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Hiking the hills, walking the trails:

Insights for science education from studies with field ecologists

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Abstract

In the past several years a number of authors suggested that science education could benefit from insights gained by research in the social studies of science that documents and theorizes science as it is actually done. However, in the past such research was mostly concerned with the practices enacted in male-dominated scientific disciplines such as physics and chemistry. Suggestions for the teaching of science drawn from this work reflect these origins, and highlight the paucity of research into the practices of other disciplines such as field ecology. In this paper, we present findings from our own ethnographic work in field ecology. Our research shows that many traditional claims about the nature of scientific research are not consistent with how ecological understandings are actually constructed—and these practices are perhaps more accessible to female students because of how the work and community are constructed. If science educators want to teach science that reflects how it is actually practiced, our work has considerable implications for what science teachers have to do in classrooms.

In recent years, a number of science educators have suggested that science education curricula and research could be enriched by drawing on research findings from studies of scientists and science (e.g., Cunningham & Helms, 1998; Roth & McGinn, 1998b). To provide insights for science education, these papers focused on aspects of the social studies of science including: methods used to investigate the work of scientists, the practices of the scientists themselves, and the effects on learning of considering these issues when designing learning environments. For instance, sociological and anthropological studies of science make use of models and techniques that are potentially useful to science educators including actor network theory, discourse analysis, ethnomethodology, new literary forms, and reflexivity (cf., Roth & McGinn, 1998a). A better understanding of the characteristics of scientific practice—including its interpretive flexibility, frequent modification of language games, the centrality of inscriptions, and the importance of negotiation—also contributes to a shift in how we view science classrooms, and may provide for greater authenticity and inclusiveness in today's science classrooms (Cunningham & Helms, 1998).

While this recent work on rethinking science education is of considerable importance, it also falls prey to an oversight, which it inherited from science studies. Science studies contain at least one blind spot, for the practices of field science such as ecology is dramatically under-represented (Nutch, 1996). Thus, the nature of science as it emerged from science studies focused almost exclusively on laboratory studies in the "hard" sciences, that is, in chemistry and physics. Consequently, the model of science adopt by science educators is that of the "hard"' sciences which may not be reflective of other sciences, despite significant disciplinary differences between biology and physics.

> Most programs in education research have taken physics as their implicit model for all science without considering the inevitable distortions that result when a research framework is applied to disciplines outside physics. More problematic has been the tendency for science educators to use the physics model in the development of curriculum to address issues concerning the nature of science, thus perpetuating a misunderstanding of scientific method. (Rudolph & Stewart, 1998)

This would appear to be problematic from a number of perspectives, including aspects of inclusiveness and teaching students about the nature of science (NOS). For instance, the traditional view of science has it that variables are chosen prior to conducting of a study; further, scientific research practices are held to be replicable. Yet, such a view ignores that observational studies and those involving wild animals do not easily fit into this paradigm; observational studies in biology may in fact have more in common with the social sciences than laboratory sciences (Roth, Hall, Bowen, John, & Torralba, 1999). There is some evidence that the various sciences are quite distinct. Yet many portray science more traditionally including three mistaken images: "(a) that there is a nature of science to be discovered and taught to students, (b) that a list of tenets can describe the nature of science; and (c) that for a discipline to count as a science, each of these tenets must be true of that discipline" (Eflin, Glennan, & Reisch, 1999, p. 108). Such images are often based on the way physics research is conducted, which is, coincidentally, also a male-dominated science. It is therefore of some irony that such a science acts as a model for science education. Such mistaken images of what science is like also reign in social studies of science, which has traditionally focused on male-dominated disciplines (i.e., physics and chemistry). This is not an issue without consequence. Thus, some science educators concluded that "without considering questions about the nature of science itself… it seems unlikely that improving the content of science education will help to attract or retain more women or minorities" (Eisenhart & Finkel, 1998, p. 27). Others suggest that taking laboratory sciences (especially physics) as the model for all sciences partially accounts for the difficulties encountered in the teaching of evolutionary biology and ecology in high schools (Rudolph & Stewart, 1998).

Field research in biology is often viewed as more female friendly. The involvement of women in field research changed the fundamental interpretations of nature in disciplines such as primatology with the work of well-known primate researchers such as Jane Goodall and Diane Fossey (Haraway, 1989). It is difficult to quantify the changes in gender representation in the field disciplines, as these are usually not examined separately from laboratory biology in surveys of graduate schools or employment. But our own ethnographic work among field ecologists on the American and Canadian west coasts suggests that female participation in ecology field research is quite high. For instance, at two recent ecology conferences for graduate students, about half of the presenters were female (72 of 132 and 35 of 70). This approximately represents the university population of ecologists that we have gotten to know through our own participation. It also matches the patterns in another study of field ecologists (Nutch, 1996). This more equitable gender balance in the "soft" sciences may have occurred for several reasons.

