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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 data sets and their subsequent analysis, reanalysis, 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 2010). But it is much more surprising that continual reanalyses of the *same* data sets (Whittaker and Heegaard 2003, Gillman and Wright 2006, Pärtel et al. 2007) have yielded such disparate results that Whittaker (2010) 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 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 (2010), only Mittelbach et al. (2001) actually conducted a formal meta-analysis. The others, as pointed out by Whittaker (2010), 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 data sets into a common, derived data set and then applying one or more (statistical) models to this derived data set 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 data sets, choices made as to which data or data sets were included in, and which were excluded from, the derived data sets, and tools and techniques used to analyze the derived data sets. Of all the papers under discussion by Whittaker (2010), Mittelbach et al.'s (2001) paper comes closest to achieving such transparency, although neither the raw data nor the derived data set 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-

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[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/⟩

Forum

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 data sets 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 that help investigators create descriptive metadata also are maturing (software *available online*).[7]

But it is not enough simply to find a data set and understand its origin and structure. Once data sets 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. Whittaker and Heegard 2003, Whittaker 2010: Appendix A), a derived data set 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 data set. Thus it is imperative that researchers document clearly each of the steps used to produce derived data sets. This *process metadata*—the documentation of the processes used to produce a data set—provides one way to assess the reliability of a derived data set (Osterweil et al. 2005, Ellison et al. 2006). Storage of the original data sets *and* the processes applied to create the derived data set provides the mechanism to reproduce it.

Such audit trails that include archived data sets and tools allow can allow future users to determine effects of changing particular processes on the structure and subsequent analysis of the derived data set (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 (2010) 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 data sets 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 data sets are treated differently. Importantly, we can assess these differences by running new analyses on available data sets. 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 vs. 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 (2010) 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 data sets 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) are attractive (and affordable) alternatives, 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 1999) and making their data freely available within a short time of collection and publication (for analysis and agency-specific implementation of this regulation, see assessment at The Center for Regulatory Effectiveness

[5] ⟨http://metacat.lternet.edu/knb/⟩

[6] ⟨http://daac.ornl.gov/⟩

[7] ⟨http://knb.ecoinformatics.org/morphoportal.jsp⟩

TABLE 1. Analytical methods used in the syntheses of the species richness–productivity relationship.

Author	Analytical method(s) used	Analytical tool(s) used	Comments
Waide et al. (1999)	linear and quadratic regressions	none specified	not repeatable
Mittelbach et al. (2001)	ordinary least-squares regression	SYSTAT 8.0	possibly repeatable; current available version is 12.0
	Poisson regression	NAG statistical add-in for Excel	not repeatable; software discontinued
	"Mitchell-Olds and Shaw test" (Mitchell-Olds and Shaw 1987)	none specified	not repeatable; software unavailable (but algorithm available); which of three tests proposed by Mitchell-Olds and Shaw was also not specified
	chi-square exact test	StatXact	possibly repeatable; no version given
	meta-analysis using mixed-effects model	MetaWin 2.0	repeatable; commercial software version still available
Whittaker and Heergard (2003)	Poisson regression	not specified	not repeatable
Gillman and Wright (2006)	ordinary least-squares regression on "some" data sets of Mittelbach et al. (2001)	software not specified; data sets reanalyzed not specified	not repeatable
Pärtel et al. (2007)	multinomial logit regression	Statistica 6.1	possibly repeatable; current release is 8.0
Laanisto et al. (2008)	Fisher exact tests	not specified	possibly repeatable using available algorithms
	general linear model	Statistica 6.1	possibly repeatable; current release is 8.0

Note: Manufacturers of software are: SYSTAT 8.0, Systat Software, Inc., Chicago, Illinois, USA; NAG statistical add-in for Excel, Numerical Algorithms Group, Oxford, UK; StatXact, Cytel, Inc., Cambridge, Massachusetts, USA; MetaWin 2.0, Sunderland Associates, Inc., Sunderland, Massachusetts, USA; Statistica 6.1, StatSoft, Inc., Tulsa, Oklahoma, USA.

Web site, *available online*).[8] 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 (*available online*).[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 (see National Science Foundation, Office of Cyberinfrastructure, *online*).[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 data set provenance and storage of analytical tools applied to derived data sets, include Kepler (Ludäscher et al. 2006) and the Analytic Web (Osterweil et al. 2010). Ecologists should work with these software development teams, and others like them, to learn how better 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).

[8] ⟨http://thecre.com/access/index.html⟩

[9] ⟨http://nceas.ucsb.edu/products⟩

[10] ⟨http://www.nsf.gov/dir/index.jsp?org=OCI⟩

Rather than abandon data synthesis and meta-analysis as Whittaker (2010) 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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