Ecology, 84(6), 2003, pp. 1412–1414

TRAINING ECOLOGISTS TO THINK WITH UNCERTAINTY IN MIND

Carol A. Brewer[1,3] and Louis J. Gross[2]

[1]*Division of Biological Sciences, University of Montana, Missoula, Montana 59812 USA*
[2]*Department of Ecology and Evolutionary Biology, University of Tennessee, 569 Dabney Hall, Knoxville, Tennessee 37996 USA*

Abstract. Predictive capacity is needed to anticipate the consequences of global change. Along with the computational challenges inherent in accounting for uncertainly in models of ecological and physical processes related to global change, we face educational challenges related to developing the intellectual capital for thinking with uncertainty in mind. Hand in hand with promoting the kinds of research needed to advance the evolving science of ecological forecasting, we need to set an education agenda for developing and enhancing computational literacy of current and future ecologists, managers, and policymakers. Key elements of an educational agenda are (1) defining the audiences and what each needs to know and be able to do; (2) developing curricula and pedagogical strategies in which thinking skills and conceptual understanding are, by design, linked; (3) addressing training needs of faculty to teach effectively about uncertainty to these different audiences; and (4) creating and implementing assessment tools to explore the impact of programs designed to train ecologists to think with uncertainty in mind. Assessing the extent to which new training models have impacted forecasting research and the conceptual understanding of ecologists is an important topic for future scholarship in education, and a natural area for collaboration between forecasting and education researchers.

Key words: assessment; computational literacy; ecological forecasting; education; professional development; uncertainty.

Special Feature

Training Ecologists to ''Think with Uncertainty in Mind''

Anticipating the causes and consequences of global change requires that we develop an understanding of the roles that uncertainty and variability play in environmental processes (Clark et al. 2001, Michener et al. 2002). Accounting for uncertainty in ecological forecasting has significant implications, given that model results may be used to inform decision-making and, if the results are perceived to be credible, society's responses (e.g., Gross 1994*a,* Peterson et al. 2003, Pielke and Conant 2003). Dealing with uncertainty effectively in ecological models requires much more than experts skilled in the application of the technical tools used to develop projections of the future (e.g., Brewer 2001). It also requires a pool of scientists with knowledge and skills that allow them to collaborate effectively with managers and policymakers.

Promoting the research that is needed to advance the evolving science of ecological forecasting (see other articles in this Special Feature) requires an agenda for developing and enhancing computational literacy of current and future ecologists, managers and policymakers, and the general public (Gross 2000). This requires integrating and synthesizing new conceptual knowledge while creating opportunities in our undergraduate and graduate courses for students to develop the skills necessary to make contributions in ecological forecasting. There are no standards for quantitative training of graduate students in the environmental sciences. What are reasonable expectations for our graduate students, who enter such programs with highly variable quantitative backgrounds? How might curricula balance the needs for rigorous training in biological and quantitative methods? How will we measure success?

Clearly, there is a need for curricula and pedagogical strategies that link technical skills and conceptual understanding of uncertainty. Student comprehension of probability statements derived from statistical models is inextricably linked to both their probabilistic conceptual foundations and their technical ability to carry out calculations. How we address these educational challenges depends upon the audience (i.e., students and postdocs, faculty, managers, policymakers, and the general public). What does each audience need to know, and what do they need to do with that knowledge? The answers can depend on technical skills, conceptual foundations, attitudes, and their willingness to account for the relevance of risk and uncertainty in environmental analysis. These factors all help to guide instructional approaches which might well differ significantly for different groups.

Cultivating Uncertainty Thinking

What does it mean to ''think with uncertainty in mind''? Ecological systems are subject to forces other

Manuscript received 26 September 2002; accepted 26 September 2002. Corresponding Editor: J. S. Clark. For reprints of this Special Feature, see footnote 1, p. 1349.
[3] E-mail: brewerc@mso.umt.edu

than internal feedbacks and spatial or temporal contingencies. Included here are processes and controllers that are stochastic at many levels. Realizing that we need to (1) expect such forces in the systems we seek to understand, and (2) cope with the statistical models needed to understand them, are the keys to what we might call thinking with uncertainty in mind (A. Berkowitz, *personal communication*). Furthermore, having uncertainty in mind means that we know when to ask whether stochasticity matters in the system we are trying to understand and how should we account for it.