First, environmental biology is viewed in opposition to the ‘hard’ sciences (Eisenhart, 1996). Second, the soft sciences lack the oppressive supervisory and competitive structure found in the hard sciences (cf., Traweek, 1988). Finally, there are tremendous networks of relationships that lead to bonding among members and therefore cohesion within the community of ecologists (Bowen, 1999).

Some authors consider of vital importance that students have first-hand experience in field research to learn both conceptual information and practices of sampling and data collection (Gray, 1982). Not only is there evidence that ecology and its practices are poorly taught in schools, but teachers, curriculum developers, and researchers also neglect this subject by (Orion & Hofstein, 1994). Even well intentioned studies with the purpose to better educate students about ecology (e.g., Fernandez-Manzanal, Rodriguez-Barreiro, & Casal-Jimenez, 1999) often present a view of ecology that cannot be confirmed by observing ecologists at work. Given that there are almost no ethnographic studies of how field ecologists do their day-to-day work, we do not intend to criticize these science educators. To better inform science education, we therefore need more appropriate thick descriptions of scientific practices in ecology that do not underdetermine what scientists of that discipline actually do (Bowen, 1999; Gross, 1996).

Some readers may want to argue that studies of natural scientists at work should be left to anthropologists and sociologists whereas science educators should concern themselves only with the implication from the work in these other fields. However, Guba and Lincoln (1989) pointed out that transportability (which is interpretive inquiry’s equivalent to generalizability) of research claims and implications are much more viable and stable when the same research (team) conducts the studies in the different contexts to be compared. In our research program, we therefore study science as it is enacted by scientists, environmental activists, and ‘just plain folks’ in the community (e.g., Lee & Roth, 1999; Roth & Bowen, 1999). We feel that this provides us with the ground for better understanding the transportability of particular science-related practices into school contexts.

The purpose of this paper is to provide a description of typical research practices enacted in field ecology. These descriptions provide evidence of “authentic” research that goes against the traditional image of science. We provide several starting points for discussing the implications to science education from studies such as ours.

Methods: How to Observe Ecologists at Work

Over the past three years we have increasingly relied on our own ethnographic work among scientists as a resource for our science education reform efforts. Doing this work has come with a number of benefits. First, because of the lack of research on field ecology, our studies provided the necessary background for implementing innovative curriculum in middle school science. Second, because we did the research ourselves, we can test the extent to which our own descriptions carry across the different contexts. We were able to show in a number of case studies which type of practices are enacted by scientists and grade 7 to grade 8 students (e.g., Roth, Hall et al., 1999).

Data Sources

Over the past two years, we conducted an ethnographic study among ecologists, which included participation in field work, attendance at ten local, national, and international conferences, attendance at talks to interested lay groups, formal structured and informal interviews with nearly 20 ecologists, and participation in informal gatherings. To better understand the field research practices of ecologists, we participated as field assistants in two different field seasons with ecologists from several universities in Western Canadian as they conducted research projects on lizards, snakes, frogs, and birds in a mountainous area in the midst of southern British Columbia. In total we spent seven weeks as assistants working at this site as we conducted our ethnographic research. Our main informant during this time was Sam (all proper names in this study are pseudonyms), who collected field data concerning ecology and evolutionary biology of a lizard subspecies, as well as less central informants who worked on projects with other species or who were other assistants working for Sam. As field research assistants we engaged in the daily practices of research, data collection, site maintenance, etc. as directed by Sam at both the field site and the field laboratory (where lizards were housed and other data collected). Data sources from this work included extensive fieldnotes and hundreds of annotated digital photographs. In addition, we conducted formal and/or informal interviews with the various participants involved in studies in the area, collected computer scans and photocopies of paper artifacts (including data records), and made videotape records of pivotal events in the field and field laboratory.

This fieldwork was contextualized in our analysis by field notes recorded as we later attended symposia or conferences with the graduate students engaged in this field research. We interacted informally with informants at least once a week in informal settings upon return to the home university and visited various members of the community in their laboratory settings at the universities. We also observed and had discussions with members who were working as teaching assistants for various biology courses at their home universities, and conducted interviews with ecologists on their field practices. In addition, extensive (ten hours) videotaped interviews with Sam were conducted between the two field seasons regarding her research practices, the construction of claims from the data she collected, and other subsequent analyses.

