Our second article is by William E. Magnusson, Coordinator of Ecological Research with the National Institute of Research of Amazonia, in Brazil. Dr. Magnusson has many years of experience in teaching scientific writing, and reports on an interesting and effective method for teaching students to communicate ecology in writing.—Ed.

HOW TO WRITE BACKWARDS

Lertzman (1995) presented many useful suggestions for writing papers and theses. Many of these appear to relate to form, but experienced writers will realize that most are intimately related to function. The paper summarized many interesting ideas that are to be found in how-to-write books, and as such may make them more accessible to beginning writers. However, in a decade of teaching scientific communication, I have found that even five pages of text, with a dozen grammatical suggestions, are too much for the beginner trying to punch out his/her first draft, especially if English is not his/her mother tongue. If the writer gets the content right, it is relatively easy to correct the draft for style using a text such as Lertzman's, or for a more experienced writer to indicate the flaws.

The following five simple rules have helped many inexperienced writers to get started, and have also helped more experienced writers, such as myself, to get out of a hopeless tangle of observations and inferences.

Rule 1: Write the conclusions to your paper. Even a large paper or thesis chapter will not have more than five or six substantial conclusions. Each conclusion must be succinct, and occupy one sentence and less than two lines. The conclusions as written here will not enter into the final work so they do not need modifiers such as "however" and "that is."

Rule 2: Write only the results necessary to make the conclusions you presented.

Rule 3: Write only the methods necessary to understand how these results were obtained.

Rule 4: Write the discussion, which should present only additional information (e.g., literature) that modifies, extends, confirms, or contradicts the conclusions based on your results.

Rule 5: Write the introduction, which will have only the minimum information necessary to present the questions to which the conclusions are the answers.

When you have this, the story is told. You can go over it for stylistic errors, such as those pointed out by Lertzman (1995). If your major professor requires that you include other things such as reviews of the literature about the species/ecosystem, speculations not based on your results, etc., put them in separate chapters, sections, or appendices. After the thesis defense, these can be thrown out and the rest sent off for publication. The process is direct, the student learning to write a thesis and publish at the same time. This avoids having to unlearn all the techniques acquired during the making of the thesis so that he/she can start to learn to be a researcher and publish.

Acknowledgments

I thank all my students who, when all else failed, adopted these rules and made their theses coherent.

Literature cited

Lertzman, K. 1995. Notes on writing papers and theses. ESA Bulletin **76**:86–90.

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Our third article is by Bill Streever, University of Newcastle, New South Wales, Australia. You may remember that Dr. Streever authored an article in our September 1995 issue entitled "Ecology for liberal arts students." This time, Dr. Streever has clarified some of the basics of statistics most often used (and sometimes misused) in ecology courses. After reading this article, I'm sure many of us will want to contact Dr. Streever with some statistics questions related to our own teaching/research specialties.—Ed.

STATISTICS FOR ECOLOGY AND ENVIRONMENTAL SCIENCE STUDENTS

Ecologists are statistics junkies. The vast majority of articles in *Ecology, Ecological Applications,* and *Ecological Monographs* discuss methods and report results in a form assuming at least a basic understanding of statistical methods; *P* values, confidence intervals, and regression coefficients abound. Some articles concentrate solely on statistical methods, and in June 1993 *Ecology* published a special feature entitled "Statistical Methods: An Upgrade for Ecologists." Critical reading of Ecological Society of America journals requires a good working knowledge of statistics; for example, to fully understand all of the articles in the September 1995 issue of *Ecology,* readers need the ability to evaluate ANOVAs, Ryan's *Q* test, stepwise multiple regression, various nonparametric methods, Principle Components Analysis, and Canonical Discriminant Analysis. Despite the importance of statistics, instructors of undergraduate classes seldom integrate statistical methods with ecology or environmental science. Statistics training given through statistics departments focuses on numerical methods while ignoring underlying conceptual issues. Students graduate with a vague knowledge of t tests, ANOVAs, and P values, but with little ability to design, interpret, or critically evaluate analyses. How can ecologists train students in the concepts of statistics? During the past semester, I had the opportunity to teach statistics to future environmental managers. I started with some trepidation, but by the semester's end I felt that many of my students could approach statistical issues responsibly.

