Practical interpretation of ecological meta-analyses

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Brief note on meta-analysis for ecology.

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Abstract

Meta-analysis offers ecologists a powerful tool for knowledge synthesis. There is however obvious and subtle issues to consider specific to ecology with respect to the appropriate interpretation of meta-analyses once the statistics are completed. Meta-analysts in any field must clearly define *a priori* the scope of inference and the purpose of the meta-analysis, but ecological meta-analysis often faces issues particular to this field. For example, the primary studies being combined, even for tests of the same hypothesis, in ecology are generally conducted at different study sites or have difference ecological contexts (i.e. often few studies are not conducted in a laboratory) and use very different methods to test a single hypothesis. General objectives of the meta-analysis could include assessment of confidence limits of the treatment or ecological process of interest, detection of differences in treatments from no effect, identification of research gaps, and differences between groups such as different populations or communities. Meta-analyses can also be used in ecology to assess whether the scope of tests of a hypothesis are adequate. Reporting more than one summary statistic such as different effect size metrics is an excellent means to enhance synthetic potential for ecologists. Magnitude and sign of effect sizes can also be interpreted in novel ways for ecology given the broad scope of forms of hypotheses explored in this discipline. Ecology is now poised to take advantage of the synthesis developments common in other disciplines and this brief conceptual methods review provides the appropriate framing for this endeavor.

Keywords: ecology, interpretation, meta-analysis, practical, review, synthesis.

Introduction

We propose that progress in ecology is best promoted by using a range of non-exclusive methods including data synthesis based on formal meta-analyses, systematic reviews, conceptual and theoretical papers, and large and small experimental studies. 'Conceptual evolution' can occur through detailed experimental tests that refine and hone hypotheses thereby increasing the depth of our understanding of a natural system or set of ideas describing patterns or predicting processes (Paine 2002). Synthesis in ecology can however also be achieved via the integration of different concepts (Ford 2000; Ford and Ishii 2001) and quantitative syntheses of studies testing related ideas or hypotheses (Arnquist and Wooster 1995). It may seem obvious that science can progress effectively through both avenues, but the majority of ecological research in recent decades has focused on experimental tests of hypotheses. Similar to other mature/maturing disciplines, ecology is now in a position to capitalize on these intensive efforts since the literature has accrued adequate capacity in breadth and depth on many dominant ideas. Ecology is thus ripe for a profound shift in focus to use reviews as a means to develop ideas, explore conceptual evolution, seek general conclusions, and assess validity. This paradigm shift is not a new idea in evidence-based medicine (Higgins and Green 2006) nor in ecology (Arnquist and Wooster 1995; Gurevitch and Hedges 1993; Gurevitch *et al.* 1992), but the reviews in ecology are shifting from narrative descriptions to systematic reviews (Pullin and Stewart 2006), and meta-analysis is an excellent quantitative means to synthesize broad trends (Gates 2002).

Meta-analysis provides the user effective tools for synthesizing independent research efforts, comparing the relative success of treatments associated with groups of studies, testing whether mean treatment effects are significantly different than zero, and whether the effects are

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homogeneous or heterogeneous among and within groups or categories of studies. Meta-analyses thus offer readers and analysts in ecology additional capacity to assess attributes of a hypothesis such as testability, generality, consistency, accuracy, and bias in the studies published on a topic at the time of analysis. In contrast to experimental hypothesis testing, the only attribute of a hypothesis perhaps not best tested via meta-analysis is direct falsification. Meta-analyses can be used to summarize evidence for or against an ecological hypothesis. However, when the evidence in a meta-analysis fails to support a hypothesis this does not necessarily constitute rejection of the hypothesis as useful or predictive in ecology per se given that there are a wide range of hypotheses in this discipline ranging from purely descriptive to more formally falsifiable when associated with sets of manipulative experiments (i.e. trials are uncommon in ecology). A meta-analysis is not a test of the hypothesis, the respective experiments summarized are often so however, and failure to support may be a product of the set of studies testing the general proposition. In summary, a meta-analysis is not an experiment and does not test hypotheses but is a means to explore the strength of evidence associated with hypotheses. This is a critical clarification for ecology because there are often large collections of studies documenting only pattern, randomized controlled trials are not used, and even the replication of experiments or general protocols is unfortunately relatively infrequent.

