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Formalized synthesis opportunities for ecology: systematic reviews and meta-analyses

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Narrative reviews are dead. Long live systematic reviews (and meta-analyses). Synthesis in many forms is now a driving force in ecology. Advances in open data for ecology and new tools provide vastly improved capacity for novel, emergent knowledge synthesis in our discipline. Systematic reviews and meta-analyses are two formal synthesis opportunities for ecologists that are now accepted as traditional publications, but the scope of validated syntheses will continue to expand. To date, systematic reviews are rarely used whilst the rate of meta-analyses published in ecological journals is increasing exponentially. Systematic reviews provide an overview of the literature landscape for a topic, and meta-analyses examine the strength of evidence integrated across different studies. Effective synthesis benefits from both approaches, but better data reporting and additional advances in the culture of sharing data, code, analytics, workflows, methods and also ideas will further energize these efforts. At this junction, synthetic efforts that include systematic reviews and meta-analyses should continue as stand-alone publications. This is a necessary step in the evolution of synthesis in our discipline. Nonetheless, they are still evolving tools, and meta-analyses in particular are simply an extended set of statistical tests. Admittedly, understanding the statistics and assumptions influence how we conduct synthesis much as statistical choices often shape experimental design, i.e. ANOVA versus regression-based experiments, but statistics do not make the paper. Current steps – primary research articles need to more effectively report evidence, sharing scientific products should expand, systematic reviews should be used to identify research gaps/delineate literature landscapes, and meta-analyses should be used to examine evidence patterns to further predictive ecology.

Ecology and the environmental sciences are increasingly engaging in pluralistic forms of synthesis. This is not a new phenomenon, but as a discipline, the recent evolution of accessible, open big data provide opportunity for novel synthetic synergies. Synthesis in ecology is the integration of disparate components of research including data, methods and concepts (Carpenter et al. 2009, Hampton and Parker 2011) whilst 'big data' are datasets with large volumes, high levels of complexity, and perhaps specific to ecology are often diverse, heterogeneous and distributed (Hampton et al. 2013). Ecology has a very strong history of data-intensive primary research endeavors, but with a changing culture of data sharing and the dramatic advances in sharing and retrieval tools (Chaudhary et al. 2010) such as those provided by DataOne (Michener et al. 2012), we are now poised to capitalize on broader, big science generalizations. Even if specific sub-disciplines of ecology have not necessarily crossed thresholds into the realm of big data, the powerful synthesis and sharing tools associated with this movement can identify research gaps and opportunities for novel, useful research. Synthesis, open data, and initiatives that explore emergent knowledge in ecology thus have the capacity to not only reshape how we evaluate the strength of our evidence but also change how we function as a community and interact with society at large.

The paradigm shift in handling big data and synthesis occurred over 20 years ago in evidence-based medicine. The implications and risks associated with false positives and errors in medicine precipitated a very early adoption of data sharing of randomized controlled trials and replicable, transparent reviews such as those of the Cochrane Collaboration (Higgins and Green 2009). Importantly, a parallel shift from interpreting the strength of evidence based on significance tests (i.e. p-values) to interpretation in the context of study details and other evidence is still ongoing (Sterne and Smith 2001) – even today. Consequently, reporting both the strength of evidence directly in publications by providing effect size estimates, precise p-values, and variances and effectively sharing data is a continuing challenge for evidence-based medicine practitioners and a more critical issue for ecologists (Wolkovich et al. 2012). There are many notable forms of novel synthesis including integration of disparate datasets (Pickett et al. 2007) such as <http://wethedata.org>, <http://impactstory.org> or <www.oceanhealthindex.org>. Formalized methods of synthesis are thus evolving to use data mining, collective understanding,

