Practicing scientific inquiry: what are the rules?

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Ecologists attempt to establish general principles from a vast range of organizational, spatial, and temporal scales (Belovsky *et al.* 2004). The process of developing generalities in ecology involves two approaches often not addressed in introductory science courses – inductive and deductive. One way of thinking about this is to consider the inductive approach as examining particular cases and deriving general conclusions or rules from them, and the deductive approach as using generalities to make specific predictions that can then be tested. In this issue of *Frontiers*, Knapp *et al.* (pp 483–91) underline the need for general principles or "rules" in ecology, and research that tests the predictive limits of those rules. The rules illustrated in this article are based on long-term studies from the Konza prairie and Sevilleta Long-Term Ecological Research (LTER) sites. Existing data from savanna grasslands in South Africa are used to test rules derived from Konza studies of grassland responses to fire.

Learning goal

Two general principles that underpin scientific teaching in this series of articles are that (1) students acquire deeper understanding by actively constructing knowledge and (2) successful assessments demonstrate students' abilities to use their knowledge. In Hodder *et al.* (2004), students used a guided-inquiry approach to define a problem, construct hypotheses, and design a method to test a hypothesis. In Williams *et al.* (2004), students applied the process of science to explore general principles about plant invasions. In this article, students will use *open-ended inquiry* to understand that the process of science is more than a rote series of steps (NRC 2000). Rather, it is an iterative process that uses both inductive and deductive reasoning to design experiments that generate new data, and to synthesize existing data. Both types of reasoning are means by which we identify patterns, construct arguments or rules to explain them, develop and test predictions about their causes and nature, and ultimately refine or possibly modify the rules. The assessments help students understand the varied processes of science and investigate how generalities in ecology arise and how they can change. Thus, a major outcome is for students to realize that ecological systems are complex and that their hypothesis may not hold true for all systems. Their conception that science is learned as a series of facts is challenged by this inquiry.

Instructional design

Many datasets are available to help instructors achieve these outcomes (LTER: www.lternet.edu/data; ESA: http://tiee.ecoed.net; GLOBE: www.globe.gov). Here the LTER data are used as the basis for an open-ended inquiry. Students will engage in the processes of science as they search for patterns and predict causal effects about the influence of precipitation and temperature on net primary productivity in different biomes.

This instruction is designed for a large enrollment introductory course and begins as homework by teams of two to four students. Knapp *et al.* is assigned as reading (particularly the first section). Each team selects two LTER sites from the LTER Net Primary Productivity database (http://intranet.lternet.edu/cgi-bin/anpp.pl) and searches for patterns that describe the effect of precipitation and temperature on primary productivity (Knapp and Smith 2001). Approximately 25 years of data are available for import, for plotting graphs (Panel 1). Open-ended inquiries will have multiple results, depending on the questions students ask and the analytical approaches used.

Homework

Teams are asked to:

- Describe the pattern they observed and propose a rule (for example, as temperature increases, primary production decreases).
- Support it with two graphs or models based on the data.
- Test the rule by comparing the figures from their LTER sites to those constructed using data from one or two different LTER sites.
- Use what they know about biomes and ecophysiology from the course resources, and interpret the results.
- Ask: "Is the rule supported?". If it is not supported, propose one or two reasons that could explain why not; if it is supported, propose one or two other factors that were not measured or included in the database that might alter the patterns detected by students.

Ask students to submit their results before class (one response per group, via email or internet). The instructor selects two or three rules or predictions that were not supported.

Classwork

In class, the instructor presents two or three of the unsupported rules (using overheads, PowerPoint, or the Web,

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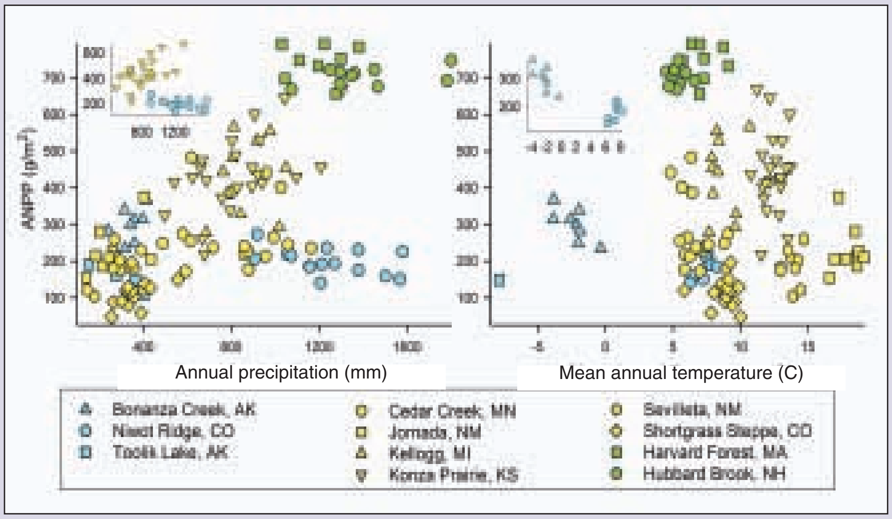
with rules and figures that do and do not fit). Teams select one example and derive a new rule or causal relation that could be tested next.

After their group discussion, individuals write up their new rule or prediction, with supporting reasons, and turn it in. Then the instructor can call on some groups to show their new rules and others can suggest ways to test them. The instructor can use that time to clear up any errors in logic, discuss variability in the data, and assure students that "messy" data are not to be feared or discarded. Rather, those inconsistencies help us better understand how natural systems work. Students seldom have opportunities like this, to rethink and adjust a rule so they can test it again, as happens in scientific processes.

Panel 1. Relationships between annual precipitation and temperature (1975–1998) for eleven sites in the LTER database (cited in text).



General biome types are coded by color: yellow = grasslands; green = temperate forests; blue = boreal and tundra habitats. Inserts show contrasting data for Niwot/Konza and Niwot/Bonanza to exemplify alternate relationships students may discover.

Assessment

An instructor can use the following questions to develop a rubric (see www.flaguide.org/cat/rubrics/rubrics7.php) to assess students' understanding of the processes of inquiry and ecological concepts:

How do students conduct the process of inquiry?
Are the data represented accurately in graphs? (eg Are the dependent and independent variables correctly illustrated?)

What do students learn?
How well do students answer "why" questions about ecological concepts through the accurate and logical interpretation of patterns and supporting evidence from their inquiry?

After students attempt to derive new rules in class, to what degree has the activity enhanced their understanding of controls on net primary productivity and how those controls vary among different biomes?

Final note

Knapp *et al*. conclude that proposing and testing rules or general principles in complex systems can inform future research in ecology. Similarly, engaging students in open-ended inquiry and assessing their ability to use processes of science is a method to test rules and predictions about how students learn science. This too, informs future research in education.

By completing this inquiry, students will see that hypotheses are built on observations of different types – even from other peoples' datasets. This will also demonstrate how several interpretations can come from the same data and that some may be better supported than others. Students often think that a goal of science is to support hypotheses and predictions in ways that lead to formal principles and theories. This activity will allow students to see that refuting, rather than just supporting, hypotheses can lead to a more complete understanding of how the world works. Ultimately, this inquiry can demonstrate how the complexities of biotic and physical interactions make it so difficult to come up with major principles of ecology.

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