a given type of visualization. For content visualizations (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 visualized using any basic graphing software.

facilitate 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 (Table S1 in the supplemental information online). We show some examples of these tools in Figure 3.

Publication

What does a research weaving publication look like? A typical research weaving paper would include some or all of the maps and webs depicted in Figure 2 (and potentially more). However, the application of the conceptual framework goes beyond just creating a hybrid of systematic and bibliometric maps. For example, meta-analysis can be supplemented or enhanced by adding bibliometric maps, as we show in Box 2; interactive maps and webs might be well served by online accompaniment to a scientific publication (e.g., [73]). Conversely, researchers wanting to map the history of a field can mainly use bibliometric mapping, while also following a systematic-review approach. For applied areas of research or public outreach, we can use visual components of scientific publications in policy briefings, reports and blogs. By keeping procedural transparency, the research-weaving framework ensures it is possible to regularly update a review or keep weaving a tapestry of evidence and influence, in line with **living systematic reviews** [74,75] (Box 3). Most importantly, using part of the research weaving toolbox, anybody can obtain a better view of the literature on a topic they are working on, to help one's research and when writing research publications.

Current Limitations

Research weaving promises to provide a richer analysis of a research field than systematic mapping or bibliometrics alone. 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 as low as 40–50% [76]). However, different databases also structure their content differently, which presents technical challenges to smoothly merging overlapping content [18,77]. Encouragingly, some programs are capable of merging disparate database outputs (e.g., bibliometrix [36]).

Second, current software packages for bibliometrics are mainly developed for using the information from Web of Science and Scopus (see Table S1 in Supplemental Information online), but these two databases do not cover **gray literature** such as theses and governmental reports. Google Scholar, however, provides greater literature coverage, including gray literature [78]. Some practical tools are already available to extract bibliometric data from Google Scholar and other web-based search engines, and no doubt more are in the pipeline [79], enabling us to incorporate gray literature into research weaving (Figures 1 and 3; see Table S1 in supplemental information online).

Third, despite the majority of bibliographic information about an article being reliable within databases, multiple versions of the same publication might stem from variants of journal or author names or even different book editions (e.g., one version with a full journal name, but the other with a shortened version of the name) [18,36]. This can require substantial data cleaning 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.

Fourth, 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 (Figure 1). Even with some automation, much of a body of work will still require manual processing to ensure extracted content is relevant and correct [18].

Finally, we see the current limitations discussed above as future opportunities, because the research-weaving framework is likely to bring (and indeed is already bringing; Evidence Synthesis Hackathon [https://evidencesynthesishackathon.com]) researchers and developers together to solve these problems. Advances in text mining and machine learning (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 attention [80]. Research synthesis is a vital tool for sorting through ever-increasing amounts of data and associated publications. The research-weaving framework visualizes research landscapes by utilizing emerging methods of systematic mapping and bibliometrics. Thus, research weaving navigates researchers through complex research terrains 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' (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.

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 syntheses 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 research findings to the politicians and the general public?

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