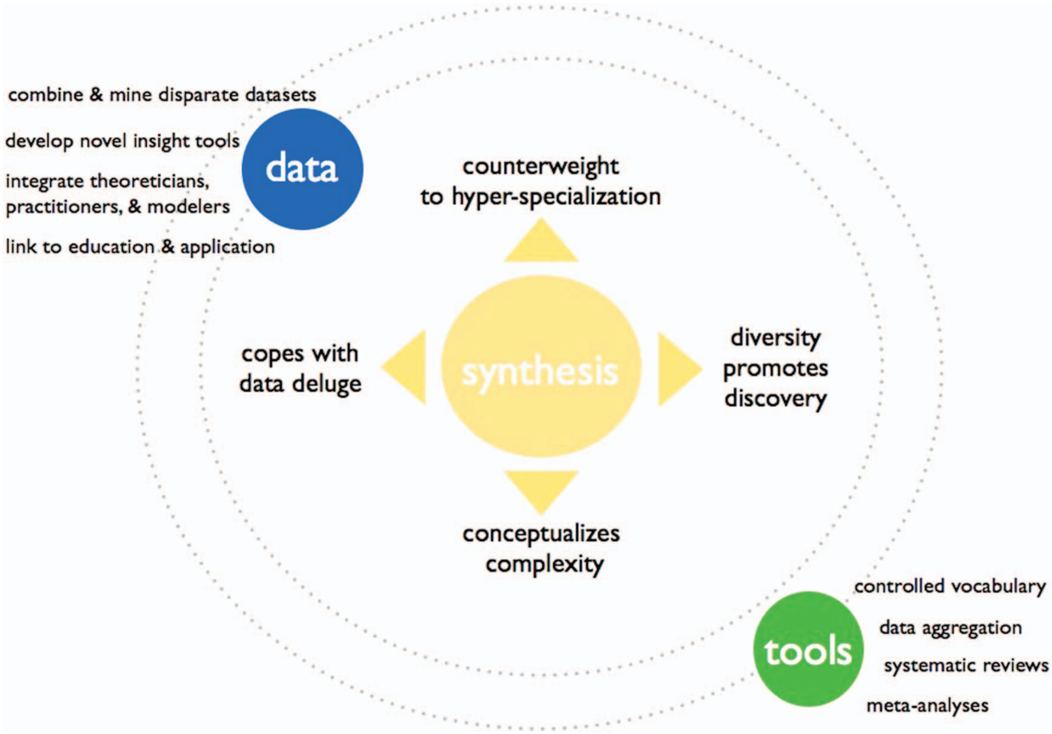

Figure 1. A visual summary of the implications of synthesis for ecology, i.e. the synthesis solar system for this discipline. The four core implications directly associated with synthesis are from Hampton and Parker 2011 whilst the opportunities associated with data are from Carpenter et al. 2009. The tools listed in the outer ring are a simple list of the dominant forms of synthesis prevalent in ecology. Importantly, open data – i.e. accessible in some form including reported in paper, published in repositories, in tables, in appendices, or as independent data publications - become evident as a key element needed to accelerate or further stimulate synthesis within this discipline. Systematic reviews and meta-analyses are powerful tools associated with synthesis and open data promote this integration. .

and text mining more extensively. Traditional modes of peer-reviewed synthesis such as systematic reviews and meta-analyses are nonetheless predicated upon clear reporting of evidence, and accessible data is a common element (Fig. 1). Synthesis is a critical step in the evolution of a scientific discipline for at least the following four reasons: it is a counterweight to increasing hyper-specialization, it provides a mechanism to cope with the data deluge, it conceptualizes complexity, and it requires a diversity of skills and often datasets that subsequently promote discovery (Hampton and Parker 2011). Admittedly, there are various modes of synthesis including data aggregation, methodological integration, conceptual synthesis, and reuse of results (Sidlauskas et al. 2009) – all very powerful tools for ecology – but data are frequently a critical component to conduct these integrative efforts either directly or indirectly to calibrate the scope of inference. Synthetic projects that include data integration (Fig. 1, first associated orbiting body of concepts) facilitate combination and mining of disparate datasets, development of novel insight tools, integration of individuals with different skills, and the opportunity to link to education and application (Carpenter et al. 2009). More broadly, synthesis promotes adoption of general tools such as controlled vocabularies, data aggregation, systematic reviews, and meta-analyses (Fig. 1, second associated body of concepts). The ecological community is actively pursuing these channels of knowledge development through synthesis centers such as NCEAS and NESCent, large distributed collaborations such as NutNet, working groups and other collaborations, and through open date initiatives and organizations including the Collaboration for Environmental Evidence. Nonetheless, there is still a pressing need for refinement and advances to formalized synthesis in the forms of systematic reviews and meta-analyses for ecology and for additional shifts within our community to fully embrace replicable, transparent reviews and data decisions in conducting rigorous synthesis. Open data and better reporting in publications must also continue to evolve in ecology.