Meta-analyses can also quantitatively address ideas and qualitatively assess or describe the scope of inference of a set of ideas (Arnquist and Wooster 1995; Treadwell *et al.* 2007). Depending on whether the work is basic or applied, expectations or needs-led research may dictate the particular scope of a meta-analysis and its use in synthesis (Pullin and Stewart 2006). Meta-analyses can thus be both conceptual and broad, i.e. how well does this set of studies describe an

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ecological process or pattern, and methodological and narrow in ecology, i.e. does these methods of application elicit the response needed to explore an ecological process. Albeit a powerful tool, epistemologically a meta-analysis possesses its own strengths and limitations with respect to knowledge development and this need to be explored as they are applied to new disciplines with different forms of experiments and datasets. We summarize a number of considerations in the interpretation of meta-analyses in ecology.

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General guidelines for the interpretation of meta-analyses in ecology

When interpreting ecological meta-analyses, quality of evidence used in the synthesis should be assessed carefully to ensure that the review has the capacity to detect the ecological process or hypothesis of interest.

Although meta-analysis has considerable potential as an analytical tool, it is also very easy to misinterpret the results in ecology (Lortie and Callaway 2006). The scope of the search, choice of relevant studies, and the methods used to combine studies are critical to the outcome of the analysis. A brief summary of criteria used in the interpretation of systematic reviews is provided here (Text box 1) primarily for the analyst but some of these considerations also apply to the savvy reader. The extent to which a meta-analysis can generate robust results depends not only on the quality of the synthesis but also on the scope and quality of the included studies. Meta-analysis of invalid studies (either methodologically flawed or irrelevant) may produce an array of misleading results, including overestimating or underestimating pooled effects and their variance; and also distorting within and between study variance with serious consequences for explorations of heterogeneity. Evaluation of the validity of the included studies is an essential component of a robust meta-analysis, and should influence the analysis, interpretation and conclusions of any synthesis.

It is useful to consider two elements of study validity when interpreting the results of ecological meta-analyses. The first element, internal validity, relates to whether a study answers its research question using methods that are free from bias (Gates 2002; Juni *et al.* 1999; Treadwell

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et al. 2007). A quality assessment of internal validity might consider the experimental design or sampling accuracy of a study (Text box 1). Tight experimental control tends to result in studies with high internal validity. The second element, external validity, relates to the generalizabilty of the research question. Studies with high external validity (i.e. have a broad scope in spatial scale or are not very taxon specific) have high generalizability, thus the use of appropriate spatial and temporal scales may be important elements of external validity (text box 1). Ecology often involves tradeoffs between internal and external validity with reductionist approaches having high internal validity and holistic approaches increasing external validity but decreasing internal validity. These tradeoffs are considered in the context of interpreting ecological meta-analyses below.

Philosophical considerations in the interpretation of evidence

Formal study inclusion criteria have been proposed and discussed extensively for meta-analysis due to its quantitative nature relative to reviews (Moher *et al.* 1995; Moher *et al.* 1996) and for ecology (Gates 2002). The primary purpose of inclusion criteria is to both determine whether the strength of evidence within the meta-analysis is generalizable to a broader set of studies and to ensure that the analyses are repeatable. Effective interpretation of a meta-analysis should at some level address the quality of the studies used in the analysis. This does not necessarily lead to the exclusion of 'low-quality' ecological studies. Using several sets of guidelines (Gates 2002; Pullin and Stewart 2006; Treadwell *et al.* 2007), we propose that ecological meta-analyses should consider specific criteria for effective interpretation of the evidence used in the meta-analysis (Text Box 2).

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Importantly, several general principles are particularly relevant for ecologists. Firstly, the sole criteria for the interpretation of a good ecological study should not be its p-value but rather an assessment (using the criteria listed in Text Box 2) of whether a given study has the capacity to detect the treatment effect or ecological process of interest. In meta-analyses, the capacity of the primary study to test for an effect is called the pre-study odds that a true effect can be detected (Wacholder *et al.* 2004), and this is an assessment or judgment made by the reviewer when deciding to include a study in a review. Interpretation of the strength of evidence can be tested empirically via recursive meta-analyses essentially adding in studies or increasing the cumulative sample size tested relative to the change in the treatment effect (Ioannidis and Lau 2001). In the event that many studies are used in the meta-analysis, each with a low capacity to detect a treatment effect (i.e. relatively small sample sizes), cumulatively adding single studies does little to increase the capacity of a meta-analysis to necessarily detect treatment effects (Ioannidis *et al.* 1998; Ioannidis and Lau 2001). A major strength of meta-analysis is nonetheless that many small studies can be combined to provide a comprehensive overview of a hypothesis when each independent experimental test may be equivocal or less than compelling.

