Repeatability and transparency in ecological research

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INTRODUCTION

A fundamental tenet of science is that results must be reproducible by other scientists before they are accepted as factual. However, because ecological phenomena are context-dependent, and because that context changes through time and space, it is virtually impossible to reproduce precisely or quantitatively any single experimental or observational field study in ecology. Yet many ecological studies can be repeated. In particular, ecological synthesis – the assembly of derived datasets and their subsequent analysis, re-analysis, and meta-analysis – should be easy to repeat and reproduce. Such syntheses also demonstrate qualitative and quantitative consistency among many ecological studies (Gurevitch et al. 1992, Warwick and Clarke 1993, Jonsen et al. 2003, Walker et al. 2006, Cardinale et al. 2006, Marczak et al. 2007, Vander Zanden and Fetzer 2007) and provide strong support for general ecological theories.

It should come as no surprise that meta-analysis by Mittelbach et al. (2001) of the effect of productivity on species richness has led to the development of a cottage industry focused on empirical testing of this relationship (post-2001 examples abound in Appendix A of Whittaker 2009). But it is much more surprising that continual re-analyses of the same datasets (Whittaker and Heegaard 2003, Gillman and Wright 2006, Pärtel et al. 2007) have yielded such disparate results that Whittaker (2009) has suggested abandoning the effort to obtain consistent results from the available data. He goes even further, suggesting that ecology may not yet be ready for

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meta-analysis and data synthesis. For two reasons, I respectfully suggest that Whittaker’s critique is misplaced. First, of all the studies critiqued by Whittaker (2009), only Mittelbach et al. (2001) actually conducted a formal meta-analysis. The others, as pointed out by Whittaker (2009: ms. p. 4, line 7) undertook extensive primary analyses but the authors did not conduct formal meta-analyses (Gurevitch and Hedges 1999). Second, and more importantly, if ecological synthesis is transparent – data, models, and analytical tools are available freely to the research community – then it should yield consistent, repeatable results. We may then disagree on the interpretation of the resulting synthesis, but at least we will be able to agree on the reproducibility of the results themselves.

REQUIREMENTS FOR REPEATABLE ECOLOGICAL SYNTHESIS

In a nutshell, ecological synthesis proceeds by assembling available datasets into a common, derived dataset and then applying one or more (statistical) models to this derived dataset to test the prediction of a hypothesis of interest (Ellison et al. 2006). Repeatability and reproducibility of ecological synthesis requires full disclosure not only of hypotheses and predictions, but also of the raw data, methods used to produce derived datasets, choices made as to which data or datasets were included in, and which were excluded from, the derived datasets, and tools and techniques used to analyze the derived datasets. Of all the papers under discussion by Whittaker (2009), Mittelbach et al.’s (2001) paper comes closest to achieving such transparency, although neither the raw data nor the derived dataset they analyzed are publicly available.

But achieving this level of disclosure and transparency is difficult. First and foremost, researchers must be committed to transparent production of ecological knowledge. We may be
blissfully unaware of our own intellectual biases, but there are no excuses for not making data, methods, and tools freely available in a timely fashion. Yet despite mandates from funding agencies and research networks that data be made available publicly (Arzberger et al. 2004), raw data are not easily accessed. Research teams can spend many weeks searching data archives only to find summary statistical tables, lists of means, or concise graphs. Contacting individual investigators may yield raw data in digital form or in yellowing notebooks, or it may yield nothing at all. Fortunately, archives of ecological data are growing (examples include ESA’s data registry,\(^2\) *Ecological Archives*,\(^3\) the data repository of the National Center for Ecological Analysis and Synthesis [NCEAS],\(^4\) the data archive of the Long Term Ecological Research Network\(^5\), and Oak Ridge’s Distributed Active Archive Center\(^6\) among many others), but archiving ecological data is not yet a requirement for publication in any journal. Ecologists also have developed standard methods for describing ecological datasets with *descriptive metadata* (Michener et al. 1997, Jones et al. 2006, Madin et al. 2008) that make it easier to interpret and hence re-use them. Software tools such as Morpho\(^7\) that help investigators create descriptive metadata also are maturing.