Immediate opportunities for ecological publications: systematic reviews and meta-analyses

Narrative reviews are dead! Long live systematic reviews! A systematic review is a form of synthesis that examines a predefined question or issue using systematic, explicit methods to populate the list of studies included, critically appraise and filter the research, and collect data from these studies to generate a replicable review (Higgins and Green 2009). Meta-analytical statistics of effect sizes may be included in the review but are not necessary elements. Formal meta-analyses, specifically defined for ecology, are any set of statistics combining the strength of evidence across studies, such as effect sizes, on a related topic (Koricheva and Gurevitch 2013). Hence, systematic reviews may include meta-analytical statistics, and meta-analyses should also include at least a clear statement of study selection criteria. Whilst the divide between the two may seem arbitrary and semantic, the distinction is valid in that the extent of the development of each potential set of analyses differs, as does the purpose. Systematic reviews are often focused on defining the research landscape, identifying research gaps, and describing the extent that sets of hypotheses, methods, or species have been studied. The relative strength of evidence is generally not included in systematic reviews in ecology to date. Published meta-analyses in ecology must de facto include some form of strength of evidence aggregation and include the criteria used to populate the study list but often report the latter to a lesser extent relative to a systematic review. This is entirely acceptable as the focus is to examine the strength of evidence defined a priori in the synthesis. For example, two recent systematic reviews on ecological topics literally defined the scope of the synthesis associated with the respective research topics by mapping the location of all studies globally (Reid et al. 2010, Spafford et al. 2013). Systematic reviews can also list the number of studies associated with important factors and examine how thoroughly the topics have been tested to date in terms of types of studies. Hence, systematic reviews provide an opportune synthesis method to define the research on a topic as a whole even if strength of evidence estimates are not available. An excellent paradigm shift for ecology in educating students would be a change from introductory thesis chapters as narrative stories describing in serial what has been done to systematic reviews that process the literature in parallel, collectively and not selectively, and quantitatively identify the gaps in the research that lead to the graduate research. Importantly, this structured appropriate to research topic assessment reshapes the context of any research program and is an invaluable contribution to the knowledge associated with a specific topic.

Systematic reviews and meta-analyses are not the only forms of published synthesis in ecology. Narrative reviews and vote counting are alternatives. Nonetheless, the limitations of these formal syntheses likely preclude their use in most modern ecological synthesis contexts (Koricheva and Gurevitch 2013). Narrative reviews basically tell a story given a set or subset of studies. Without an indication of how studies were selected or how the evidence is contrasted, there is however limited opportunity for repeatability. Absence of quantitative descriptions of the literature is also an important potential limitation in effectively describing research gaps in narratives. Vote counting efforts tally up the publications supporting a hypothesis and compare to those that do not. This is a very ineffective synthesis technique in that the strength of evidence within studies is not examined. For instance, 10 poorly conducted, weak studies that interpret findings as support beat out several rigorous studies with much larger sample sizes or better designs that reject the same hypothesis. Importantly, larger study pools actually increase the likelihood of spurious findings in vote counts (Koricheva and Gurevitch 2013). These and other more advanced issues are well described in detail in the 'Handbook of meta-analysis in ecology and evolution' (Koricheva et al. 2013). Whilst the historical influence of narrative reviews populating the synthesis literature landscape skews the representation in

Figure 2. Word cloud showing the frequency of a general collection of synthesis terms. The counts were generated by a search of Web of Knowledge using only titles and for ecology as sub discipline. The term 'review' excluded systematic reviews. Additional common terms associated with synthesis in ecology were also provided to calibrate importance of term importance in titles.

ecology (Fig. 2 depicts the frequency of terms in title from Web of Knowledge), the citations per item to meta-analyses rival that of narrative reviews (Fig. 3). Like all vote counts however, even contrasts of narrative reviews versus meta-analyses do not provide an indication of the effectiveness in handling the evidence. Appropriately, there have been at least two meta-analyses of meta-analyses in ecology to date that applied the same direct quantitative statistics to published meta-analyses (Castellanos and Verdu 2012, Jennions and Møller 2002). The general trends in citations per item are a likely indication that the quantitative processing of evidence inherent in meta-analyses is becoming an important substrate for modern synthesis.

The decision between a formal systematic review and a meta-analysis is a much more important decision than narrative reviews or vote counts. That said, it might often be easily resolved for a particular topic. Ecological meta-analyses have been increasing in frequency for some

Figure 3. Word cloud showing the frequency of citations per item for each synthesis term explored. The citation estimates were from a search of Web of Knowledge using only titles and for ecology as sub discipline. The term 'review' excluded systematic reviews. Additional common terms associated with synthesis in ecology were also provided to calibrate importance of term importance in titles.