The more diverse the designs used in a meta-analysis, the more likely the synthetic conclusions are to be false (Ioannidis 2005). Ecologists frequently use very different methods to test hypotheses since we measure populations, communities, ecosystem properties, and organisms. Arguably this is a strength since we can attack hypotheses from various angles, but we must carefully interpret the results and conclusions of meta-analyses, taking into consideration the diversity of the study set included and frequently consider testing groups of studies independently that used similar research protocols and standards provided sufficient numbers of

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similar studies are available. Finally, relevance of the studies used in the meta-analyses should be assessed to ensure that the review addressed the needs of the particular context. Perhaps the best way for the ecological meta-analyst to address this issue is to (i) ensure that the criteria for evidence evaluation are transparent, (ii) assess the benefits of including more diverse sets of evidence into the analysis (Detsky *et al.* 1992), and (iii) use sensitivity analysis to assess the importance of exclusion of sets of studies to examine the relevance or scope of the hypotheses.

Choice of model

Choice of statistical model is an important consideration in meta-analyses. In general, we suggest that interpretation of statistical models (whether fixed or random for instance) be decided *a priori* based on the purpose of the meta-analysis, i.e. is this treatment effective, are these groups different, has this hypothesis been successfully tested etc. When interpreting a model, the following criteria should be considered: degree of fit, amount of heterogeneity explained, and appropriateness of the statistic generated in satisfying the purpose of the meta-analysis. Furthermore, some ecologists have emphasized that different models and metrics may be appropriate depending on the type of variation associated with the set of studies (Osenberg *et al.* 1999), although some aspects of this recommendation are controversial (Hedges and Gurevitch 1999). As developed above, definition of the scope of review, evaluation of the respective evidence, and assessment of the sensitivity of the model to exclusion of sets of evidence provides a means to infer robustness of the model to alternative interpretations. In some instances, single summary estimates or models may not be adequate to encompass the range of natural variability associated with an ecological hypothesis and may warrant presentation of multiple estimates and models to satisfactorily explain the context dependence.

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Magnitude and sign of effect sizes

Interpreting the magnitude of effect sizes differs from the interpretation of significance levels of statistical tests within a given study. The purpose of any meta-analysis is to compare standardized data across studies, but the interpretation of relevance of the meta-analysis takes place in a larger context. A frame of reference is thus needed to assess outcome of a meta-analysis and several options are available to generate context. These include comparison to other meta-analyses, translation of effect sizes to other metrics, or direct contrasts to contexts or specific groups that readers can comprehend readily (Lipsey and Wilson 2001). For example, a very general delineation was made from 300 meta-analyses of small vs. large effect sizes in the social sciences (in terms of standardized mean difference) with ‘small’ being less than 0.2 (i.e., the means of the experimental and control groups differ by 0.2 standard deviations) and ‘large’ being 0.8 or greater (Lipsey and Wilson 2001) similar to the original levels proposed for individual studies (Cohen 1992). Provided an adequate body of published meta-analyses, the statistical distribution of meta-analytic effect sizes for ecology could be compiled and calculated to generate a relative numerical context for any given meta-analysis (Lipsey and Wilson 1993). This would facilitate comparisons among the results of different meta-analyses thereby providing the capacity for general benchmark use in ecological synthesis.

To date, a single general survey of meta-analyses in ecology and evolution has been done. It generated 44 published examples (that met particular criteria including reporting effect sizes etc.) with a mean number of data sets of 5.3 +/- 1.0 (Jennions and Moller 2002), and mean effect sizes ranging from Pearson r = 0.180 to 0.193 and Hedges’ d=0.631 to 0.721 (Moller and Jennions

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2002). As a starting point, this is an excellent example of an opportunity to both calibrate and estimate the efficacy of sets of ecological approaches. Other researchers reported in a summary note that most effect sizes in ecology and evolution are less than d=0.3 (Kotiaho and Tomkins 2002). In general however, interpretation of the magnitude of mean effect sizes in ecology, at least at this point in time, conforms to the coarse benchmarks for other disciplines with d=0.2 as small, 0.5 moderate, and 0.8 large, and as such we propose that ecological meta-analysts adopt a similar perspective on inferring relevance until further meta-analyses accumulate. Nonetheless, meta-analytical statistical relevance does not necessarily map directly onto biological significance, and smaller mean effect sizes may be highly relevant and ecologically important in complex, diffuse natural systems.

