Enhancing Student Understanding of Environmental Sciences Research

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ENGAGING students in original inquiry or research is a cornerstone of the national science education reform movement (AAAS 1993; NRC 1996). Ideally, students should participate in each step of the research process, starting with defining a research question and proceeding through carrying out experiments, analyzing and interpreting data, and raising new questions based on their results (Moss et al. 1998). Students who conduct research generally develop a better understanding of science content and processes than do students whose exposure has been limited to traditional classroom science teaching (SRI 1997).

However, even students who have conducted all phases of a research project may not have an opportunity to reflect on and discuss key issues in the practice of science, and thus may have an unrealistic picture of how scientists actually conduct research. They may miss key understandings of the "sociology of science," such as science can be "messy" or "fuzzy" and involves creativity and making decisions; scientists often work collaboratively; and an experiment does not always give a definitive answer to the original research question (AAAS 1993; Cunningham & Helms 1998). Students are more likely to gain accurate insights into the nature of scientific research if, in addition to conducting a research project, they also have a framework for discussing and reflecting on concepts related to research (Friedler & Tamir 1986).

As part of a summer enrichment program for high ability 11th graders, we developed a class project designed to give students experience conducting research and to enhance their understanding of the sociology of science. The research project focused on the impact of non-indigenous worms on forest soils. We used a series of readings, journal-writing exercises, and class discussions to address one key sociological understanding of science—the importance of investigator judgment and creativity at all stages of the research process.

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The overall goals of this paper are to:

1. Present one model for an authentic student research project that incorporates sociology of science concepts
2. Provide preliminary observations on the success of this model in enhancing student understanding of the research process.

To reach these goals, we have included in the paper:

1. An overview of the students' research project
2. Descriptions of exercises we used to weave sociology of science concepts into the students' research
3. Excerpts from students' journals illustrating their understanding (and misunderstanding) of the research process and of the sociology of science concepts.

Although the journal entries do not necessarily represent what the entire class learned, they demonstrate the level of understanding students may attain as well as areas in which students appeared not to gain important insights. We hope this model and our accompanying observations will prove useful to teachers trying to foster students' understanding of scientific research.

Research Project

The students' research focused on the impact of a regional invasion of non-indigenous worm species on decomposition in forest soils. We chose this topic because it:

1. Provided a local example of a global environmental problem (i.e. changes in ecosystem processes brought about by invasive organisms [Alban & Berry 1994])
2. Lent itself to experiments students could conduct from start to finish in a short time frame
3. Involved both lab and field components
4. Permitted a research design that gave students freedom to make decisions.

We designed this project as a semi-guided investigation, to allow students freedom to make important decisions while also providing sufficient direction for them to complete the research successfully. We specified the techniques the students would use, i.e. a standard method for estimating faunal and microbial activity in soils, which involves incubating and measuring CO_2 evolution from soils in Mason jars. However, we left unspecified a number of factors including type of soil (organic vs mineral), species of worms, and worm density. We also gave students control over methodological decisions regarding the processing of organic and mineral soil samples. For example, soil could have been left as intact as possible, roots could have been removed, or all soil samples could have been homogenized.

The final experiment, which emerged from a combination of instructor guidance and student suggestions, was designed to test the hypothesis that CO_2 flux from soil increases in the presence of worms and in organic and mineral soil compared to mineral soil alone. The students conducted a replicated experiment in which they measured CO_2 fluxes over a 24-hour period in the presence and absence of worms, from mineral soil only, and from mineral and organic soil. As a control for any CO_2 that might result from worm respiration rather than carbon turnover in the soil, they measured CO_2 in jars with sand and worms, and in jars with sand only. Students also measured the mass of organic and mineral soil and worms in each jar, so that they could account for differences due to mass and could compare data among jars. One student took all the CO_2 measurements for the class using a gas chromatograph; however, simpler methods including soda lime absorption (Edwards 1982; Pongracic et al. 1997) or titration (Trautmann & Krasny 1998) could be used by students without access to expensive equipment. The entire project occupied eight 2- to 3 1/2-hour class sessions over a period of four weeks. In a high school classroom setting, we estimate this project could be completed as a focused unit in two to four weeks, depending on which aspects were emphasized and the extent to which the instructor could build on concepts covered previously. Many of the exercises we used could also be adapted for use within existing curricula. (For more specific instructions on how to conduct the project, readers can contact M. Krasny).