To increase reflexivity of the research, we opted for a particular style of ethnography in which one investigator works on site (Bowen) and the other acted as a reflective partner from the distance (Roth). Using email, we interacted extensively on a daily basis. For example, during the first field season, Bowen daily sent materials such as field notes, photographs, and transcriptions (of video and audio materials); Roth returned more theoretically-oriented reflections and comments or requests for further data collection. Interacting like in this manner forces the “part native” on site to make explicit any of his tacit assumptions. This distribution of roles also embodied a particular form of Ricœur’s (1991) hermeneutic phenomenology which draws on the complementarity of explanation derived from critical structural analysis (here conducted by Roth) and understanding derived from lived experience (here deriving from Bowen’s participation in the day to day activities).

Analysis of Data

Analysis of the data of the ethnographic data examining field practices was conducted in both an on-going fashion and at the conclusion of the study. On-going analysis of the field data was conducted to help establish the “credibility” of claims from ethnographic or qualitative research—a parallel to internal validity (Guba & Lincoln, 1989). Two of the criteria for establishing credibility are peer debriefing and member checking and these both occurred as a consequence of the ongoing analysis of data as the study progressed. During the study, active analysis of the field data was shared between the authors so that interpretations and observations could be critiqued and further questions asked. In addition, analyses could then be checked with the member ecologists or un/substantiated with further observations. To aid this, field interviews were transcribed in an ongoing fashion and contributed to the analysis of the field observations.

Our first set of analyses were checked with our main informant after the first field season we had spent with her. During ten hours of video taped interviews, we followed up our tentative hypotheses about ecology as a field science. During these interviews, we also used graphs and other formal mathematical representations to find out more about Sam’s understanding of research methodology. Finally, we used these interviews as an occasion to find out more about Sam’s plans for the subsequent field season during which we participated again. In this way, we gained an understanding of the extent to which the research emerged in the field versus how much of it could be and was pre-planned. (Other results of our extensive study can be found in the sociological literature [e.g., Roth & Bowen, 1999a, 1999b].)

At the conclusion of the data collection (which spanned over two years), analysis of all resources (video- or audio-tapes, transcriptions, written field notes, photographs, published papers, copies of conference papers) was first conducted individually and further tentative assertions made and then checked against the data set. In this analysis, we subjected all texts to an interpretive text analysis grounded in discourse analysis, (Potter & Wetherell, 1987), semiotics (Bastide, 1990), and hermeneutics (Guba & Lincoln, 1989) of scientific texts. Collaborative data analysis then followed as we convened in joint sessions (with other members of our extended research group) to compare and critique our independently arrived at interpretations. When members agreed upon an interpretation, the entire database was then reviewed for evidence that substantiated or did not substantiate our taken-as-shared interpretation. Several such sessions in which we progressively focused our claims resulted in the information reported in this paper.

The Nature of Ecologists’ Research Practices

Two major areas of the research practices of ecologists warrant mention—those related to issues of actually conducting their research and those related to narrative exchanges important to constructing social aspects of their community. These two areas are not unrelated to each other, but are separated in our text to best allow a thorough discussion of each. To support claims we present examples found in our field notes, interviews, discussions, or presentations by ecologists.

Emergence of Field Practices

Science, particularly in its formal writings in journal articles, is presented as a rationalistic enterprise. In the past, philosophers and sociologists of science used this as evidence for the claim that scientific research is conducted in a planned, linear fashion, which has become known as “the scientific process.” In science education, this led to many teaching and curriculum practices that emphasize a similar linear form: statement of problem, hypotheses, experimental design, data collection, (inductive) data interpretation, and conclusions. In part, this linear form provides authority to the scientific text such that the knowledge claims and methodologies are beyond question. Our observations of field ecologists while they conducted and discussed their day-to-day work suggests that the formal texts of ecology do not adequately represent how field research is conducted. We noted several major practices of field ecologists that differ from laboratory sciences, especially those that are experimental.

Ecological field studies examine interactions that occur between different components of highly complex natural systems. As a result, ecology is more an observational than an experimental science. In part, this can be ascribed to the fact that ecological systems resist the reduction to a small number of factors necessitated in experimental research. This resistance arises from the difficulty of resituating experimental findings in complex systems. That is, experiments with small number of variables are seldom generalizable to natural settings as a whole and thereby negate the utility of the experimental results. (In this, ecology is not unlike education where laboratory studies conducted by educational psychologists rarely scale up to natural settings.) In addition, the results of field studies are highly contingent: the local circumstances mediate research design to such an extent that the techniques and approaches useful in one setting may be inappropriate in another. This contingency means that ecologists can rely less on standardized practices than laboratory scientists who frequently follow strict protocols (the model for school science laboratory activities). (Ample research shows that even with strict protocols, there is so much contingency in the laboratory sciences that protocols do not lead to the same practices in two different laboratories even if the same researchers are involved [e.g., Collins, 1982; Jordan & Lynch, 1998; Knorr-Cetina, 1981].) This has several consequences for the conduct of ecology research. In the following, we discuss four salient properties of ecological field research that differ from the traditional image of scientific process. Thus, (a) research design in ecology has an emergent character, (b) tools are highly context-specific, (c) the most important variables often emerge *after* the research has started, and (d) studies are not easily replicable because of the dynamic nature of ecological systems.

