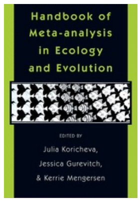

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Gurevitch, and K. Mengersen, editors. Handbook of meta-analysis in ecology and evolution (pp. 339−347).
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21

Graphical Presentation of Results

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Data are the currency of science. Visualizations of data are thus one of the most compelling means to effectively communicate ideas in science (Cleveland 1985, Ellison 2001, Tufte 2001). Graphs present data in a visual form enabling the reader to read values, identify patterns, assess the outcome of a statistical technique, or analyze relationships within or between variables (Tukey 1972, Higgins and Green 2011). Not every graph has to serve all these functions; however, most sets of best practices for visualization in science also apply to meta-analyses. Unfortunately, there is a tendency to underreport data in ecology, erring on the side of presenting only average effects. Solutions to this problem include presenting average effects for groups of studies where relevant, including data in text form on graphs, and including raw data or additional analyses in online appendices.

While providing raw data has numerous advantages, including the opportunity for additional analysis by others, it is the responsibility of the authors of a paper to analyze and interpret their own data. Graphics should enable readers to visualize the trends and effects of modifying factors (e.g., how plant growth conditions might alter responses to elevated CO_2) as well as the central tendency with variances (i.e., overall means across studies and their confidence limits). Meta-analysis is particularly suited to effective visualization since its primary objective is to present standardized data synthesized across studies including the important modifying factors (Lipsey and Wilson 2001, Cooper et al. 2009).

Most of the best practices for presenting quantitative information pertain to meta-analysis. A general issue for effective data displays is that there is a dynamic tension between simplicity and communicating adequate information accurately (Tufte 1990). Clarity, structure, and choice of representation method should also highlight the patterns of differences detected statistically (Higgins and Green 2011), and a good rule of thumb is that a figure should include enough information to convey relationships without the need to describe the figure in the text (see Box 21.1 for best practices). General principles of graphical presentation, such as the degree of resolution of the data presented in a graph (coarse vs. very detailed) should be carefully considered in meta-analysis, as in primary data papers (Tufte 2001).

Effective visualizations of meta-analyses have been discussed extensively in the evidence-based medical literature (Light et al. 1994; Lau et al. 1998, 2006; Wang and Bushman 1999; Sterne et al. 2001; Barrowman and Myers 2003; Higgins and Green 2011) and to a lesser extent in ecology and evolutionary biology (Gurevitch and Hedges 1999, Rosenberg et al. 2000, Møller and Jennions 2001, Gates 2002, Lortie and Callaway 2006). The two most common meta-analysis plots are derived from the social sciences and include (1) modified error bar plots called forest plots (Lewis and Clarke 2001) used to summarize and compare weighted

BOX 21.1.
Best practices for effective meta-data visualization.

(1) Ensure that plots can stand alone within a publication.
(2) Include text in meta-analytic figures listing study weight, number of studies, variance, groups of data, or meaning of treatment effects.
(3) Use reference lines of "no effect" within plots.
(4) Visualize the studies used in the meta-analysis in some capacity and include information on the groups of studies. Histograms clearly communicate frequency or number of studies in different categories or number of studies reporting different magnitudes of effect size.
(5) Explore heterogeneity using visualizations and statistics. Graphics include funnel, trim and fill, and meta-regression plots.
(6) If covariates (explanatory moderating factors) are available and meaningful, publish graphics to communicate important factors that account for heterogeneity between studies. This provides the reader with a direct tool to assess generality and predictability of the hypothesis in question.
(7) Forest plots are common and very accessible to readers as they are simple and clearly convey central tendency and relative variation. At a minimum, use forest plots to summarize comparison of different groups of studies within a meta-analysis.
(8) Since meta-analyses are a synthetic endeavor promoting cross comparison of data between studies, always include tables in the electronic appendices with effect sizes for all individual studies.

Sources: Higgins and Green 2011, Tufte 2001

mean effects, and (2) meta-regression plots (scatterplots with significant fit lines) used to show the relationship between main effects and covariates (Lau et al. 1998, Thompson and Higgins 2002). In this chapter, we describe these two standard meta-analysis plots and provide sample graphics to illustrate usage. Details are also included for the use of simple histograms and funnel plots. A list of all meta-analysis plots is provided for the reader (Table 21.1); however, only those that are most commonly found in ecology and evolutionary biology are explained in detail in this chapter.

