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Bayesian methods for hierarchical models: Are ecologists making a Faustian bargain?

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It is unquestionably true that hierarchical models represent an order of magnitude increase in the scope and complexity of models for ecological data. The past decade has seen a tremendous expansion of applications of hierarchical models in ecology. The expansion was primarily due to the advent of the Bayesian computational methods. We congratulate the authors for writing a clear summary of hierarchical models in ecology.

While we agree that hierarchical models are highly useful to ecology, we have reservations about the Bayesian principles of statistical inference commonly used in the analysis of these models. One of the major reasons why scientists use Bayesian analysis for hierarchical models is the myth that for all practical purposes, the only feasible way to fit hierarchical models is Bayesian. Cressie et al. (2009) do perfunctorily mention the frequentist approaches but are quick to launch into an extensive review of the Bayesian analyses. Frequentist inferences for hierarchical models such as those based on maximum likelihood are beginning to catch up in ease and feasibility (De Valpine 2004, Lele et al. 2007). The recent “data cloning” algorithm, for instance, “tricks” the Bayesian MCMC setup into providing maximum likelihood estimates and their standard errors (Lele et al. 2007). A natural question that a scientist should ask is: if one has a hierarchical model for which full frequentist (say, based on ML estimation) as well as Bayesian inferences are available, which should be used and why? This can only be

answered based on the philosophical underpinnings. The convenience criterion, commonly used to justify the use of Bayesian approach, no longer applies, given the recent advances in the frequentist computational approaches. Although the Bayesian computational algorithms made statistical inference for such models possible, it is not clear to us that the Bayesian inferential philosophy necessarily leads to good science. In return for seemingly confident inferences about important quantities in the face of poor data and vast natural uncertainties, are ecologists making a Faustian bargain?

We begin by stating our reservations about the scientific philosophy advocated by the authors. The authors claim that modeling is for synthesis of information (Cressie 2009). Furthermore, they claim that subjectivity is unavoidable. We completely disagree with both these statements. In our opinion, the fundamental goal of modeling in science is to understand the mechanisms underlying the natural phenomena. Models are quantitative hypotheses about mechanisms that help us connect our prospective understandings to observable phenomena. Certainly in the sociology of the conduct of science, subjectivity often enters in the array of mechanisms hypothesized. However, good scientists are trained rigorously toward considering as many alternative explanations as imagination allows, with the ultimate filters being consistency with observation, experiment, and previous reliable knowledge. Introducing more subjectivity into the process of acquiring reliable knowledge introduces confounding factors in the empirical filtering of hypotheses, and so as scientists, we should be striving to reduce subjectivity instead of increasing it. Just because there is subjectivity in hypothesizing mechanisms, it does not give us a free

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pass to introduce subjectivity in testing those mechanisms against the data.

Obtaining hard, highly informative data requires substantial resources and time. Can expert opinion play a role in inference? Eliciting prior distributions from experts for use in Bayesian statistical analysis has often been suggested for incorporating expert knowledge. However, eliciting priors is more art than science. Aside from this operational difficulty, a far more serious problem is in deciding “who is an expert.” In the news media, “experts” are available to offer sound bites favoring any side of any issue. As scientists, we might insist that expert opinion should be calibrated against reality. Furthermore, the weight the expert opinion receives in the statistical analysis should be based on the amount and quality of information such an expert brings to the table. Bayesian analysis lacks such explicit quantification of the expertness.

We do believe that expert opinion can and should be brought into ecological analyses (Lele and Das 2000, Lele 2004), although not by Bayesian methods. Recently, Lele and Allen (2006) showed how expert opinion can be incorporated using a frequentist framework by eliciting data instead of a prior. The methodology suggested in Lele and Allen (2006) automatically weighs expert opinion and hard data according to their Fisher information about the parameters of the process. The expert who brings in only “noise” and no information automatically gets zero weight in the analysis. Provided the expert opinion is truly informative, the confidence intervals and prediction intervals after incorporation of such opinion are shown to be shorter than the ones that would be obtained without its inclusion. It is thus possible to incorporate expert opinion under the frequentist paradigm.

Hierarchical models are attractive for realistic modeling of complexity in nature. However, as a general principle, the complexity of the model should be matched by the information content of the data. As the number of hierarchies in the model increases, the ratio of information content to model complexity necessarily decreases.

Unfortunately expositions of Bayesian methods for hierarchical models have tended to emphasize practice while deemphasizing the inferential principles involved. Potential consequences of ignoring principles can be severe when such data analyses are used in policy making. In the following, we discuss some myths and misconceptions about Bayesian inference.

“Flat” or “objective” priors lead to desirable frequentist properties.—Many applied statisticians and ecologists believe that flat or non-informative priors produce Bayesian credible intervals that have properties similar to the frequentist confidence intervals. This idea has been touted by the advocates of the Bayesian approach as an important point of reassurance. An irony in this claim is that Bayesian inference seems to be justified under frequentist principles. However, the claim is plain

wrong. The Bayesian credible intervals obtained under flat priors can have seriously incorrect frequentist coverage properties; the actual coverage can be substantially smaller or larger than the nominal coverage (Mitchell 1967, Heinrich 2005; D. A. S. Fraser, N. Reid, E. Marras, and G. Y. Yi, *unpublished manuscript*). A practicing scientist should ask: Under Bayesian inferential principles, what statistical properties are considered desirable for credible intervals and how does one assure them in practice?