Contrasts of effect sizes from meta-analyses can also be interpreted relative to other groups to provide context. For instance, instead of direct comparison to 0 or interpretation of 'no effect' as the sole meta-analytic comparator to interpret a meta-analysis, the standardized effect of mensurative versus manipulative experiments or relative ecological context of a set of studies such as latitude, temperature, rainfall, etc. can be contrasted to one another to provide the reader with a more practical and potentially useful baseline context for interpretation of relevance of a particular meta-analysis. This can be done by comparing means and confidence interval overlap, or more formally, using tests of heterogeneity, among other approaches.

Interpreting the sign of the grand mean effect size of a meta-analysis or the means of a group of studies within a meta-analysis is also frequently useful for ecologists. If the magnitude of the effect size is large, positive and different from 0 this would be interpreted as a significant

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positive effect of treatment relative to control, or if negative, as a significant relative net reduction due to treatment (or as positive and negative associations between the two variables of interest). Of course, if there is significant heterogeneity in that effect, the interpretation of the grand mean may change. Comparison of sign changes between groups in ecology is useful as it allows one to infer whether outcomes of the treatment differ depending on the group studied. For this reason, meta-analyses can lead to the interpretation that an effect exists (within subgroups) even when grand mean effects are not different from 0. We urge practitioners to focus more exploring the variation between studies; causes of heterogeneity among studies are often very important in ecological meta-analysis.

In addition to “true” heterogeneity among studies or groups of studies, in some instances the studies may be of ‘low quality’ for various reasons, may be diverse in methodology, and vary in standards. Nevertheless it may still be valuable to do a systematic review or even preliminary meta-analysis with the intention of qualitatively describing the body of studies (Treadwell *et al.* 2007). In this situation, the primary purpose could be to determine net sign, sign differences between groups, or compare levels of variation. In ecology, many sets of studies may fall into this qualitative category, and the purpose can be to assess sign, bias, consistency, and generality of outcomes. The ecological research synthesist should thus clearly differentiate between ‘no significant mean effect’ and ‘no differences’ depending on the purpose of the meta-analysis (Higgins and Green 2006). Interpretations rejecting support for an ecological process or hypothesis may not be correct if the evidence loaded into the meta-analysis has low capacity to test the ideas. As such, we encourage ecologists to use magnitude, sign, sign changes, and

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comparison between groups as well as formal analysis of heterogeneity to interpret meta-analyses.

Two additional refinements are also recommended for ecological meta-analyses. First, consider the breadth of confidence intervals when evaluating the magnitude of mean effect size since variation is such an important aspect of ecology in general. For instance, d = 0.8 is a large effect but if its 95% confidence interval varies from 0.1 to 1.5, one or two extra studies can change its statistical significance from 'different from 0' to 'not significantly different'. If this can potentially occur, we recommend that further inspection of the studies enhance the robustness of the conclusions since ecological experiments can vary so dramatically. Considerations include the following: is the number of studies very low, is there an important source of variation which has been ignored in the analysis, is there partial reporting of important covariates in some studies and not others which could be added to the meta-analysis, and is there another response variable available to assess whether the patterns of variability associated with the confidence interval is a property of this particular biological system or the response variable selected? Second, one should always consider potential dependencies between moderators provided more than one is available, i.e., the importance of latitude in plant community studies or plant size in interaction studies. Tests comparing many small groups are not as powerful as tests comparing few large groups (Ioannidis *et al.* 1998), and as such, use sensitivity analyses to determine whether studies should be subdivided into smaller groups regardless of the Q_t reported in the meta-analysis. Hence, confidence intervals and heterogeneity between and within groups provide the ecological meta-analyst with an opportunity to not only more soundly make inferences about the grand

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mean, but to assess whether additional studies are needed and if the studies are best categorized into groupings or by moderators.

Summary of practical considerations for ecologists

Effective interpretation of a meta-analysis should include discussion, perhaps albeit briefly of all the elements described above in this chapter (and listed in text boxes). To summarize, we propose that there are several general aspects of interpretation that ecologists should be aware of in synthesizing studies to discover broad patterns and reach general conclusions. These include defining the scope and purpose of the meta-analysis which to date is not common in meta-analyses published in ecology, examining variability in evidence and sign, and careful use of groups to determine the importance of moderators, covariates and subgroups which could be particularly relevant in ecology since ecological context can be significant. Sensitivity analyses are often very useful.