Emergent Nature of Research

Ecological field research is highly contingent. This often means that studies must be designed specifically for each setting, and this design only emerges from the activities as researchers spend long periods of time making extensive observations of their setting. For this reason, graduate students are expected to work several years in the field. Masters-level students usually spend two seasons and Ph.D. students spend three or four seasons in the field before they can aspire to writing their theses. (Sam, our primary participant, was in her fifth and sixth field season.) As ecologists engage in prolonged observations, various features and interactions within their field setting become more salient to them, and from this they then begin to ask specific questions (or identify variables) about which they begin to record data. In this, mature researchers in the field differ little from the grade 8 students in one of our projects who, as they became increasingly familiar with their research, conducted projects with up to three dependent and three independent variables simultaneously (Roth & Bowen, 1994). Lack of familiarity with a setting (not unlike that experienced by students when facing a new project) require prolonged periods of observation so that salient dimensions can be identified. For example, an ecologist—known for his research on salmon and forest in the Pacific North-West who had already spent some 20 years in the area—describes the emergence of variables for a new project after he spent several days just walking around. During these days he simply observed the bio-diversity in one estuary and stream:

> Looking at sort of all utilizers of salmon, all the species that utilize salmon, and the consequences of how these salmon are used and what this means actually for forest bio-diversity. And this was one of the unexpected, serendipitous observations that came from this initial interest—we began to focus on bears because they were one of the major consumers of salmon. We actually looked for bears in the daytime and they're not present in the estuary at all. From seven o'clock through to about three to four o'clock in the afternoon, no bear is ever on the estuary despite the prevalence and abundance of salmon everywhere in the estuary. Come twilight, rustle, rustle out of the forest comes the first bear, and five minutes after night you have the maximum number of bears feeding and throughout the night these bears are capturing salmon.

Even as he becomes familiar with the estuary and stream, new research questions emerge and with it, new research designs that focuses the ecologist's observations and permits new variables to emerge. Sometimes ecologists enter the field with a general question. Thus, before Sam went into the field, she asked “What is the natural history of a species of lizard?” However, as we participated as field assistants, we observed many variables become salient that had not been pre-determined. Thus, it was only after she had been at her research site for some time that Sam constructed “lizard color” as a salient variable that she should measured. Only in her second year did she construct and attend to the “distance between a capture site and the nearest rock pile.” Also, the “effect of time in captivity” and “type of housing” became salient only during the intermittent period between year one and two of her study. All these variables emerged during the research process, but were presented during conferences as if they had been there all along.

In another instance well documented in our data base, the salmon and forest researcher in the Pacific North-West, the focus of research became the bear-salmon interactions as a consequence of observing how often bears predated salmon. Originally, he had attended to neither species but had a long standing, two-decade old research on some stickleback species. However, the new interest sparked by incidental observations led to extended observations on the bear. From these observations, he began to formulate a new research agenda during which specific variables emerged again over the course of several years of explicitly focusing on the salmon-bear interactions. This is illustrated in the following excerpt:

> If it’s a male [salmon], it takes the brain and the back, but one tissue that the bear will not feed on, that the bear will **not** feed on, are the testes. And what you find when you walk through the forest, are testes strewn around every tree. Bears, for whatever reason, do not like testes. What a nice bonus that is for a biologist. You can pick up these white sacs, and think there’s got to be some information there, but is this sac half full? Is it 3/4 full? How do we figure this out? Well, we can go down to the estuary and all those salmon that got stranded and were dead, we cut them open. These were all pre-spawned, and here’s a male with a great giant sac of testes, 3.1% of the bodyweight. So we can also go into the river and look at the bottom of these pools where spawned out salmon accumulate, these sort of rotten carcasses. We can cut them open and here’s this little sac, this empty sac. This is spawned out. This is 1.1% of the body weight. So out here in the forest where the bears only left us a bit of the jaw, the odd bit of muscle tissue, and the testes. What do we do? Well, we can weigh the testes. We can then figure out the pre-spawned testes’

> weight. We now measure the jaw, we then look at our conversion of what that salmon originally weighed, and then we can determine the portion of testes that remain.