But it is not enough simply to find a dataset and understand its origin and structure. Once datasets are obtained, it is usually necessary to transform the data into common units and scales (e.g., species/ha or kg/ha). Interpolated values may need to be substituted for missing data, and methods of interpolation will vary among investigators (Ellison et al. 2006). Finally, and usually after still further manipulations and making decisions as to which data to include or exclude (cf.

\(^2\) <http://data.esa.org/esa/style/skins/esa/index.jsp>
\(^3\) <http://www.esapubs.org/archive/>
\(^4\) <http://knb.ecoinformatics.org/knb/style/skins/nceas/>
\(^5\) <http://metacat.lternet.edu/knb/>
\(^6\) <http://daac.ornl.gov/>
\(^7\) <http://knb.ecoinformatics.org/morphoportal.jsp>
Whittaker and Heegard 2003 and Appendix A of Whittaker 2009), a derived dataset is ready for analysis.

Each step – e.g., digitization, rescaling, interpolation, inclusion or exclusion – requires individual judgment and provides an opportunity to introduce bias or error. If subsequent synthesis is to be repeatable, users must have confidence in the reliability of the derived dataset. Thus it is imperative that researchers document clearly each of the steps used to produce derived datasets. This *process metadata* – the documentation of the processes used to produce a dataset – provides one way to assess the reliability of a derived dataset (Osterweil *et al.* 2005, Ellison *et al.* 2006). Storage of the original datasets and the processes applied to create the derived dataset provides the mechanism to reproduce it.

Such audit trails that include archived datasets and tools allow can allow future users to determine effects of changing particular processes on the structure and subsequent analysis of the derived dataset (Ellison *et al.* 2006). For example, Mittelbach *et al.* (2001) classified the relationship between species richness and productivity in one of five categories (unimodal humped or U-shaped, monotonic positive or negative, or no relationship) whereas Laanisto *et al.* (2008) classified this same relationship simply as unimodal or not. Whittaker and Heegard (2003) and Whittaker (2009) excluded data that Mittelbach *et al.* (2001) included. Gillman and Wright (2006) used some of the regression results reported by Mittelbach *et al.* (2001) but also reanalyzed some of the original datasets using different software and without specifying which data were reanalyzed. Clearly results will differ if the same data are classified differently; if different subsets of data are analyzed, or if individual datasets are treated differently. Importantly, we can assess these differences by running new analyses on available datasets. The resulting differences in approach to and analysis of the data may reflect differences in questions on the
part of the investigators, honest disagreements regarding the “best” available evidence (*sensu* Slavin 1995), or strongly held opinions regarding the most appropriate statistical analysis (*e.g.*, ordinary least-squares regression *versus* general linear models with a variety of error distributions and link functions). However, these differences and disagreements do not in and of themselves invalidate the activity of ecological synthesis.

It is equally important to document and whenever possible archive the statistical tools and models used for analysis and synthesis (Thornton *et al.* 2005); such an archival record should be a requirement for publication of any meta-analysis or data synthesis. The various authors critiqued by Whittaker (2009) all used different statistical tools (Table 1), and it would be impossible to repeat precisely any of the author’s analyses.

Documentation and archiving of analytical processes, including those processes used to create derived datasets and the statistical tools and models applied to them, is difficult, and software tools for such documentation and archiving are rudimentary. It may seem wasteful to archive software, but numerical precision of arithmetic operations changes with new integrated circuit chips and different operating systems, functions work differently in different versions of software, and implementation of even “standard” statistical routines differ among software packages (a widely unappreciated example of relevance to ecologists is the different sums-of-squares reported by SAS, S-Plus, and R for analysis of variance and other linear models (Venables 1998)). Finally, there are no standards for process metadata (Osterweil *et al.* 2005, Ellison *et al.* 2006) and no easy way to archive model code used by, or specific versions of, commercial software packages. While open-source software tools such as R (R Development Core Team 2007) is an attractive (and affordable) alternative, they evolve even more rapidly than their commercial counterparts, and regular changes in functionality of familiar routines are not
uncommon (implementation of the cor function for calculation of Pearson’s correlation coefficient in early versions of R is a notorious example). But without archiving software, tools, and associated process metadata, it is unlikely that we will be able to accurately reproduce any ecological synthesis.