We note that standard meta-analysis software (Chapter 12) generally provides the capacity to plot the graphics discussed in this chapter. However, we also recommend that ecologists and evolutionary biologists consider using dedicated plotting applications for publication-quality graphs. Meta-analysis plots should emphasize relationships among studies, facilitate assessment of the relative contribution of each study (how it was weighted in the meta-analysis), and show the magnitude of the mean effect across studies and its confidence limits. To this end, meta-analysis plots often include the effect sizes and confidence limits of each study, summarize average effects for different categories or groups of studies, show central tendency for the overall model, and in some instances examine the influence of continuous modifier variables by using scattergraphs of effect sizes plotted against modifying variables (Higgins and Green 2011). Several of the data sets common throughout the book are used to illustrate the various graphics described herein.

TABLE 21.1. A list of common, useful meta-analysis plots in ecology. "Source" refers to whether the plot is used in its standard statistical form, derived from another plot type, or specifically developed for meta-analyses. "Figure number" refers to the notation in this chapter.

Plot	Source	Purpose	Figure
Histogram	Standard	To visualize frequency or distribution.	21.1
Funnel & Trim and fill	Modified scatterplots	To explore heterogeneity and bias.	21.2
Forest	Error bar plots	To summarize central tendency of effect size measures.	21.3
Meta-regression	Weighted regression	To explore heterogeneity and assess importance of ecological context.	21.4
Stem and leaf	Standard	To visualize central tendency and distribution of data.	
Normal quantile	Standard	To visualize central tendency and distribution of data.	
Box plot	Standard	To compare central tendency and distribution of data.	
Galbraith	Meta-analysis	To explore heterogeneity and outliers.	
L'Abbé	Meta-analysis	To compare event rates in treatment and control groups.	
Raindrop plot	Meta-analysis	To visualize central tendency, likelihood, and distribution of data.	
Response surface	Standard	To visualize effects of multiple factors.	
Bland-Altman plot	Standard	To compare two methods measuring the same parameter.	

A DESCRIPTION OF META-ANALYTIC VISUALIZATIONS

First, the studies should be graphed to show the factors and the groups relevant to the meta-analysis. Next, heterogeneity and publication bias should be explored. Plots that reveal patterns of heterogeneity are often useful to the reviewer even if they are not included in the final publication. Effect sizes for individual studies, groups of studies, or mean effects for from each study are graphed, with covariates as needed to elucidate the relative importance of modifying factors (i.e., temperature, latitude, etc. of each study) on study outcomes. Meta-analysis graphs can help identify groupings of studies and alternative modifying factors (Lau et al. 1998), in addition to presenting overall effects.

COMMON GRAPHS USEFUL IN ECOLOGICAL META-ANALYSIS

Histogram

Purpose: Show distribution of effect sizes from individual studies included in the meta-analysis.

Histograms effectively communicate central tendency, variation, and distribution (i.e., normality). Typically, the frequency of studies or effect sizes used in the meta-analysis is shown using histograms in their standard form (Fig. 21.1).

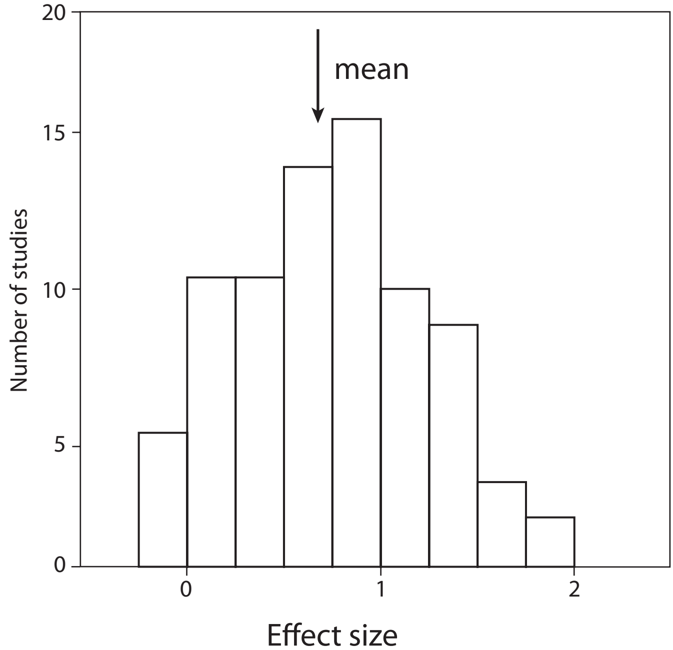

Figure 21.1. A comparison of the frequency of studies by effect sizes. This is an example of a conventional histogram to illustrate the distribution of effect sizes used in a sample data set of a meta-analysis (Torres-Vila and Jennions 2005). The arrow denotes the mean effect size.