The researcher did not begin this study with a focus on bears or expect bears to carry salmon into the woods, to find “testes strewn around,” or to stumble upon salmon jaws left behind. As this ecologist spent time observing the artifacts left behind by the bear, he developed data which could be correlated and thereby construct new knowledge about the natural conversion of biotic energy sources (salmon) by complex chains of interacting events and organisms. He became so interested that he decided to develop this into a new research project.

In both examples, the lizard and salmon-bear projects, important aspects of the research—specific variables—emerged from tentative observations and became increasingly salient with the familiarity of the researchers as they spent years in their ecosystems. This emergent aspect of fieldwork makes it necessary that researchers learn to adapt their day-to-day plans to local and temporal contingencies. That is, ecologists have to be flexible to deal with the particulars of their setting including the unfolding climatic conditions that mediate what they can do at any single day or season. One of our informants spent an entire summer in an area that was turned into a swamp by constant rains mediating what data he could collect. Individuals who found themselves unable to deal with these constantly changing conditions were considerably stressed and sometimes abandoned a project and even their graduate work. Being flexible and being able to adapt research plans to changing situations (such as weather) is a necessary skill for a successful field biologist.

In summary, then, research in field ecology often emerges as researchers become increasingly familiar with their site rather than existing a priori. In contrast, science educators (e.g., in the curricula that focused on “scientific processes” such as SAPA) traditionally accepted research as an entity that pre-dates research and can be easily identified by just looking at the system. (For a critique of this position see Roth & Roychoudhury, 1993.) If students are to experience the nature of science first hand, these findings therefore imply that students be provided with sufficient time to become familiar with a system and construct salient variables as part of an ongoing process.

Tools are Highly Context-Specific

Based on our observations of field ecologists we arrived at the conclusion that tool use is complicated by unexpected and unpredictable conditions in which researchers might find themselves. This often means that field ecologists need to adapt local resources for their research purposes. For instance, our lizard ecologist Sam noted in the course of her project substantial differences in skin color of her animals. She had the hunch that skin color may mediate the interactions with other lizards and predation (more visible lizards are less likely to survive). She decided to determine (perhaps even measure) skin color so that she could gain additional insights. In the remoteness of her research site, she attempted to collect some initial information with the resources at hand in a small nearby town. This meant that her ability to obtain tools were limited both by budget and her location so that she tried to *make do* (Harper, 1987) with those resources actually available. In the following field note, we captured her effort in quantifying the skin color of lizards, which she wanted to monitor over time:

> She first tried taking pictures, then shifted to “paint chips” (i.e., strips of paint color for color matching in homes) from the local hardware store. However, the pictures were unreliable from day to day, and the paint chips did not have sufficiently subtle variations to label lizard color accurate enough. In addition, she felt labeling lizards as “forest tan” or “sand” inappropriate for a “scientific” research project. When she shifted to using Munsell soil charts during the following year, she took the idea from a paper that looked at changes in color in the throat of a chameleon. However, the ranges in color categories used by the authors in the article were considerable, but in her lizards the color difference was tiny. She needed the finest determination possible so that she wanted to work with the numbers. She talked her supervisor into buying Munsell soil charts that allowed her to quantify lizard color.

In this case, we see how tool use changed in the course of the investigation. The Munsell soil charts came into play only during the subsequent year and only after she stumbled over another piece of research that had made use of this tool. Munsell soil charts are standardized colors which give quantify hue, value, and chroma of each color. This demonstrates that tools are used as necessary to accomplish a task—in this case, a color scale intended for using with soil was adapted to use with lizards. However, even this standardized tool did not immediately lead to a standardized practice. Repeated attempts to make color determination consistent (using both within and across rater reliability) showed a great variability in the assessments. Similar to the difficulties in other research projects, standard tools do not necessarily lead to standard practices (e.g., Jordan & Lynch, 1993) so that researchers have to work with others who are already experts at using the tool. However, in her isolated camp Sam did not have this option. If she wanted to get anything done, she had to find in her own activity a way that reliably assessed color. In her effort, Sam did not need to meet some arbitrary or external protocols or standardized practices, but instead needed to be able to convince others that her practices made the most sense in the context where she worked:

> Sam then set up for doing the color analysis of the lizards. Color analysis takes place in a box placed sideways with a clip-on lamp designed to maintain consistent light for day-to-day consistency and the Munsell chart standards are placed in the box. Sam brought over her first lizard and asked Stephanie to record the numbers. Sam first called out a number representing the percent black, and then laboriously examined the lizard against the color standards. She moved the lizard back and forth from hole to hole in the Munsell chart, and switched cards three or four times until she finally announced numbers representing hue, value, and then chroma based on the closest color match to the lizard. She recorded the temperature of the room within a few minutes of measuring the lizard and again some time later (about 1/2 an hour) after recording the color. Sam was concerned that dirt and dust affected the skin color so that, after doing a number of lizards, she began wiping them before the actual determination. But then, she noticed that the lizard was about to shed and decided to keep track of shedding schedules—to see if that was related to basking behavior and the color. Yet another variable has emerged.