A meta-analyst should *a priori* define the scope and purpose of the meta-analysis since even non-statistically significant results in synthetic endeavors may be potentially informative (Treadwell *et al.* 2007). Ecology often takes place in less controlled environments (relative to some other scientific fields) and incorporates many aspects of natural variation in the field, sometimes using very diverse methods to test a hypotheses. As such, systematic review methodology and even formal meta-analyses can also be used in this domain to infer progress by assessing consistency, bias, and variability associated with outcomes. Appropriate interpretations should describe the protocol and literature used in the analysis. The strength of evidence should be discussed including the criteria for selection and whether sensitivity was

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explored. Variability in magnitude of effect size is also useful in interpreting the results of a meta-analysis, and can be used to potentially determine why study outcomes differ or groups are different. Finally, ecology is now in a position to interpret hypotheses for practical purposes using meta-analyses to determine whether sets of ideas are robust and useful in explaining natural processes. Interpretations derived from meta-analyses within this domain have the opportunity to both assess whether a hypothesis generally explains a pattern or process and how well it does so.

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Text Box 1. Sample criteria for the interpretation of systematic reviews by readers.

Identification of the evidence and potential biases
Defined inclusion/exclusion criteria for identification of relevant (evidence) studies
Reasons for inclusion/exclusion documented for each study
Inclusion/exclusion controlled
Assessment of the each studies quality/validity
1. Experimental designs
2. Sampling accuracy
3. Appropriate timescales
4. Baseline survey
5. Scale
6. Pseudo-replication
Data extraction methodology documented and repeatable
Estimation of publication bias

Data-synthesis and analysis
Descriptive qualitative synthesis
Planned quantitative synthesis of evidence
Undertook quantitative synthesis
Performed meta-analysis
Investigation of sources of heterogeneity
1. Sub-group
2. Meta-regression
Sensitivity analysis (excel of certain data, etc.)
Investigation of power to accept/reject H0 or H1

Reporting
Reporting the key results of the review
Provides references of all studies within the review
Identification of evidence gap for the main question
Identified other evidence gaps related to subgroup/sensitivity analyses
Recommendations for future studies
Advised on future experimental designs and/or sample sizes for future experiments
Listed excluded studies in reference list or appendix/online material

Source: Pullin, A. S., and G. B. Stewart. 2006. Guidelines for Systematic Review in Conservation and Environmental Management. Conservation biology 10.1111/j.1523-1739.2006.00485.x.

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Text Box 2. Criteria for the interpretation of evidence in meta-analyses

General criteria for evidence

1. Derivation of evidence: Was a consistent and transparent method used to search for studies?
2. Source of evidence: Are studies in the meta-analysis from similar sources identified (English-language journals, grey literature, all published data) and is the outcome of the analysis sensitive to exclusion of sets of evidence?
3. Magnitude of evidence: Do the larger effect size studies or number of studies included in the meta-analysis influence the outcome of the meta-analysis?
4. Nature of evidence: Does the type of data combined influence the meta-analysis?

Specific criteria to consider when interpreting ecological meta-analytic evidence

1. Identify whether studies were mensurative or manipulative and interpret appropriately.
2. Identify ecological context, i.e. factors or covariates, both general and specific in the studies used in the meta-analysis.
3. Explore and interpret the heterogeneity within and between the studies.
4. Code whether the studies used in the meta-analysis directly test the hypothesis in question – this is a good point, but it is not discussed in the chapter.
5. Assess degree of reporting within studies used in meta-analysis.
6. Consider whether the interpretations within the studies are well founded and based on the evidence reported therein.

Sources: (1) *Gates, S. 2002. Review of methodology of quantitative reviews using meta-analysis in ecology. Journal of Animal Ecology 71:547-557. (2) Moher, D., A. R. Jadad, and P. Tugwell. 1996. Assessing the quality of randomized controlled trials: current issues and future directions. International Journal of Technology Assessment in Health Care 12:195-208. (3) Treadwell, J. R., S. J. Tregar, J. T. Reston, and C. M. Turkelson. 2007. A system for rating the stability and strength of medical evidence. BMC Medical Research Methodology 6:52.*

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