Application

(1) Use histograms to visualize the distribution of studies within a meta-analysis.

(2) If possible, include groups, covariates, or important factors that might be important sources of heterogeneity or useful explanatory variables.

(3) Bar charts can be used to plot effect sizes but we recommend forest plots for this purpose.

Funnel Plots and Trim and Fill Plots

Purpose: Show the relationship between effect sizes and some measures of variances from individual studies.

Funnel plots are derived from scatterplots and have been used extensively in meta-analysis to examine publication bias (Egger, Davey Smith, and Phillips 1997; Light et al. 1994). In a funnel plot, some measure of study size or weight, such as sample size, standard error, or inverse variance is plotted on one axis while effect size is plotted on the other axis (Fig. 21.2). Visual estimates of asymmetry are used to assess publication bias wherein a gap (an absence of studies) shows overrepresentation of negative effect sizes for studies with small sample sizes (Fig. 21.2) (Light and Pillemer 1984). Trim and fill plots are formal statistic models using the asymmetry of a funnel to estimate bias (Chapter 14). The most extreme effect sizes are trimmed out and the gaps are replaced using iterative nonparametric estimates (Copas and Shi 2000, Sutton et al. 2000, Song et al. 2002). This process generates an estimate of relative publication bias and the plots are simply "trimmed" funnel plots; this means that they are identical to

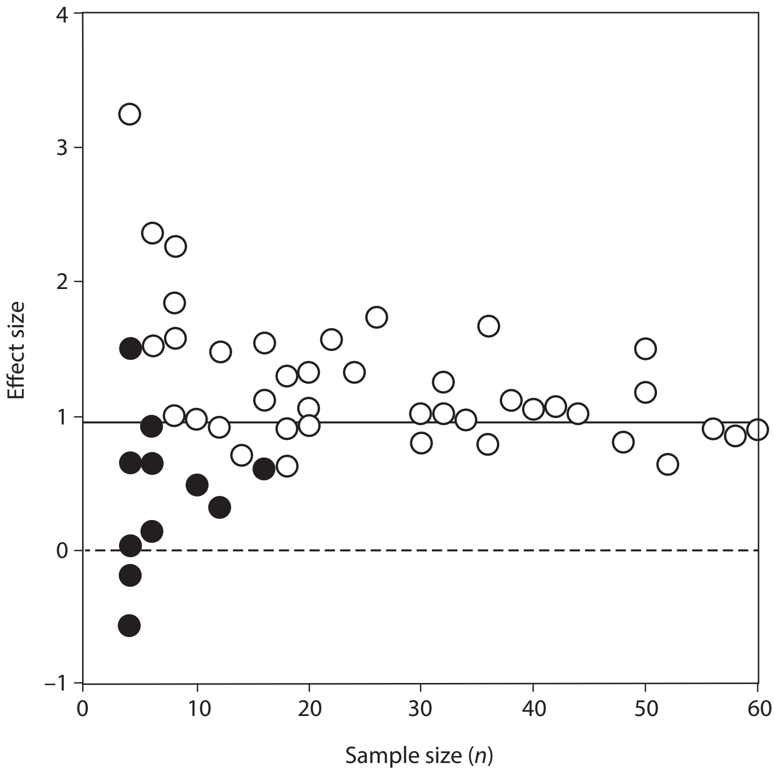

Figure 21.2. Typical funnel plot used to explore patterns of heterogeneity among studies within a meta-analysis. Each point represents the mean effect size for a single study. Note the overall funnel (or inverted funnel) shape to the plot. Open symbols indicate actual values, and filled symbols denote potential missing values that could suggest publication bias. The effect measures can be plotted on either axis.

funnel plots but with potential gaps filled and outliers removed. Graphics can also sometimes include simple scatterplots of the number of primary studies used in the meta-analysis plotted against the relative publication bias. The latter is calculated from the trimming or the probability that the true effect sizes are captured (Peters et al. 2007). However, both the visual and statistical assessments of funnel plots suffer from significant limitations including uneven treatment effects in small studies, subjectivity, and other small-study effects not related to bias, and thus may be very limited in their capacity to detect publication bias (Sterne et al. 2001, Lau et al. 2006). As such, we recommend that this approach be used cautiously. Further methods to explore publication bias are discussed in Chapter 14.