This excerpt also offers further examples of the emergence of variables as further observations were made as the research unfolds. In developing practices related to color measurement, Sam was constantly aware that she would have to justify her decisions to both peers and more seasoned field researchers. She therefore spent considerable time attempting to make her methodological approaches as well-grounded and seen-to-be-sensible as possible though it was also clear from our observations that audits are never conducted because they are too labor intensive and time consuming. Yet in her effort to accountably determine color emerged her new concerns about temperature and shedding because of their possible effect on color.

In summary, then, not only variables but also how they are measured—that is, their operationalization and tools used to implement it—have an emergent character. What and how something is measured therefore does not pre-exist the phenomenon, but emerges with the phenomenon. In this, field ecology shares a family resemblance with cutting-edge research in particle physics where tools and phenomena emerge together in a mutually constitutive fashion (e.g., Galison, 1997), a phenomenon that has been described as a “mangle of practice” (Pickering, 1995). As previously, if students are to experience the nature of “authentic” science, there should be opportunities for them to engage in the re/construction of tools that construct and measure the phenomena that they are after. (“Open-inquiry” environments provide such opportunities, and there exists at least on description of the activities of high school physics and chemistry students who designed and build their own equipment [Roth, 1994].)

Significant Variables often Emerge from the Research

During our work among field ecologists, it became increasingly clear that their field practices were little driven by theoretical discourses in the field of ecology (see also Roth & Bowen, 1999a). The measurements they made were less driven by local or global theories and more because it was possible to make them. Thus, lizard tail length, arm length, leg length, and body length were measured first because they were measurable. Variables came into being not on conceptual grounds but—somewhat tautologically—because instruments found use in the particular context. These variables developed increased significance only later when Sam found that they were reliably correlated with other factors as shown in her statistical analyses conducted during the winter after the second field season.

> *Sam in the field laboratory, timing lizards as she chases them along a racetrack* ‘I don’t know if I will be able to use these speed measures, but I do it anyway. Maybe there is something, maybe not.’
>
> *Sam presenting the results of her work in a colloquium:* ‘And it turns out the longer the lizards are kept in the lab, the slower they run. Which is kind of interesting, but I can statistically control for this effect and go on to look to see if there are other things that are important. And it turns out there are. One of the things that’s important is what sex you are. Adult males are typically shorter than adult females, uh, their body lengths are shorter. And adult males also have relatively longer back legs than adult females. And it turns out that this body length and back leg length is important for predicting how fast it runs.’

Thus, variables gained their (new) significance as correlations between measures, which were originally conducted for different purposes, are brought together analytically. Sometimes, such a new variable emerged during statistical analysis when the expectations about correlations were not met. For example, Sam pursued the hunch that leg lengths and spring speeds are correlated. However, her initial statistical analysis did not support this hypothesis. Then, and based on remembering a single observation of a female lizard being particularly slow after five days in captivity, Sam decided to run the analysis again, this time controlling for time in captivity. Lo' and behold, the sought for correlation became statistically significant. In this way, a record that she had kept only incidentally—the days of capture and measuring sprint speed—allowed her to calculate days in captivity which then became another salient variable. Although this variable did not exist while we were in the field camp, it was certainly salient during the presentation Sam later gave and from which the above excerpt was taken.

Ecologists engage in exploring data in a manner that allows them to find relations between variables that they had not previously considered to be of any importance to each other. From such a statistical study, Sam concluded that body size and leg length were significantly related to the speed at which a lizard could run. Furthermore, "outliers" also provide ecologists with information which affects their analysis and interpretations. Our field notes describe how an accident in the laboratory, which resulted in a lizard becoming an outlier (i.e., a notably distinctive individual) in Sam's data set, resulted in her further investigating what she concluded was a significant relationship:

> Sam was in a buoyant mood because she had <u>finally</u> found a strong statistical relationship between the factors she had measured "and what determined litter size." She said that the key was the female lizard that she accidentally tore the tail from. Based on this one observation, she created the hypothesis "the more you invest in your tail, the less you invest in your kids" which was confirmed by statistical analysis.

