Mongolian Journal of Biological Sciences 2003 Vol. 1(2): 55-57

Why Do You Need Mathematics to Learn Ecology?

Bazartseren Boldgiv

Department of Ecology, Faculty of Biology, National University of Mongolia, Ulaanbaatar 210646, Mongolia
Present address: Department of Biology, University of Pennsylvania, Philadelphia, PA 19104-4207, USA e-mail:boldgiv@sas.upenn.edu

John Maynard Smith, one of the most influential evolutionary biologists of our time, once said "*If you can't stand algebra, then stay away from evolutionary biology*." A similar phrase can be said about ecology: "*if you can't stand mathematics, then stay away from ecology*." At the outset I should say that I am not trying to discourage readers who have not had an opportunity to have and use the great tool of mathematics, but my intention is to help young ecologists to develop into competent professionals from the beginning by emphasizing its importance.

After I started this short note, incidentally, the *Science* published a special issue on Mathematics in Biology on February 6, 2004. In this issue, Sir Robert M. May (2004) offers his overview of uses and abuses of mathematics in biology; whereas Bialek and Botstein (2004) propose ways to improve quantitative thinking of future biologists by designing a unified introductory science curriculum in colleges. The issue of improving quantitative background of biologists is very important nowadays as the science of biology has been transforming not only with advances in biological understanding, but also with dramatic advances in experimental techniques and computational analyses (Bialek & Botstein, 2004).

Application of quantitative thinking in biology dates back to the Middle Ages and earlier. Sir William Petty in about 1300 composed a table "*shewing (showing) that the People might have doubled in the several ages of the World*", starting with eight people one year after the great Flood, which was quite an accurate calculation. Leonardo of Pisa, a.k.a. Fibonacci, born in Italy, derived in early 1200s one of the first mathematical models for population growth, in this case for a closed population of rabbits (Britton, 2002). Galileo, arguably the founder of modern science, apparently realized that "*the book of nature is written in the language of mathematics*" (Bialek & Botstein, 2004). Unfortunately, in about 400 years of modern science, biology has mostly been left out of mathematical culture, whereas physics and engineering marched together with it. The consequence of that can be seen even in case of Charles Darwin, one of the great thinkers in biology, who wrote that "*I have deeply regretted that I did not proceed far enough at least to understand something of the great leading principles of mathematics; for men thus endowed seem to have an extra sense*" (May, 2004). From today's viewpoint, it is believed that, with such an "extra sense," Darwin could have easily circumvented some of the major problems in his theory of evolution by natural selection, including a setback of his theory for using the *blending inheritance* (Fisher, 1930), which was the well perceived mode inheritance in his time (under which variation could have easily been shown to be lost from generation to generation). It is possible that he could have easily grasped the idea of Mendelian genetics and used it to the benefit of his theory, rather than ignoring Mendel's correspondences with him, had he had that "extra sense."

In recent years, biology has come long ways in using mathematical tools and computing powers that took many different forms (probability theory in experimental design, pattern recognition in bioinformatics, models in ecology, evolution, statistical analyses in all fields and more) and opening up many new frontiers of interdisciplinary approach. Biological education has not kept pace with these developments in general. Ecology is no exception and this situation is especially at its worst in Mongolia where biologist and mathematicians go their own ways without their paths ever being crossed.

Ecology is a relatively young science and it has been maturing very fast in the last few decades. That means ecology has started asking some serious questions by expressing theories and experiments in mathematical terms and getting answers to those questions. Ever-increasing use of mathematical tools is the tendency that can be seen in any ecological journal over the years. However, ecological research in Mongolia is still in its infancy which can be seen by largely descriptive work done without much consideration of proper research design and analysis used later. This situation needs to be changed even though it inevitably takes much effort and time.

So, why do you need mathematics to learn ecology? To answer this question, perhaps we should address the following question “why ecology is so hard such that ecologists use so much hardcore mathematics?”

The very first answer to this question is that ecological systems are so complex that they have been argued to be quantitatively more challenging than most fields of physics. This has the following reasons: (*a*) Each organism, that is the fundamental unit of ecological processes, is unique not only because of inheritance, but also the unique history of interacting with the environment. This makes it difficult to aggregate individuals by imposition of the *law of large numbers* and the assumption that all individuals are the same (in physics, on the contrary, fundamental particles such as electrons can be aggregated). (*b*) Ecological questions are such that they attempt to understand the results of several, if not many, *simultaneously acting and potentially interacting causes* (Quinn & Dunham, 1983). As a result, ecological patterns are more difficult to discern, both theoretically and empirically. It is impossible to measure all individual components of ecological systems, because they change over time and it would take forever to do so. However, mathematical models provide us with a much simplified system of interacting causal mechanisms when constructed with an appropriate level of reductionism. This gives us direction about what variables are far more important than others. Moreover, mathematical models can generate testable predictions. By verifying or falsifying these predictions, the field can make much faster progress by highlighting the difference between the patterns seen in nature and mechanisms that may cause those patterns (Gotelli, 1998).