Application

(1) Use funnel plots only as a very preliminary means to explore the weighting of studies within a meta-analysis or gaps in the available literature.

(2) Use alternative and multiple methods to more thoroughly explore publication bias or heterogeneity between studies, such as sensitivity analyses or meta-regression models.

Forest plots

Purpose: Show effect sizes and confidence intervals from individual studies as well as group or overall mean effects and confidence intervals.

Forest plots are the meta-analytic equivalent of error bar or confidence interval plots, and are useful for showing mean effect size and variation among studies or groups of studies (Light et al. 1994; Egger, Davey Smith, and Phillips 1997; Lewis and Clarke 2001). Perhaps curiously to ecologists, meta-analysis forest plots are often drawn with the dependent (Y) axis horizontal, while the vertical axis is nonquantitative (individual studies). Typically, the symbol denotes effect sizes, and the horizontal lines show the confidence intervals (Fig. 21.3). The grand or pooled mean is often presented above or below individual points (Higgins and Green 2011). A dotted vertical reference line at zero is usually provided as a visual guide.

Text can be incorporated into forest plots to show number of studies, experimental levels or groups, author names, or other identificators for each study, percent weighting of study, or the effect size measure in numbers with confidence intervals adjacent to each point. Showing

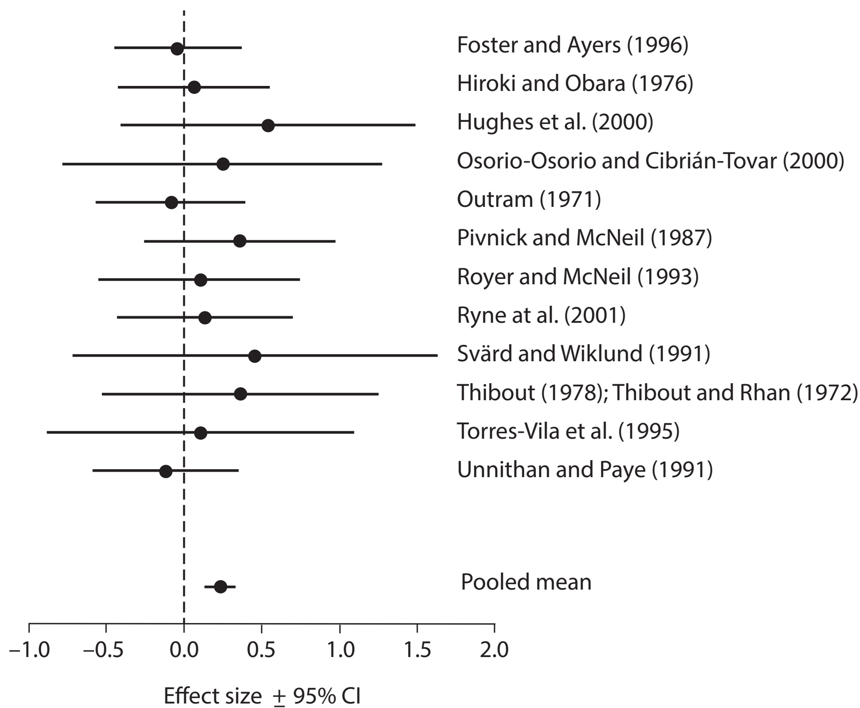

Figure 21.3. Forest plot showing effect sizes and 95% confidence intervals for individual studies included in a meta-analysis on mating history in Lepidoptera (Torres-Vila and Jennions 2005). As described in the text, at times it is desirable to present one set of studies from a larger meta-analysis; in this instance, data are from the monandrous studies only—otherwise there would have been too much to plot in a single, clear forest plot. The effect sizes are denoted by the circles, confidence intervals by the horizontal lines, and a dashed vertical line denotes no effect, or a mean of 0. The pooled mean is usually plotted slightly apart from individual studies and labeled as such.

information from each individual study (authors, year, effect size, sample size, etc.) is feasible only if the number of studies is relatively small; otherwise, a simplified version of forest plot with group means and overall means only is shown. The complete forest plot of individual studies can be provided in an electronic appendix (as is common in medical studies). On the horizontal axis, the effect size meaning can be stated with "favors treatment" or "favors control," or in ecology as a test result, such as "herbivore effect," "exclusion effect," and so forth. The results of cumulative meta-analysis (Chapter 15) can also be plotted in the form of a forest plot with year of publication listed vertically, and adjacent to each point. A variation of forest plots that commonly occurs in ecological meta-analyses could be best termed as "range" plots (Curtis and Wang 1998). Range plots resemble forest plots in almost every respect, but show the effect sizes from individual studies sorted by their sign and magnitude.