MOVING FORWARD

More and more ecologists are following federal guidelines (Office of Management and Budget Circular A-110)\(^8\) and making their data freely available within a short time of collection and publication. Cultural impediments to data sharing among ecologists are disappearing as more and more ecologists recognize not only that sharing of data benefits the entire scientific enterprise (Baldwin and Duke 2005) but also results in successful collaborations and subsequent publications such as those facilitated by NCEAS.\(^9\) Rapid development of data archiving and sharing tools has been facilitated by funding initiatives focused on development of software for production of descriptive metadata and distributed access to permanently and stably archived data.\(^10\) There is increasing recognition that similar efforts must be undertaken to document analytical tools and processes and to archive the software tools themselves (Thornton et al. 2005, Ellison et al. 2006). Software tools in development for creating process metadata, including documentation of dataset provenance and storage of analytical tools applied to derived datasets, include Kepler (Ludäscher et al. 2006) and the Analytic Web (Osterweil et al. 2009). Ecologists should work with these software development teams, and others like them, to learn how better

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8 <http://www.whitehouse.gov/omb/circulars/a110/a110.html>; for analysis and agency-specific implementation of this regulation, see <http://thecre.com/access/index.html>
9 <http://nceas.ucsb.edu/products>
documentation and archiving of scientific processes and work-flows can advance our science and 
to provide challenging tests of these evolving systems (Boose et al. 2007).

Rather than abandon data synthesis and meta-analysis as Whittaker (2009) suggests, 
ecologists should embrace these activities as the very essence of our science. With appropriate 
attention to documentation of data and analytical processes and a commitment to unbiased 
inquiry and full transparency of analytic activities, data synthesis and meta-analysis will become 
the most repeatable and reproducible activities that ecologists undertake. The results of such 
syntheses and meta-analyses will be the grist for the mill of ecological forecasting, perhaps the 
most important endeavor of 21st century ecology (Clark et al. 2001).

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Whittaker, R. J., and E. Heegaard. 2003. What is the observed relationships between species
Table 1. Analytical methods used in the syntheses of the species richness-productivity relationship.

<table>
<thead>
<tr>
<th>Author</th>
<th>Analytical method(s) used</th>
<th>Analytical tool(s) used</th>
<th>Comments</th>
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<td>Waide et al. (1999)</td>
<td>Linear and quadratic regressions</td>
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<td>Mittelbach et al. (2001)</td>
<td>Ordinary least-squares regression</td>
<td>SYSTAT 8.0</td>
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<td></td>
<td>Poisson regression</td>
<td>NAG Statistical Add-in for Excel</td>
<td>Not repeatable; software discontinued</td>
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<td>“Mitchell-Olds &amp; Shaw test” (Mitchell-Olds and Shaw 1987)</td>
<td>None specified</td>
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<td>Not repeatable; software unavailable (but algorithm available). Which of three tests proposed by Mitchell-Olds and Shaw was also not specified.</td>
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<tr>
<td></td>
<td>Chi-square Exact test</td>
<td>StatXact</td>
<td>Possibly repeatable; no version given.</td>
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<tr>
<td></td>
<td>Meta-analysis using mixed-effects model</td>
<td>MetaWin 2.0</td>
<td>Repeatable; commercial software version still available</td>
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<td>Study</td>
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<td>Poisson regression</td>
<td>Not specified</td>
<td>Not repeatable</td>
</tr>
<tr>
<td>Gillman and Wright (2006)</td>
<td>Ordinary least-squares regression on “some” datasets of Mittelbach et al. (2001)</td>
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