I always begin a semester by assessing my students' knowledge. On the first day of class, I asked for a show of hands from those who knew how to run an ANOVA; a few hands were halfheartedly raised. Next I asked about r^2 values; the same hands stayed up, but they wavered. Then I asked for hands from those who knew when a chi-square test should be used in lieu of a t test; all hands dropped. All of these students had taken an ecology course that required the use of ANOVAs, regression, and t tests, and many students had taken a semester of statistics, so their apparent ignorance surprised me. I shifted tactics, asking for a verbal response instead of a show of hands. "What do you know about statistics?" I said.

Students stared at their desks, tied their shoelaces, searched through book bags, and generally avoided any risk of eye contact. After an awkward silence, one student looked up from his notebook, glanced around the room, then called out "It's a good way to lie."

"That comes from Mark Twain," I told him. "The full quote is 'There are three kinds of lies: lies, damned lies, and statistics.'" I added another quotation, from Andrew Lang, who said that people use statistics "as a drunken man uses lampposts—for support rather than illumination."

Although the student's comment was probably meant as sarcasm—a rebellion against statistics, statistics courses, and statistics instructors—it allowed me to push home a point. "By the end of this semester," I told the class, "you should be able to evaluate the use of statistics in journal articles. While you are in college you can rely on instructors and journal editors to filter out the worst abuses of statistics, but when you begin work you will need to judge the validity of various approaches for yourselves. Also, this class will teach you to design simple analyses of your own and provide you with the groundwork to educate yourselves about advanced methods commonly used in environmental science and ecology."

By the end of the first session I had learned an important lesson: to promote interest I would have to make statistics relevant to environmental managers. I introduced important concepts by taking the class to one of my research sites—a salt marsh impacted by diking and cattle grazing. We discussed possible approaches to assessing change following removal of culverts that restricted tidal flow to the marsh. Students suggested the collection of before and after measurements of vegetation. "But vegetation changes all the time," one student pointed out. Another student suggested collection of vegetation data for several years before and after culvert removal; the change before could be compared to the change after. A third student suggested the possibility of collecting data at the marsh with the culvert removed and at a second marsh that would remain "unchanged." I introduced the concept of pseudoreplication, and with minimal guidance from me the class moved very close to the Before-After/Control-Impact designs discussed in *Ecology* and *Ecological Applications* (Stewart-Oaten et al. 1986, Schroeter et al. 1993, Underwood 1994).

I asked about the cattle. How could we assess the impact of cattle on salt marsh? One student suggested removing the cattle and observing the effect, another suggested the need for a control marsh where cattle continued to graze, and a third suggested that we would need more than one marsh with and without cattle. We also discussed approaches to assessing methods of vegetation establishment and testing for interspecific competition through reciprocal transplanting.

At the end of the field trip, I stood at the edge of the marsh and told the class that we had just covered some key issues of statistics without wincing in pain or even opening a book. "After all, statistics is just rigorous common sense. Take the ideas you have come up with today, add a little math, and you have statistics."

I ended the session by passing out a quotation from *Ecology* (Carpenter 1990):

> *At its best, statistical analysis sharpens thinking about data, reveals new patterns, prompts creative thinking, and stimulates productive discussions in multidisciplinary research groups. For many scientists, these positive possibilities of statistics are overshadowed by negatives: abstruse assumptions, emphasis of things one can't do, and convoluted logic based on hypothesis rejection. One colleague's reaction to this Special Feature [on statistical analysis of ecosystem studies] was that "statistics is the scientific equivalent of a trip to the dentist." This view is probably widespread. It leads to insufficient awareness of the fact that statistics, like ecology, is a vital, evolving discipline with ever-changing capabilities.*

Another exercise took the relevance of statistics one step further. We discussed nominal variables in class, and I agonized over a practical experience that could make reasonable use of a chi-square analysis. After some time I decided to have the class compare the use of statistics in chemical and ecological articles dealing with environmental science issues. I expected each student to find 10 articles, note whether each article was primarily chemical or ecological, then decide if the author(s) had used statistics to analyze their data. I wandered among students to lend a hand where needed. At the end of the session, we combined data collected by all students and performed the chi-square analysis. But we had done more than just collect data. We had seen first hand that articles relevant to environmental management relied heavily on statistical analyses, we had browsed through a variety of environmental journals, and we had been forced to confront those pesky written discussions of statistical analyses.