That is, based on the observation of a single female lizard who had lost its tail during capture, Sam came to think that the more energy is spent on building a tail or building fat storage (in the tail), the less energy there is for growing off-spring. This and previous examples illustrate that analytic approaches in ecology are also emergent unlike the hypothesis testing of experimental results promoted in laboratory studies. It is important to note that these emergent practices are strongly contraindicated in the writings of ecologists. For instance, in journal articles one might be led to believe that variables and analytic methods pre-dated fieldwork. Our observations suggest that this is a stylized construction intended to lend authority to the eventual claims made from those studies. Similarly, our observations of field ecologists while teaching university classes show that they maintain the classical image of a science. Strikingly enough, the very researchers whom we had observed constructing variables in an emergent fashion suggested in their university teaching that variables and analytic methods pre-dated research. That is, we observed a stark contrast between how ecologists conducted their research and the way they presented it in their formal texts and in their lectures to future biologists.

Ecological Studies Are not Replicable in a Strong Sense

Science is often presented as only being able to draw claims from studies that are replicable. Yet, such is not possible in ecology research for several reasons. First, local environmental conditions, although they may be similar from year to year are never “the same” and thus studies conducted in later years may or may not come close to the claims of the original studies. Secondly, studies of ecology often involve data collected from individual organisms and thus variation in the population (behaviorally, genetically, etc.) might result in differences. Even in situations in which the same individuals are available (such as in studies where all members of a population are known and identifiable) those individuals change from year to year due to aging and changes in the local context (predator numbers, food availability, etc.). This changes the organism-environment unit which, according to many biologists, is irreducible (e.g., von Uexküll, 1973) so that even research with individual organism is not replicable in a strong sense. Finally, the emergent nature of ecological studies also undermines the concept of replication. For instance, in the study with lizards Sam was concerned that the size of her enclosures in the first year of her work dramatically affected the stillborn rate of her pregnant females. Sam therefore altered the enclosures in the second year. Thus, in some aspects it was not possible for her to compare her findings from the first year from those in second and third (although she could statistically control for some of these differences). As another example, the earlier mentioned ecologist who spent a summer in a waterlogged area found entirely different, drier conditions during his second year. Thus, though the site and researcher can be considered under some aspects as “the same,” the organism-environment units he studied were not the same at all.

Published journal articles are also of little help here because they detail only surface aspects of the conduct of fieldwork (see Bowen, 1999). Therefore, even if the other problems related to replication did not exist, the methodology sections of journal articles are insufficiently detailed to follow prescriptively to replicate field research. At best we are forced to the conclusion that “in contemporary reports the possibility [of replication] has replaced the fact of replication” (Gross, 1996, p. 87). It generally appears a stronger statement than that to which much of ecology research could aspire.

Interactions Foster a Sense of Community

The field of ecology is strongly characterized by the role of anecdotal narratives to the knowledge and social cohesion to the community of ecologists. Shared anecdotal narratives are an important way in which they develop their insights into ecological situations. For ecologists, “anecdotes” are important observations, insights, or experiences they have had that nevertheless do not fit the structure of scientific writings (whether stylistically or for reasons of insufficient data) that they nevertheless feel are important enough to warrant communication to other ecologists. The following field note excerpts detail how a conversation in an informal setting (over lunch) between two ecologists who work on different organisms provided each further insights into their own work:

> **Ecologist 1:** Described how he could wade into the stream and literally “pet” the fish which hardly moved. He said this was quite different from how they behaved in the daytime where they would impossible to approach and reacted to any shadows or movement near them. He speculated that this might have something to do with the seals. At night, water is slightly phosphorescent and movement of the fish would lead to them showing a glowing outline, possibly visible to the seals waiting for the salmon in the mouth of the estuary. It would therefore be better for salmon to move as little as possible at night (in evolutionary terms, they would likely be selected for not moving at night).
>
> **Ecologist 2:** The ecologist told a story about radio-tracking porpoises and not being able to figure out why they logged [seemed not to move] at the surface at night time until they had one in captivity in a large salmon net and watched him doing the same thing. When he moved his outline was quite noticeable and sharks, which are major predators of porpoises, might have cued in on this.

These anecdotes describe field observations and interpretations of them that provided insights into predator-prey relationships; but were not the sort of thing reported in a journal articles. However, these individual field observations and interpretations gained more significance when combined and contributed to the broader ecological understandings amongst the ecologists socializing in that group.

Our observations suggest that ecologists spend a considerable amount of time socializing with each other, and that often the socialization involves discussion not of knowledge claims, such as found in journal articles, but of their own diverse practices and observations. It is in this manner that ecologists develop a repertoire of methodological approaches to use in the field settings and learn to focus their attention on different aspects of the settings they are studying. Thus, for ecologists, narrative exchanges, particularly in informal settings, compensate for the manner in which formal writings are styled for publication.