Application

(1) Forest plots are an excellent tool to communicate individual and mean effect sizes, weighting of studies, and variation or likelihood.

(2) Use grouping and distance on the vertical scale to facilitate comparison between groups or studies.

(3) Include a reference line of "no effect" and show the grand mean.

(4) Enhance forest plots with text on vertical axis further describing the data or groups, and label the effect size axis with its metric and meaning.

Meta-regression

Purpose: Show relationship between studies, overall results, and relations to covariates.

Meta-analyses may be carried out with continuous moderating factors as well as with categorical moderators. In both cases, weighted analysis is carried out that accounts for the precision of each data point (i.e., study sample size or variance). Meta-analysis data using weighted regressions on continuous moderators can be plotted to explore the effects of the moderators and to communicate results in published papers (i.e., relationships between an ecological covariate and the effect sizes or effect signs detected in a meta-analysis) (Fig. 21.4).

Typically, a scatterplot with a fitted line is used to visualize the meta-regression with the factor or covariate on the horizontal axis and effect size on the vertical axis. Confidence intervals for each point (or the fitted line), and study weightings denoted by relative symbol size can be shown. Considerations on what to plot include choice of covariates (Lau et al. 1998) or availability of data necessary to describe and model the heterogeneity between studies (i.e., productivity, nutrient levels, etc., may not be reported for all studies in the meta-analysis). Reference lines of "no effect" can be used as a visual guide. Between-study heterogeneity can also be derived from meta-regressions by comparing realized and predicted values, and calculating a metric of heterogeneity such as I^2 (Higgins and Thompson 2002, Higgins et al. 2003). In summary, it is usually clear whether there is overlap or divergence between studies or groups of studies when values are spread out on meta-regression plots of key factors.

Application

(1) Weighted regression analyses of ecological factors and effect sizes can be useful to explore heterogeneity and to visually describe ecological context.