Journal Assignments & Class Discussions

Over the course of the project, we gave students assignments and conducted class discussions designed to motivate thinking about their decisions at the following stages of the research process:

1. Developing a context for the research
2. Field sampling
3. Experimental design
4. Data analysis and interpretation.

These exercises asked students both to reflect on decisions they had already made and to anticipate judgments they would need to make in future sessions. At the end of the project, we asked students to reflect on what they had learned through the entire research process. Below we present the exercises along with selected student journal entries and observations of the instructor (N. Gurwick) for each of the five steps and overall research experience.

Developing a Context for the Research

We began the class with readings and discussion of two large conceptual issues: how humans, and in particular introduction of exotic species, influence ecosystem processes (Vitousek 1990) and how ecologists conduct experiments at varying spatial scales, from microcosms to whole ecosystems (Carpenter et al. 1995). Through strongly advocating whole-ecosystem experiments as opposed to reductionist approaches, the Carpenter et al. (1995) article offered a clear introduction to the existence of debate about appropriate research approaches and to the role researcher judgment plays in science.

We designed the journal exercise associated with the article on whole ecosystem experiments (Carpenter et al. 1995) to help students understand the role of debate in science research and the merits and limitations of experimentation at different scales. To help students consider these large concepts in the context of their research, we also had the students read about carbon cycling, soils, earthworm ecology, and the use of Mason jars to measure decomposition rates. The journal assignment read:

> *Imagine you are going to give a presentation in conjunction with Stephen Carpenter about how to design experiments in environmental research. The point of the meeting is to get people thinking about the pros and cons of whole ecosystem experiments and of laboratory-based experiments. . . . You will want to justify carrying out the lab experiment (on organic matter decomposition in the presence/absence of worms) despite Carpenter's criticisms. You suspect that both of you will use examples to illustrate your points.*
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> *As a first step in preparing for this meeting, you have decided to think out loud by writing down what you think Carpenter will say and how you might reply. Spend about 30 minutes doing so.*

The students identified a number of limitations of laboratory experiments. These included environmental factors (e.g. temperature, light) not representative of field conditions, and the small scale of the Mason jars which might exclude some aspects of the carbon cycle. In support of laboratory experiments, students pointed out that relative differences between treatments might be the same in lab and field conditions; the time scale of the experiments might be too short for differences between laboratory and field populations to manifest themselves; and laboratory experiments have the advantage of allowing the researcher to change one independent variable at a time and to set up controls. They also discussed how they might overcome some problems inherent in laboratory experiments, by comparing their results to the results of others and by trying to simulate the natural environment (e.g. diurnal temperature fluctuations).

Field Sampling

After working in small groups to develop ideas for their laboratory experiments, the students traveled to Cornell's Arnot Research Forest about 20 km south of Ithaca, New York, to collect worms and soil samples. Because weather limited the amount of time we had to discuss sampling in the field, we used a retrospective approach to help students appreciate the numerous small decisions involved in field sampling, as illustrated in this assignment.

> *Choose one decision we made at the Arnot, and consider whether you think we made a mistake. Could we have learned more by making different decisions? Will the decisions we made make it so difficult to interpret our data that we will have difficulty saying anything at all? Often, scientists realize part way through an experiment that there is a better way to answer the question of interest. Can you think of particular advantages or disadvantages to the decisions we made that we did not consider at the time?*

The following journal entry shows a good understanding of how research involves decisions about how to balance collecting more information and working within a limited time frame.

> *One decision that stands out in my mind was the concentration of effort to simply get earthworms, rather than trying to [increase] diversity [of] the species collected. As a member of the group that proposed we study the impact of different species, I especially took notice of this decision.... An advantage of neglecting a study of species impact is less work required to do so. The good of this is that with only 6 weeks to run a study, getting too specific would slow things down by complicating things. But, in the end, we have lost potential knowledge that would help us better understand the ecosystem.*

Experimental Design

The next exercise was intended to elicit thinking about experimental design.

> *On Thursday, we will use the worms, mineral soil, and forest floor we collected at the Arnot to set up an experiment investigating the influence of this biological invasion on carbon cycling in the forest floor. We will use jars in which we can measure the concentration of carbon dioxide in the air. Try to anticipate decisions we will need to make. To help you think about those decisions:*
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> 1. *Diagram what you think the experiment should look like, as it might be presented in a laboratory workbook.*
> 2. *Diagram a chart or table for collecting data. Include a place for each number you think we should collect.*
> 3. *Diagram what you anticipate the results will show.*
>
> *What graph(s) do you want to be able to draw when we have the data in hand? What data points will you need in order to do so?*

Students experienced difficulty making the leap from hypothesis formation to designing an experiment that would test their hypotheses. Although student diagrams and descriptions demonstrated familiarity with controls and treatments, they showed confusion about how to graph independent and dependent variables and did not address replication. Students encountered facets of experimental design several times subsequent to this initial assignment, for example during a class discussion about how to balance numbers of jars per treatment with numbers of treatments, and while analyzing their data. Lacking additional journal entries on this topic, we cannot assess student understanding of experimental design following the entire course. Teachers wishing to enhance student understanding of concepts such as replication and relationships between variables prior to designing the experiment might have students explore an existing data set.