Secondly, the *lack of generality* of principles in ecology is a serious issue. There are only a few *scale-independent* principles (i.e., they remain valid irrespective of the temporal, spatial, or individual scales over which they are applied). These include the *second law of thermodynamics*, *energy and mass balance*, and *evolution by natural selection*. Consequently, all other processes or principles that ecologists employ to understand the patterns that they study are not general, i.e., they have restricted *domain of generality* (Dunham & Beaupre, 1998). Thus, patterns observed in ecological systems are most often the special cases. This argument raises an issue of the important criterion of *predictive power* (Peters, 1991) and prediction is the most important objective of any scientific field. To avoid this ecological suffering, large scale pattern seeking approach has been proposed, i.e., *macroecology* (Brown, 1995). Because ecological systems are *complex*, *adaptive* and *dynamic*, they show certain *emergent properties* which can be revealed by rigorous, large scale mathematical analyses.

On the other hand, the foremost use of mathematics by ecologists is mainly limited to the use of statistical packages. However, the importance of designing proper experiments that require least possible effort is also crucial and this demands not only a great deal of knowledge of the system of interest, but also a background in *probability theory*. *Designing research* is the hardest part of ecological study (or any research in general). Once a research project has been designed in a way that really considers careful control of variables that are not under question, then what type of statistical analyses should be used will follow. Two approaches in statistics can be used (Hilborn & Mangel, 1997): *maximum likelihood approach* (uses the probability that a model fits the data observed) and *goodness-of-fit approach* (which calculates the probability that data fit the model). Which one is a better approach is still a much debated subject. Nobody in their right mind questions the importance of statistical analysis, so I will leave it at that.

However, one should observe some caution when using mathematics in research. As mentioned, most ecologists restrict their mathematical creativity by the use of statistical packages, which is fine, at least in the near future. But using any statistical package without regard of underlying *assumptions* of tests and models the software uses can lead to erroneous results and interpretation. Researchers also point out that using mathematical models in ecology has two inherent dangers (Gotelli, 1998). First is that we build models too complex, so that the models contain many variables that we can never measure in nature, and mathematical solutions may be complex, sometimes even impossible (many *differential equations* can be proven to be unsolvable by the methods of *calculus*). The second issue is that we often forget models are abstract representations of nature. However logical a model might appear, nothing says that nature must follow its rules. Therefore, it is absolutely crucial to understand that any *model is always inherently false*. What you build into a model is what you get as an output; i.e., a mathematical model is a "*garbage in-garbage out*" system. By carefully focusing on the assumptions of the model, we may be able to pinpoint the places where it departs from reality.

Sokal and Rohlf (1995) showed that ever-increasing importance and application of mathematics to biological data by a cursory inspection of eleven decennial volumes of *The American Naturalist* (between 1890 and 1990) because of its coverage and influence in ecological research. They showed that, by 1990, papers that contained no numerical results had decreased to <5%, those with numerical results but no computations made up about 2%, those with simple statistical analyses were about 42%, and papers with major emphasis on mathematics have increased to about 51% of all papers published. This trend is irreversible and can be seen in a wide range of peer-reviewed journals that have broad coverage and indicate the level and direction of ecological research. Therefore, mathematics is not going out of ecology, it is here to stay in ecological research.

So, my intention of this message is to convince readers to question their own quantitative background if they want to become well educated in ecology. I think it is adorable if one ended up becoming an ecologist out of childhood love of animals and plants. However, do not forget ecological research requires more than that; hopefully the reasons given above are convincing. Therefore, always question your curriculum and demand one that would promote your quantitative thinking skills and understand that prerequisite mathematics and statistics courses are not simply the barrier on your quest to be an ecologist. Additionally, I would also like to welcome discussions from colleagues on ways to improve ecological education in Mongolia and to better prepare our future specialists by exposing them to more quantitative exercises. Mathematics is simply an inseparable tool that ecologists must have and use. Like it or not, the use of mathematics in ecology is literally the question of "to be or not to be" an ecologist.

References:

Bialek, W. & Botstein, D. 2004. Introductory Science and Mathematics Education for 21st-Century Biologists. *Science* 303:788-790.

Britton, N.F. 2002. *Essential Mathematical Biology*. Springer-Verlag, London.

Brown, J.H. 1995. *Macroecology*. University of Chicago Press, Chicago, IL.

Dunham, A.E., & Beaupre, S.J. 1998. Ecological experiments: scale, phenomenology, mechanism, and the illusion of generality. Pages 27-40 *in* W. J. Resetarits and J. Bernardo, Eds. *Experimental Ecology: Issues and Perspectives*. Oxford University Press, Oxford.

Fisher, R.A. 1930. *The Genetical Theory of Natural Selection*. Dover (reprint 1958), New York, NY.

Gotelli, N.J. 1998. *A Primer of Ecology*, 2nd edition. Sinauer Associates, Inc., Sunderland, MA.

Hilborn, R. & Mangel, M. 1997. *The Ecological Detective: Confronting Models with Data*. Princeton University Press, Princeton, NJ.

May, R.M. 2004. Uses and Abuses of Mathematics in Biology. Science 303:790-793.

Peters, R.H. 1991. *A Critique for Ecology*. Cambridge University Press, Cambridge, UK. 384 p.

Quinn, J.F. & Dunham, A.E. 1983. On Hypothesis-Testing in Ecology and Evolution. American Naturalist 122:602-617.

Sokal, R.R. & Rohlf, F.J. 1995. *Biometry: the Principles and Practice of Statistics in Biological Research*, 3rd edition. W. H. Freeman and Co., New York, NY.