I continued to reinforce the relevance of statistics through constant use of examples. Examples from environmental science accompanied every method that I introduced. Nonparametric methods were associated with results of questionnaires about the perception of air pollution in different cities, *t* tests were associated with a comparison of heavy metals in two rivers, multivariate methods were associated with benthic invertebrate samples collected around a power plant's thermal effluent discharge, and so on. But I was also careful to organize the chaotic jungle of statistics in a straightforward fashion. I broke the course into three sections. First we covered descriptive statistics, including point estimates and confidence intervals. Next we covered hypothesis testing, which was subdivided into observational and experimental approaches. Third we covered predictive methods, focusing primarily on regression. In each section, I insisted that students think conceptually. I knew they could run simple statistical analyses if I told them exactly what to do, but I wanted them to think about the process.

Following Marks (1990), I defined several terms that could be used throughout the semester. The "universe" was defined as the collection of all entities of interest—for the example of grazing's effect on salt marsh, all salt marshes in the region might be the universe. The universe interests us, and we would like to draw some conclusion about the universe based on samples drawn from it. The "experimental unit" would be each entity—each salt marsh—within the universe. The "response variable" would be the variable that we measure, perhaps plant biomass or percent cover. The response variable could be "categorical" or "quantitative." For example, categorical response variables might be sex, survival, or color, while quantitative response variables might be height, mass, or number of individuals in a plot. The "population" would be the collection of response variables for the entire universe. The "universe-sample" would be composed of those experimental units chosen as samples in a study, and as such they would represent the universe. The "population-sample" would be the collection of response variable measurements for the universe-sample; the population-sample is, in a sense, the data set. By using these terms, students began to appreciate the reality of statistics. They were forced to confront the difference between the universe and the universe-sample, the population and the population-sample. These terms also provided a common thread for the course; they applied to descriptive, hypothesis-testing, and predictive studies.

Two additional terms applied only to hypothesis-testing and predictive studies. The "factor" is the general term for the treatment under consideration, while "factor levels" specifically describe the forms that the factor may take. The factor might be grazing, while the factor levels might be no grazing, occasional grazing, and year-round grazing. These terms, like those listed before, provided a common thread that joined different parts of the course—all hypothesis testing and predictive studies have at least one factor with two or more levels.

Conceptual terms also helped students organize their thoughts. For example, *t* tests might be appropriate to test a hypothesis dealing with a single factor and two factor levels, provided the response variable is quantitative, while chi-square tests might be appropriate when response variables are categorical. The universe-sample must represent the universe, so sampling strategies must be carefully considered. One-way ANOVAs may apply to one-factor studies with two to many factor levels, while two-way ANOVAs may apply to studies with two factors, each with two or more factor levels. Multivariate studies are those in which researchers measure more than one response variable. Pseudoreplication confounds the factor of interest with some extraneous factor—usually a locational or temporal factor. The conceptual terms provide compartments that allowed students to approach difficult issues one step at a time.