Future ecologists

What are the essential theoretical and quantitative tools for ecological forecasting and where, if anywhere, do they appear in the curriculum? While the tools students need to be familiar with will vary substantially, depending upon their own career goals, some comprehension of the basics of ''uncertainty thinking'' will be beneficial to all. Scientists developing ecological projections require a background in probability, including the notions of random variables, stochastic processes, and Bayesian statistics (i.e., Gross 1994*b*, Clark et al. 2001). These are essential to define rigorously uncertainty, risk, and the stochastic models appropriate for projections. However, skillful researchers also will utilize many aspects of numerical analysis and computational science to develop effective forecasting.

Today, the typical ecologist is exposed to a limited body of statistics (usually experimental design and basic multivariate; Brewer 1998). For undergraduates with little formal statistical background, the concepts of ecological projections and uncertainty can be included readily in a variety of courses, from general ecology and conservation biology, to biological modeling. An appreciation for modern statistical approaches to inference and forecasting can begin with simulation software and/or conceptual models (e.g., Beiswenger and Brewer 1993). The potential applications and limitations of projections can be reinforced through projects (either in formal courses, or as part of a research experience) which allow students to investigate aspects of forecasting related to their particular interests. While a variety of software programs are available, for example, in the area of population viability, their educational value depends on how they are used within the broader context that includes multiple sources of stochasticity. Simple manipulatives (dice, beans in urns; Brewer and Zabinski 1999) can be used effectively to illustrate how uncertainty can arise in probability experiments.

Future practitioners will require a background in applied mathematics, including modeling methods and computational statistical methods. Likewise, decision-makers will need sufficient conceptual understanding to communicate with these practitioners. Scientists need to be aware of the constraints that managers face in the real world and similarly, managers applying projections require a basic understanding of the statistical tools that underlie approaches such as population viability analysis (e.g., Clark 2003).

General public

An informed public would benefit from improved communication of model assumptions and how they contribute to predictions. The details of meteorological models (to predict weather) and general circulation models (to understand climate) cannot be readily packaged for public consumption. Regular exposure to probabilistic ideas (e.g., weather forecasts, lotteries) does not provide much of a basis for public appreciation of uncertainty in ecological forecasts. The lay interpretation of weather forecasts is enhanced by broad availability of satellite imagery, now fully integrated as part of the communication of weather forecasts. In a sense, it provides a ''picture'' of the assumptions upon which the forecast is based. Developing storm systems are tracked in real time, and images help to communicate the concepts of how forecast uncertainty expands with lead time. The potential to affect decision-making on environmental issues may likewise depend on visual or other devises that promote understanding of the processes that make up forecast models.

Beyond formal training in schools and universities, education of the general public can be aided by targeted articles in the press, especially when they can be related to local or regional projects (e.g., restoration projects, land-use reviews) for which ecological projections inform decision-making. This implies that scientists involved in the development of these projections have an obligation to disseminate information at a level that is clear to a general audience (Brewer 2001). The ready availability of web-based tools to display complex data could be used to promote public understanding of environmental decision-making. A myriad of maps and other images are now readily available through the use of geographic information systems. For example, maps illustrating the relative impacts of potential hydrologic management on ecosystem components were critical to restoration planning in the Everglades of south Florida (DeAngelis et al. 1998).

Instructional infrastructure

What types of instructional tools and techniques are available and appropriate for teaching about uncertainty in modeling ecological systems? Do we need to develop instructional modules for existing courses, web tutorials, and new text books? What skills will current faculty need if they are to teach uncertainty to diverse audiences, and where will they be able to develop the needed proficiencies?