Data Analysis & Interpretation

Students decided to summarize their data by calculating mean CO_2 concentrations for each treatment at each sampling time. Upon initial inspection, these data showed clear differences between treatments, in accordance with expectations, i.e. respiration rates (CO_2 concentrations) were higher in jars with organic and mineral soil than in jars with mineral soil only, and in jars with worms than jars without worms (Figure 1).

While their analyses may have been a useful starting point, the students showed little interest in exploring or interpreting their data beyond the appealing patterns illustrated in Figure 1. For example, they did not examine the influence of organic soil mass on CO_2 concentrations despite the fact that they had carefully collected soil mass data. They also failed to examine the effect of worm respiration, per se, on CO_2 concentrations. Not having performed more detailed analyses, the students did not engage fully in key aspects of the research process, such as developing explanations and new research questions on the basis of unexpected results.

Prior classroom experience conducting "cookbook" laboratory experiments may explain, in part, why the students had difficulty designing the experiment and showed little inclination to explore their data. Classroom experiments are generally designed to teach specific concepts or skills; thus, instructors often employ standardized procedures and students generally confirm expected results and are not encouraged to explore their results in depth. Students exposed only to classroom laboratory science fail to

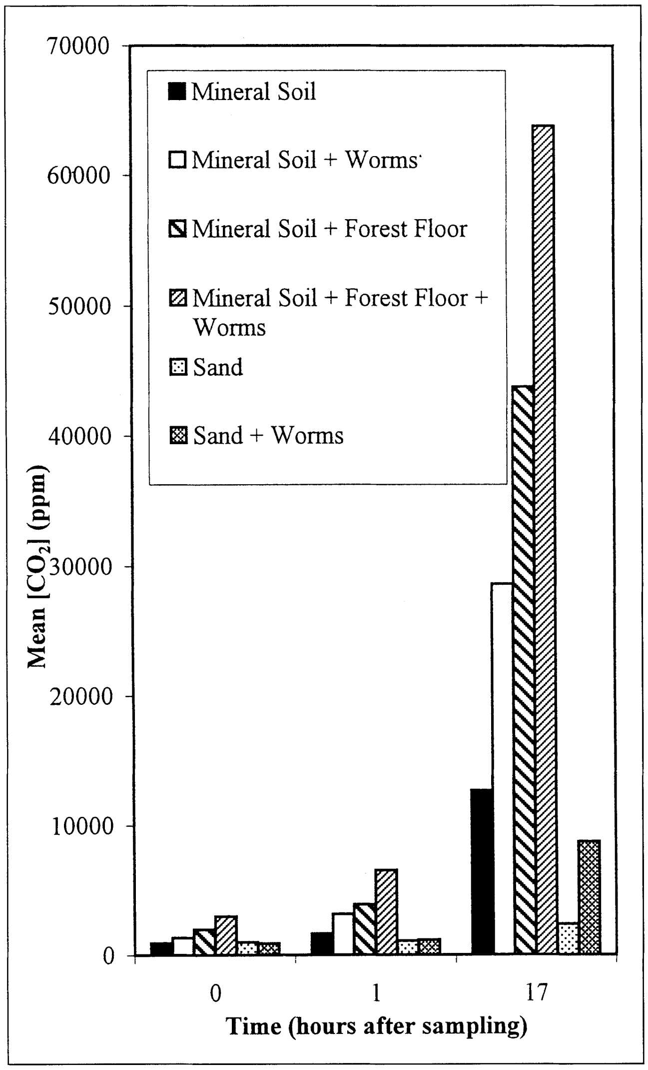

Figure 1. Mean CO_2 concentrations in jars, reflecting data analysis by students.

develop skills such as describing patterns in data, drawing inferences from presented data, and designing their own experiments (Friedler & Tamir 1986).

In addition, students who have only conducted classroom laboratory experiments often attribute any unexpected results to experimenter error (Chinn & Brewer 1998). For example, in responding to a journal writing exercise that asked students to discuss how to interpret data points that differ from others, one of our students wrote:

In order to deal with numbers that are obviously inconsistent, we need to exclude them from our data list (the entire jar's data). This is because this data is either wrong or merely not typical of a forest environment.