Non-informative priors are unique.—Many ecologists believe that the flat priors are the only kind of distributions that are “objective” priors. In fact, in Bayesian statistics the definition of non-informative prior has been under debate since the 1930s with no resolution. There are many different types of proper and improper distributions that are considered “non-informative.” We highly recommend that ecologists read Chapter 5 of Press (2003) and Chapter 6 of Barnett (1999) for a non-mathematical, easily accessible discussion on the issue of non-informative priors. For a quick summary, see Cox (2005). Furthermore, it is also known that different “non-informative” priors lead to different posterior distributions and hence different scientific inferences (e.g., Tyul et al. 2008). The claim that use of non-informative priors lets the data speak is flatly incorrect. A scientist should ask: Which non-informative priors should ecologists be using when analyzing data with hierarchical models?

Credible intervals are more understandable than confidence intervals.—The “objective” credible intervals (i.e., formed with flat priors) do not have valid frequentist interpretation in terms of coverage. For subjective Bayesians, the interpretation of the coverage is in terms of “personal belief probability”. Neither of these interpretations is valid for the “objective” Bayesian analysis. A scientist should ask: What is the correct way to interpret “objective” credible intervals?

Bayesian prediction intervals are better than frequentist prediction intervals.—Hierarchical models enable the researcher to predict the unobserved states of the system. The naïve frequentist prediction intervals, where estimated parameter values are substituted as if they are true parameter values, are correctly criticized for having incorrect coverage probabilities. These intervals can be corrected using bootstrap techniques (e.g., Laird and Louis 1987). Such corrected intervals tend to have close to nominal coverage. It is known that “objective” Bayesian credible intervals for parameters do not have correct frequentist coverage. A scientist should ask: Are prediction intervals obtained under the “objective” Bayesian approach guaranteed to have correct frequentist properties? If not, how does one interpret the “probability” represented by these prediction intervals?

As sample size increases, the influence of prior decreases rapidly.—For models that have multiple parameters, it is usually difficult to specify non-informative priors on all the parameters. The Bayesian

scientists put non-informative priors on some of the parameters and informative priors on the rest. Dennis (2004) showed that the influence of an informative prior can decrease extremely slowly as the sample size increases when there are multiple parameters. We point out that the hierarchical models being proposed in ecology sometimes have enormous numbers of parameters. A scientist should ask: How does one evaluate the influence of prior specification on the final inference?

The problem of identifiability can be surmounted by specifying informative priors.—By definition, no experimental data generated by the hierarchical model in question can ever provide information about the non-identifiable parameters. If this is the case, then how can anyone have an “informed” guess about something that can never be observed? Furthermore, as noted above such “informative” priors can be inordinately influential, even for large samples. A scientist should ask: How exactly does one choose a prior for a non-identifiable parameter, and in what sense is specifying an informative prior a desirable solution for surmounting non-identifiability?

Influence of priors on the final inference can be judged from plots of the marginal posterior distributions.—The true influence of the priors on the final inference is manifested in how much the joint posterior distribution differs from the joint prior. In practice, however, influence of priors is judged by looking at the plots of the marginal priors and posteriors. The marginalization paradox (Dawid et al. 1973) suggests that the practice could fail in spectacular ways. A scientist should ask: How should one judge the influence of the specification of the prior distribution on the final inference?

Bayesian posterior distributions can be used for checking model adequacy.—Cressie et al. (2009) correctly emphasize the importance of checking for model adequacy in statistical inference. They suggest using goodness of fit type tests on the Bayesian predictive distribution. A scientist should ask: If such a test suggests that the model is inadequate, how does one know if the error is in the form of the likelihood function or in the specification of the prior distribution?

Reporting sensitivity of the inferences to the specification of the priors is adequate for scientific inference.—Cressie et al. (2009), as well as many other Bayesian analysts, suggest that one should conduct sensitivity of the inferences to the specification of the priors. In our opinion, it is not enough to simply report that the inferences are sensitive. Inferences are guaranteed to be sensitive to some priors and guaranteed to be non-sensitive to some other priors. What is needed is a suggestion as to what should be done if the inferences are sensitive. A scientist should ask: If the inferences prove sensitive to the particular choice of a prior, what recourse does the researcher have?

Scientific method is better served by Bayesian approaches.—One of the most desirable properties of a scientific study is that it be reproducible (Chang 2008).

The frequentist error rates, either the coverage probabilities or probabilities of weak and misleading evidence (Royall 2000), inform the scientists about the reproducibility of their results. A scientist should ask: How does one quantify reproducibility when using “objective” Bayesian approach?

In summary, we applaud the authors for furthering the discussion of use of hierarchical models in ecology. While hierarchical models are useful, we cannot avoid questioning the quality of inference that results from hierarchy proliferation. Royall (2000) quantifies the concept of weak inference in terms of probability of weak evidence where, based on the observed data, one cannot distinguish between different mechanisms with enough confidence. We surmise that the probability of weak evidence becomes unacceptably large as the number of unobserved states increases. We feel that scientists should be wary of introducing too many hierarchies in the modeling framework. Furthermore, we also have difficulties with the Bayesian approach commonly used in the analysis of hierarchical models. We suggest that the Bayesian approach is neither needed nor is desirable to conduct proper statistical analysis of hierarchical models. The alternative approaches based on the frequentist philosophy of science should be considered in analyzing the hierarchical models.

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