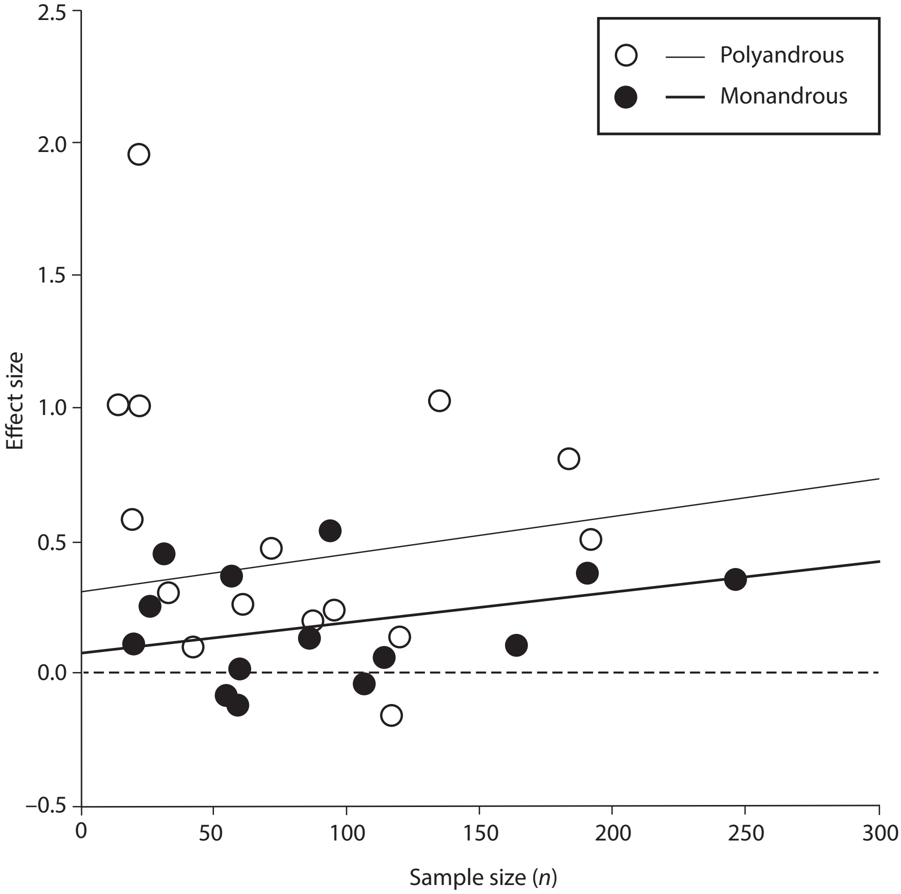

Figure 21.4. An example of a meta-regression showing the relationship between the effects size and a relevant factor (polyandrous or monandrous) for a meta-analysis on mating history in Lepidoptera (Torres-Vila and Jennions 2005). Each point represents a single study and the two different groups of studies are denoted by filled circles and the width of line.

(2) The scatterplot with fitted line can help elucidate differences between studies and assess the importance of groups of studies.
(3) Reference lines, confidence intervals, and weighting by symbol size can be included in these plots to increase the information content.

OTHER GRAPHS USED IN META-ANALYSIS

There are a number of additional meta-analysis graphics used to communicate either central tendency, variation, or a combination of both. Nonetheless, few of these are used in ecology and evolution, and are in general also becoming scarce in contemporary meta-analyses in medicine as forest plots, funnel plots, and regression plots become more widely adopted. Hence, a brief description here is provided in the unlikely event that an ecologist or evolutionary biologist encounters any of the following six alternative plot types.

The stem and leaf, normal quantile, and comparative box plots are useful to show central tendency, variation, and distribution of effect sizes (Lipsey and Wilson 2001). They all have a similar function to forest plots. These plots are used in their conventional form to present meta-analytic data, and to clearly provide visual effect size data for studies or groups of studies—provided the distributions do not encompass very large effect sizes or overly numerous entries into the meta-analysis (Wang and Bushman 1999, Lipsey and Wilson 2001). Their capacity to assess heterogeneity is however limited, particularly in the case of the stem and leaf plots; forest plots that include weighting are preferable.

Galbraith or radial plots are an alternative means to visually assess heterogeneity within a meta-analysis (Galbraith 1984, 1988); these have a similar function to funnel and forest plots. These plots are used to assess heterogeneity by showing the inverse of the standard error (horizontal axis) versus the study effect size divided by its standard error (vertical axis). This provides a means to assess asymmetry since values closer to origin have a higher standard error and are thus less precise. Galbraith plots have many positive attributes but are less intuitive to interpret and serve the same function as forest plots.

L'Abbé plots are used to compare event rates in treatment and control groups (L'Abbé et al. 1987)—there is no analog yet in ecology and evolutionary biology, but we can expect to see it in future. The event rate describes a set of dichotomous outcomes (common in medicine) for each study on a scatterplot showing control group rate on the horizontal axis and treatment group rate on the vertical axis. L'Abbé plots can serve as an alternative means to explore heterogeneity among studies within a meta-analysis that measures dichotomous outcomes (Song 1999), and may be of similar use in ecological and evolutionary meta-analyses but have not been used to date.

Raindrop plots are similar to forest plots in that effect size is plotted on the horizontal axis and symbols for each study or group are plotted on the vertical axis; however, these plots also include an estimate of log-likelihood (Barrowman and Myers 2003). Response surfaces can be used to visualize meta-analytic relationships, as between a treatment effect measure and more than one covariate or factor (Lau et al. 1998), but require adequate data on appropriate ecological covariates.

Finally, Bland-Altman plots show the average of two potentially correlated response measures, such as plant height and biomass, by plotting the difference and fitting a slope (Bland and Altman 1986). This type of plot could be used to compare two effect size measures in ecology, but in conventional statistics it is essentially the analog of plotting a correlation or residuals from a regression analysis.

CONSIDERATIONS AND GENERAL APPLICATION

There has been extensive discussion and exploration of best visualization practices for meta-analysis in the field of evidence-based medicine. Since ecological systems can be highly complex and variable, the context or potential covariates associated with each study may be important. Consequently, the meta-analysis graphics commonly used in other disciplines will certainly be useful in ecological and evolutionary syntheses, but multiple visualization approaches should be explored. This will allow ecologists to further refine interpretations and communicate meta-analytic findings effectively. While there is no need to reinvent the wheel, approaches to visualizing heterogeneity in meta-analyses are constantly evolving, and ecologists and evolutionary biologists should similarly strive to model this variation and report and visualize useful attributes in both primary and secondary studies.

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