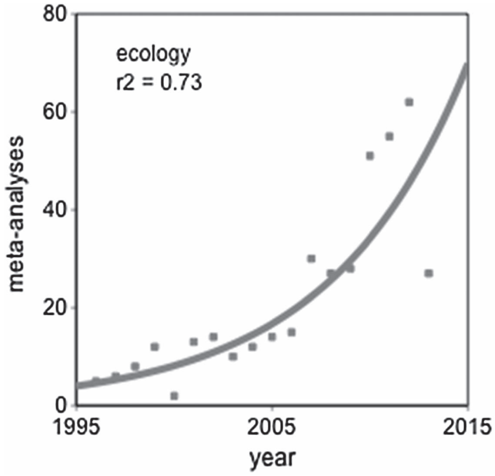

Figure 4. A very conservative survey of the literature to date of focused meta-analyses in ecology shows an exponential increase in recent years similar to the trends identified by Cadotte et al. 2012. The line of best fit was exponential with r^2 listed in plot at $p < 0.01$. Frequency estimates were from a Web of Knowledge search for ecology only, and values listed are per annum.

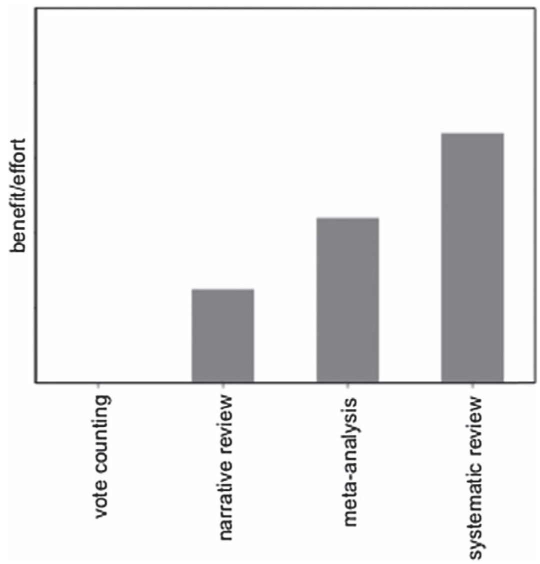

Figure 5. A conceptual model of the benefit relative to the effort associated with the four published synthesis methods in ecology. Narrative reviews are assumed to be marginally less effort than systematic reviews, there is no benefit to vote counts, and meta-analyses have many benefits relative to all other methods but are very effort intensive. Arguably, syntheses that include meta-analytical statistics are most likely to yield the important benefits to synthesis. However, given the relatively reduced effort of systematic reviews and likelihood that certain topics may lack open data, suffer from poor reporting, or have significant research gaps, systematic reviews can provide more immediate emergent knowledge in some instances. The values on the y-axis were calculated by using effort estimates from Cote and Jennions 2013 and benefits from Koricheva and Gurevitch 2013 (both chapters from Handbook of meta-analysis in ecology and evolution).

time (Chaudhary et al. 2010, Cadotte et al. 2012). A cursory examination of frequency on Web of Knowledge at this junction similarly shows exponential increases (Fig. 4, using only titles). Importantly, the complexity of meta-analyses in ecology has also been increasing with time and their capacity to inform discovery and illuminate heretofore with unresolved debates more common (Cadotte et al. 2012). Systematic reviews have not however been as frequent, i.e. there are approximately 400 meta-analyses in ecology and only 26–30 systematic reviews to date (Web of Knowledge searches with appropriate search terms). This is unfortunate in that unavailable data to calculate effect sizes or genuine research gaps associated with the examination of a topic limits meta-analytical statistics but are nonetheless amenable to systematic reviews thereby informing future research efforts. Importantly, the relative effort associated with extracting data from publications, even if provided, is relatively high. The effort associated with each step of the process for either endeavor is articulated in two flowcharts in the second chapter of the meta-analysis handbook for ecologists (Cote and Jennions 2013). The 'sweat-equity' effort estimates provided in this chapter for systematic reviews are nine and for meta-analyses an additional 22 units. Conservatively, the effort associated with a meta-analysis is thus frequently triple that of a systematic review. Assuming that narrative reviews and vote counting are marginally less work than a narrative review and that systematic reviews have many of the benefits of a meta-analysis excepting, quite notably, strength of evidence estimates, we can generate a conceptual model illustrating the benefit to effort ratio for all four published methods (Fig. 5). This does not mean to imply that systematic reviews are preferable; simply that in some instances, systematic reviews are excellent knowledge synthesis tools to illustrate research gaps, limited data, or extent of research on a topic. Meta-analytical statistics are the most likely to generate transformative research because patterns in strength of integrated evidence more definitely identifies important causative factors in ecology – the holy grail for our discipline in many respects. Ultimately, we do not need to decide on a single mode of synthesis in ecology (Sidlauskas et al. 2009), but we do need to advance on all fronts by integrating data and methods, doing conceptual synthesis, and reusing results in systematic reviews and meta-analyses. Systematic reviews are thus a major gap/opportunity in synthesis ecology, but meta-analysis is a more powerful tool to advance predictive ecology.