However, a second student seemed to show an evolution in his thinking, perhaps as a result of his experience conducting the worm research.

Upon finding numbers that are unusually inconsistent, I would react by wanting to blame the numbers on random fallacy—of collection of data and the data itself. But, that arbitrary attempt to impose consistency onto the data could be damaging for the experiment. The best way one could deal with inconsistencies would be to recognize the inconsistency and explore reasons why it might, in fact, be consistent with what is taking place in the jars. After all, the most unwanted results of an experiment are, perhaps, the most interesting and enlightening.

Including a data exploration exercise might have promoted interest in a more thorough analysis of their results and evolution in thinking about discrepant data among a greater number of students. An example activity might involve explicitly asking students to examine their data from multiple perspectives, including factors such as soil biomass, time of incubation, and worm respiration.

Overall Research Process

Perhaps most indicative of the impact of the overall research experience and accompanying assignments were journal entries students made when asked to reflect on what they had learned from doing the experiment and how their idea of what it means to do an experiment might have changed. Many students gained an appreciation for the decision making and subjectivity entailed in conducting environmental research and for how authentic research differs from classroom laboratory experiments. One of the most striking themes emerging from these entries was students' excitement about the unexpected power and freedom they experienced as part of the research process.

I learned . . . the great amount of subjectivity involved in an experiment. There are so many possibilities in terms of procedure, data collected, data treatment, experimentation, and interpretation. . . . Now, I have a greater knowledge of what it means to run an experiment—not one such as in chemistry or physics, rather one that originated with a simple question: what are the effects that an invading worm population can have on an ecosystem? Rather than following instructions, there are more options—more freedom.

Another student wrote:

I learned about how to perform an experiment from the very beginning. When I have done other lab experiments in school I was always given a problem that needed to be solved and shown a set of steps that will help me go about getting the answer to that problem. For the worm experiment we started with having to design the procedures to find a conclusion about the worms. This process made me realize how much work actually goes into just the creation of the lab experiment. . . . My idea of how to do an experiment has changed drastically from the experiments that I have done in school to this one and I enjoyed the decision making power that we had in creating our own experiment.

Many of these entries commented on the students' surprise at the complexity and amount of decision-making entailed in designing and executing an experiment.

I was amazed to see such strong arguments from both sides when a discrepancy [arose] concerning small details.

(Just think! How would our experiment have changed had we decided differently in one of those many debates?) Even with a team of around 20 people (3+ environmental experts included) we had trouble putting together the procedure/results. I have gained immense respect for the time and effort that goes in to each and every environmental survey/experiment.

Other students indicated that the course had helped them realize the importance of critical thinking and questioning relative to the hands-on aspects of conducting research.

My ideas of an experiment have changed. I think that the field work, the actual experiment part of it has decreased in importance in my mind. The questioning, hypothesizing, and interpreting have however increased in importance.

Another student commented:

During the experimentation process, the question will get rephrased and adapted.

The fact that students were presented with a research experience that differed radically from their previous classroom laboratory experiments may have been responsible for the change in their understanding of the research process. Significant conceptual change often occurs when learners discover or are shown new information that forces them to recognize shortcomings in their current understandings (Posner et al. 1982). In addition, conceptual change may have occurred because our project allowed students to become involved in many steps of the research process and spend time critically reflecting on and discussing their research. Evaluations of Student-Scientist Partnerships (Cohen 1997, TERC 1997) have shown that engaging students in multiple aspects of the research process (rather than solely data collection) is important in changing student perceptions of and attitudes toward research (SRI 1997; Moss et al. 1998).

Lessons Learned

The students' journal entries indicated that through engaging in a well-planned, semi-guided research project and accompanying critical thinking assignments, students can experience a dramatic shift in their concept of scientific research. Perhaps most important, the students became excited about the unexpected freedom and room for creativity they experienced as part of the research process and gained an appreciation for the importance of making decisions at each step of the research process. The journal exercises encouraged students to reflect critically on these decisions, as well as on other aspects of the research process; such reflection may not have occurred had they just conducted the research. Thus, we recommend that educators guiding students in authentic research allocate a significant amount of time for students to discuss and reflect critically on decision making and other aspects of how they are conducting their research.

Journal entries and instructors' observations during class discussions also indicated that students were able to compare the advantages of laboratory and field experiments and to define research questions and hypotheses. However, the students experienced difficulties in designing valid experiments and in exploring data beyond the most obvious trends. These results suggest the importance of incorporating structured exercises to build skills in experimental design and data analysis (Friedler & Tamir 1986) into a semi-guided research project.

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