Some students seemed to have acquired a poor understanding of hypothesis testing from previous exposure to statistics. While minimal coaching allowed most students to happily reject a null hypothesis when $P < 0.05$, they crumbled under the strain of nonsignificant *P* values. I believe this resulted from the common practice of creating laboratory exercises that "work out" and therefore yield $P < 0.05$. To force consideration of nonsignificant *P* values, I intentionally designed exercises that would not yield significant *P* values. For example, I asked students to test the null hypothesis stating that the mean lengths of mosquito fish *Gambusia affinis* at the upwind and downwind ends of a pond are equal. At the beginning of the exercise, I pointed out that the mean lengths of *G. affinis* cannot be precisely equal, so acceptance of the null hypothesis would not make sense. The exercise showed that high *P* values should be interpreted as providing insufficient evidence to reject a null hypothesis of equality of two means. Along a similar vein, I urged students to consider the influence of sample size on *P* values by collecting data and testing a hypothesis using an increasingly larger sample size. For example, students collected counts of plant species richness around a footpath to test an intermediate disturbance hypothesis. The null hypothesis might state that mean species richness is equal in the disturbed area of the footpath, in the intermediately disturbed area next to the footpath, and in the undisturbed area several metres from the footpath. First students performed a Kruskal-Wallis test using only 5 quadrats from each area, then 10 quadrats, and then 15 quadrats. In my experience, analyses based on five quadrats seldom yield a significant *P* value, while analyses based on 15 quadrats almost always yield $P < 0.05$. Students came to appreciate the difference between "biological significance" and "statistical significance" (Johnson 1995). These two examples—interpretation of $P > 0.05$ and the influence of sample size on P values—provide an important lesson for instructors: students should not be sheltered from difficult issues. Embrace complexity openly and wholeheartedly; it makes statistics more interesting.

How should students analyze data? The same way that professional ecologists and environmental scientists do—on a computer. I exposed my students to several software options, including spreadsheets, SAS, and Minitab. I also brought in manuals for more obscure statistics packages, such as Bloom's Community Analyses System (1994) and Ter Braak's CANOCO (1988). Many students told me that they preferred to run analyses by hand, and that learning how to interface with SAS to run a Wilcoxon test wastes time. I pointed out that the data must go into the computer to be graphed and tabulated, and that more complex analyses may be very difficult to run using hand calculations. Another reason for introducing versatile statistics software is to give students a better feel for the number of readily available analytical options. To reinforce this lesson I had students browse through the on-line help menu in SAS, which describes available procedures. I also asked them to flip through the SAS manual.

As a final assignment, I asked students to read an environmental science article and associate the various conceptual terms discussed in the course with the study reported in the article; students had to define the universe, experimental unit, response variable, and so on for the study reported in the article. I asked them to critically evaluate the approach adopted by the article and to suggest at least one other approach that might be used. Most students who go on to become environmental managers will seldom or never analyze their own data, but at least they will be able to critically assess studies that might provide managers with guidelines.

At the end of a semester, could my students fully understand all of the statistical methods used in a typical issue of *Ecology*? Probably not, but they did have the foundation to consider the methods if authors clearly described their approach. Statistics can still mislead students, but students are less apt to see all statistics as lies and more apt to constructively criticize questionable methods. They can dissect any approach by applying the conceptual terms used throughout the semester. Students leave the course believing that statistics does, after all, have relevance, and that it is more accessible than they believed at the beginning of the semester.

Literature cited

Bloom, S. A. 1994. The Community Analysis System 5.0. Ecological Data Consultants, Archer, Florida, USA.

Carpenter, S. R. 1990. Large-scale perturbations: opportunities for innovation. Ecology **71**:2038–2043.

Johnson, D. H. 1995. Statistical sirens: the allure of nonparametrics. Ecology **76**:1998–2000.

Marks, B. F. J. 1990. Analyzing research data. Robert E. Krieger, Malabar, Florida, USA.

Schroeter, S. C., J. D. Dixon, J. Kastendiek, and R. O. Smith. 1993. Detecting the ecological effects of environmental impacts: A case study of kelp forest invertebrates. Ecological Applications **3**:331–350.

Stewart-Oaten, A., W. M. Murdoch, and K. R. Parker. 1986. Environmental impact assessment: "Pseudoreplication" in time? Ecology **67**:929–940.

Ter Braak, C. J. F. 1988. CANOCO—a FORTRAN program for canonical community ordination. Microcomputer Power, Ithaca, New York, USA.

Underwood, A. J. 1994. On beyond BACI: sampling designs that might reliably detect environmental disturbances. Ecological Applications **4**:3–15.

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