There is a long history of effective short courses on various statistics topics. These can be held for periods of a few days to several weeks, or be offered as brief one-day workshops associated with professional meetings. Workshops can provide an entrée for advanced students and researchers to the key concepts needed to critically read the literature on ecological forecasting. For those ecologists, mathematicians, and social scientists wishing to collaborate on the development of forecasts, professional development workshops also are appropriate. Likewise, short workshops at professional meetings can provide effective professional development for faculty wishing to incorporate new approaches on ecological forecasting into their undergraduate and graduate courses. The depth and computational complexity of workshops and short courses can be adjusted as needed to be highly rigorous for practitioners, or more basic for collaborators and general users. Specialized short courses can be targeted for resource managers and policymakers, perhaps on site at government agencies, as well as at professional meetings.

Educational Research as Part of the Ecological Forecasting Initiative

Finally, what evidence will help us evaluate instruction on ecological forecasting and uncertainty thinking? What are reasonable expectations for learning and application, at the module/course levels and in the policy arena? And how will we measure the extent to which students in each of these audiences are able to use their disciplinary knowledge and uncertainty thinking for problems studied by professional ecologists? A possible measure of the extent to which educational efforts have impacted the research agenda is the number of dissertations that focus on or incorporate a broad view of stochasticity or the number of funded competitive research projects in the next five years. Impact should be reflected in how managers treat uncertainty and in how they use models (not simply accepting one particular prediction). We might also attempt to measure how policymakers integrate forecasting into decision-making and policy development. The extent to which educational efforts improve the utilization of science in decision-making could be an indicator of instructional effectiveness.

In summary, assessing the extent to which we have created a successful training model that has impacted forecasting research and its dissemination beyond the scientific community is, in and of itself, a rich topic for future research. Indeed, this is a natural area for collaboration between forecasting and education researchers, and an important area for future scholarship.

Acknowledgments

We thank the participants in the Symposium on Ecological Forecasting, especially Jim Clark, and the audience in the uncertainty education discussion at the 2002 annual meeting of the Ecological Society of America for sharing their ideas and insights with us. Discussions with A. Berkowitz were particularly helpful in clarifying ideas on ecological and uncertainty thinking.

Literature Cited

Beiswenger, J. M., and C. A. Brewer. 1993. Predicting biological response to global warming: a lab to promote discussion. American Biology Teacher **55**:222–226.

Brewer, C. A. 1998. Preliminary results of the ESA survey on ecology in the undergraduate curriculum. Bulletin of the Ecological Society of America **79**:106–107.

Brewer, C. A. 2001. Cultivating conservation literacy: ''trickle down'' education is not enough. Conservation Biology **15**:1203–1205.

Brewer, C. A., and C. Zabinski. 1999. Simulating gene flow in a large lecture hall: the ultimate bean counting experience. American Biology Teacher **61**:298–302.

Clark, J. M. 2003. Uncertainty and variability in demography and population growth: a hierarchical approach. Ecology **84**:1370–1381.

Clark, J. S., et al. 2001. Ecological forecasts: an emerging imperative. Science **293**:657–660.

DeAngelis, D. L., L. J. Gross, M. A. Huston, W. F. Wolff, D. M. Fleming, E. J. Comiskey, and S. M. Sylvester. 1998. Landscape modeling for Everglades ecosystem restoration. Ecosystems **1**:64–75.

Gross, L. J. 1994*a*. Limitations of reductionist approaches in ecological modeling: model evaluation, model complexity and environmental policy. Pages 509–518 *in* R. J. Kendall and T. E. Lacher, editors, Wildlife toxicology and population modeling: integrated studies of agroecosystems. Lewis and CRC, Boca Raton, Florida, USA.

Gross, L. J. 1994*b*. Quantitative training for life-science students. BioScience **44**:59.

Gross, L. J. 2000. Education for a biocomplex future. Science **288**:807.

Michener, W. K., T. J. Baerwald, P. Firth, M. A. Palmer, J. L. Rosenberger, E. A. Sandlin, and H. Zimmerman. 2002. Defining and unraveling biocomplexity. BioScience **51**: 1018–1023.

Peterson, G. D., S. R. Carpenter, and W. A. Brock. 2003. Uncertainty and the management of multistate ecosystems: an apparently rational route to collapse. Ecology **84**:1403–1411.

Pielke, R. A., and R. T. Conant. 2003. Best practices in prediction for decision-making: lessons from the atmospheric and earth sciences. Ecology **84**:1351–1358.