



Repeatability and Transparency in Ecological Research

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23 meta-analysis and data synthesis. For two reasons, I respectfully suggest that Whittaker's critique
24 is misplaced. First, of all the studies critiqued by Whittaker (2009), only Mittelbach *et al.* (2001)
25 actually conducted a formal meta-analysis. The others, as pointed out by Whittaker (2009: ms. p.
26 4, line 7) undertook extensive primary analyses but the authors did not conduct formal meta-
27 analyses (Gurevitch and Hedges 1999). Second, and more importantly, if ecological synthesis is
28 transparent – data, models, and analytical tools are available freely to the research community –
29 then it should yield consistent, repeatable results. We may then disagree on the *interpretation* of
30 the resulting synthesis, but at least we will be able to agree on the reproducibility of the results
31 themselves.

32

33 REQUIREMENTS FOR REPEATABLE ECOLOGICAL SYNTHESIS

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

44 But achieving this level of disclosure and transparency is difficult. First and foremost,
45 researchers must be committed to transparent production of ecological knowledge. We may be

46 blissfully unaware of our own intellectual biases, but there are no excuses for not making data,
47 methods, and tools freely available in a timely fashion. Yet despite mandates from funding
48 agencies and research networks that data be made available publicly (Arzberger *et al.* 2004), raw
49 data are not easily accessed. Research teams can spend many weeks searching data archives only
50 to find summary statistical tables, lists of means, or concise graphs. Contacting individual
51 investigators may yield raw data in digital form or in yellowing notebooks, or it may yield
52 nothing at all. Fortunately, archives of ecological data are growing (examples include ESA's data
53 registry,² *Ecological Archives*,³ the data repository of the National Center for Ecological
54 Analysis and Synthesis [NCEAS],⁴ the data archive of the Long Term Ecological Research
55 Network⁵, and Oak Ridge's Distributed Active Archive Center⁶ among many others), but
56 archiving ecological data is not yet a requirement for publication in any journal. Ecologists also
57 have developed standard methods for describing ecological datasets with *descriptive metadata*
58 (Michener *et al.* 1997, Jones *et al.* 2006, Madin *et al.* 2008) that make it easier to interpret and
59 hence re-use them. Software tools such as Morpho⁷ that help investigators create descriptive
60 metadata also are maturing.

61 But it is not enough simply to find a dataset and understand its origin and structure. Once
62 datasets are obtained, it is usually necessary to transform the data into common units and scales
63 (*e.g.*, species/ha or kg/ha). Interpolated values may need to be substituted for missing data, and
64 methods of interpolation will vary among investigators (Ellison *et al.* 2006). Finally, and usually
65 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>>

66 Whittaker and Heegard 2003 and Appendix A of Whittaker 2009), a derived dataset is ready for
67 analysis.

68 Each step – *e.g.*, digitization, rescaling, interpolation, inclusion or exclusion – requires
69 individual judgment and provides an opportunity to introduce bias or error. If subsequent
70 synthesis is to be repeatable, users must have confidence in the reliability of the derived dataset.
71 Thus it is imperative that researchers document clearly each of the steps used to produce derived
72 datasets. This *process metadata* – the documentation of the processes used to produce a dataset –
73 provides one way to assess the reliability of a derived dataset (Osterweil *et al.* 2005, Ellison *et al.*
74 2006). Storage of the original datasets *and* the processes applied to create the derived dataset
75 provides the mechanism to reproduce it.

76 Such audit trails that include archived datasets and tools allow can allow future users to
77 determine effects of changing particular processes on the structure and subsequent analysis of the
78 derived dataset (Ellison *et al.* 2006). For example, Mittelbach *et al.* (2001) classified the
79 relationship between species richness and productivity in one of five categories (unimodal
80 humped or U-shaped, monotonic positive or negative, or no relationship) whereas Laanisto *et al.*
81 (2008) classified this same relationship simply as unimodal or not. Whittaker and Heegard
82 (2003) and Whittaker (2009) excluded data that Mittelbach *et al.* (2001) included. Gillman and
83 Wright (2006) used some of the regression results reported by Mittelbach *et al.* (2001) but also
84 reanalyzed some of the original datasets using different software and without specifying which
85 data were reanalyzed. Clearly results will differ if the same data are classified differently; if
86 different subsets of data are analyzed, or if individual datasets are treated differently. Importantly,
87 we can assess these differences by running new analyses on available datasets. The resulting
88 differences in approach to and analysis of the data may reflect differences in questions on the

89 part of the investigators, honest disagreements regarding the “best” available evidence (*sensu*
90 Slavin 1995), or strongly held opinions regarding the most appropriate statistical analysis (*e.g.*,
91 ordinary least-squares regression *versus* general linear models with a variety of error
92 distributions and link functions). However, these differences and disagreements do not in and of
93 themselves invalidate the activity of ecological synthesis.

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

99 Documentation and archiving of analytical processes, including those processes used to
100 create derived datasets and the statistical tools and models applied to them, is difficult, and
101 software tools for such documentation and archiving are rudimentary. It may seem wasteful to
102 archive software, but numerical precision of arithmetic operations changes with new integrated
103 circuit chips and different operating systems, functions work differently in different versions of
104 software, and implementation of even “standard” statistical routines differ among software
105 packages (a widely unappreciated example of relevance to ecologists is the different sums-of-
106 squares reported by SAS, S-Plus, and R for analysis of variance and other linear models
107 (Venables 1998)). Finally, there are no standards for process metadata (Osterweil *et al.* 2005,
108 Ellison *et al.* 2006) and no easy way to archive model code used by, or specific versions of,
109 commercial software packages. While open-source software tools such as R (R Development
110 Core Team 2007) is an attractive (and affordable) alternative, they evolve even more rapidly than
111 their commercial counterparts, and regular changes in functionality of familiar routines are not

112 uncommon (implementation of the cor function for calculation of Pearson's correlation
113 coefficient in early versions of R is a notorious example). But without archiving software, tools,
114 and associated process metadata, it is unlikely that we will be able to accurately reproduce any
115 ecological synthesis.

116

117 MOVING FORWARD

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

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>>

¹⁰ <<http://www.nsf.gov/dir/index.jsp?org=OCI>>

132 documentation and archiving of scientific processes and work-flows can advance our science and
133 to provide challenging tests of these evolving systems (Boose *et al.* 2007).

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

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234 richness and productivity? Comment. *Ecology* **84**:3384-3390.

235

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 <i>et al.</i> (1999) | Linear and quadratic regressions | None specified | Not repeatable |
| Mittelbach <i>et al.</i> (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 & 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” datasets of Mittelbach <i>et al.</i> (2001) | Software not specified; datasets re-analyzed not specified | Not repeatable |
| Pärtel <i>et al.</i> (2007) | Multinomial logit regression | Statistica 6.1 | Possibly repeatable; current release is 8.0 |
| Laanisto <i>et al.</i> (2008) | Fisher exact tests | Not specified | Possibly repeatable using available algorithms |
| | General linear model | Statistica 6.1 | Possibly repeatable; current release is 8.0 |