Effective implementation of both formal methods is well described in the literature and in numerous other resources. Practical publications for systematic reviews are predominantly described for the life-sciences and not specifically for ecology, but the general guidelines apply given the purpose of this tool – transparency, repeatability, selection criteria, and quantitative description on the literature landscape as best practices (Higgins and Green 2009, Moher et al. 2009). Major initiatives include the Cochrane Collaboration (<www.cochrane.org>), the Campbell Collaboration (<www.campbellcollaboration.org>), PRISMA (<www.prisma-statement.org>), and more ecologically, the Collaboration for Environmental Evidence (<http://environmentalevidence.org>). Interpretation and appropriate application of meta-analyses are much more developed in ecology because the tool has been more applied and discussed (Gurevitch and Hedges 2001, Møller and Jennions 2001, Gates 2002, Kotiaho and Tomkins 2002, Tomkins and Kotiaho 2004, Lortie and Callaway 2006, Pullin and Stewart 2006, Stewart 2010). The handbook described in this paper for ecologists is an excellent resource for all levels of meta-analysts and also provides a more in-depth discussion of interpretation (Jennions et al. 2013) and simple rules-of-thumb for graphical presenting results (Lortie et al. 2013). In all sets of published syntheses in ecology, reliable reporting, effect scoping of the topic, clearly defined terminology, and appropriate integration are sound guiding principles.

Implications and trends

At this junction, synthetic efforts that include systematic reviews and meta-analyses will continue to persist as stand-alone publications. This is a necessary step in the evolution of synthesis in our discipline. Nonetheless, they are still evolving tools, and meta-analyses in particular are simply an example of a set of statistical tests. Understanding the statistics and assumptions influence how we conduct synthesis much as statistical choices often shape experimental design i.e. ANOVA versus regression-based experiments (Cottingham et al. 2005, Oksanen 2001), but statistics do not make the paper. Clear ideas and excellent questions do. Titles with 'a meta-analysis of …' in them may have their days numbered as these tools become more widely adopted and as we seek to integrate evidence across many scales not just between studies. Approaches associated with both sets will inevitably and appropriately also become routine mechanisms to contrast primary study-level research to the work of others. For instance, in the Introduction of a primary study, formal systematic review techniques are applied, the authors identify a gap that they proceed to examine within that particular study via an experiment, and in the Discussion, the strength of the evidence is linked to other effect size estimates reported in the literature. This is already occurring but will certainly become more frequent. There will always be a place for stand-alone systematic reviews and meta-analyses that summarize the state of the art for a particular topic or research thread broadly – much as narrative reviews were extended versions of a Discussion in a primary research article historically. Sections of ecological journals are thus an excellent mechanism to organize all forms synthesis and provide a co-coordinated channel to ensure that the highest possible standards of integration are applied.

Oikos is an ecological journal also publishing meta-a nalyses at an increasing rate, and similar to the transformative capacity of the Forum section, a dedicated section associated with formalized, replicable systematic reviews and meta-analyses will also advance discovery and integration via effective curation. Importantly, methodological comments that speak directly to improved modes of synthesis should be discussed and examined more vigorously in our discipline. A dedicated senior editor will be assigned to this section, all decisions and reviews will be completed with one month (provided referees respond in a timely manner), and referees will be selected to review not only the topic explored but also the elements of synthesis included. Transparency in the literature selection will be required through inclusion of reporting tools such as those of PRISMA, and data with meta-data will be published alongside the syntheses whenever permitted. These efforts will be open-access published to stimulate positive practices in our field more broadly and to facilitate longitudinal cross-study contrasts of ecological syntheses. Ecology is a very diverse discipline, and big-science ecology needs big bridges between our synthetic discoveries.

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