Sharing heroic stories as part of these narrative exchanges also contributes to the social construction of the communities of ecologists. These are not heroic stories in the classic sense they are used in science education (See Milne, 1998) but are rather tales of personal experiences. Although these heroic stories may relate dangerous situations or deprivation, they may also be presented as descriptions of adaptation of research plans to unforeseen challenges or other such accomplishments. (For the role of the physical and emotional duress of fieldwork in ecology see Roth and Bowen, 1999b.) Stories that relate tales of the field often are presented in an allegorical fashion so as to offer the listeners guidance as to what practices should or should not be used when conducting field research. The following excerpt from a conversation between two ecologists exemplifies a heroic story:

> Mandy: I slipped off a log when marking a trail with orange tape and fell onto my ribs across another log and fought for consciousness and then passed out. I awoke 15 minutes later with my face buried in the moss, draped over a log [described this very dramatically] almost unable to breathe or move. I painfully made my way out of the woods, which thankfully I was only into 100 meters, to my truck, and then drove to my camp. It took my camp partner three hours to drive me to the hospital over the logging roads with every bump causing me to stop breathing because of the pain and they kept me off work for ten days.

After she concluded her story, the other ecologist asked if she had spikes on her boots, to which she replied “No.” The other ecologist berated her for that and for not having other safety equipment with her. This equipment would have allowed her to call for help after she had woken up even if she was unable to make it to the road on her own. The other ecologist then related a tale of his own on surviving in the woods.

Field ecologists constitute their community and establish who is a member in that community through sharing common experiences and interconnecting stories about diverse field observations that complement each other. The type of “shop talk” found in laboratory settings (Lynch, 1985)—the discussion of work practices and interpretations as it is occurring—happens much less often in ecology because ecologists spend a substantial amount of their time working in settings far away from their home university and other ecologists. Thus, social interactions between ecologists in informal settings is an important component of the successfully doing field work—in many ways as important as the formal writings of the discipline.

In summary, the field of ecology is characterized by fieldwork narratives that both communicate knowledge (e.g., about ecosystems, research methods, and safety) and provide clues to the degree (in the sense of legitimate peripheral participation [Lave & Wenger, 1991]) of membership in the community. If students are to experience ecology as in the way it is practiced on a day-to-day basis, curricula (planned and enacted) need to provide for opportunities of exchanging and learning from research narratives of other students.

Conclusion

In this article, we identify and describe several properties of ecological field research that differ from the traditional image of scientific research. We highlight the following as characteristic features: (a) the design of research in ecology has an emergent character, (b) tool use is contingent and involves adaptation of tools, (c) salient variables often emerge *after* the research has started, and (d) studies are not easily replicable because of the dynamic nature of ecological systems and what phenomena within them interest ecologists. In addition, fieldwork narratives exchanges have a central role of making knowledge available to others and as way of bonding members into a community of practice.

The details of the practices of ecology research related above present a science that differs from the (hegemonic) descriptions of typical Western science. Our descriptions differ in ways that may offer particular advantages to female students. These differences may well explain the high proportion of women working in the discipline. Female students may therefore be more interested in this “soft” science in which members of exhibit a “feeling for the organism” that provides a considerable foundation for understanding more abstract representations of animals and ecosystems (Roth & Bowen, 1999b). Beneficial outcomes in studies of science for young women have been described when their research projects were structured to offer the opportunity to be creative and alter research approaches as studies progressed and to investigate issues about which they were concerned (e.g., Richmond et al, 1998). The practices of these young women in many ways paralleled those of ecology researchers who we observed in our ethnographic work, especially with regards to the creativity and individuality of the projects. For us, this is what represents science—opportunities for creativity and individuality—although perhaps a science that lies in opposition to the laboratory and physics-based constructions of science used in science education.

Better understanding the practices of ecologists also provides more flexibility for teachers who want to engage their students in practices that fall outside of the typical conceptions of science practices. Understanding fieldwork practices provides teachers with a model of science that is based on emergent designs and variables, the development of tools (which are scientific because of their use, not their original design), and the importance of communities that spend considerable time sharing practices and stories about their research. In essence, by being able to draw on examples of ecologists teachers are better able to present these practices as valid science.[1] If apprenticeship models in science education are to be successful—such as some researchers have called for (e.g., Brown, Collins, & Duguid, 1989; Richmond, 1998; Roth & Bowen, 1995)—science educators have to better understand the scientific practices of all disciplines of science for the design of those programs. We cannot model all science teaching on a few laboratory sciences (especially physics) and continue to believe that we are offering a science for all. Understanding the practices of ecologists is an important step to elaborating the practices found in field-based research which have been long ignored in our classroom curricula.

Implications for Education

Teachers do not just act as knowledge resources, but also as validators as to what is acceptable knowledge. However in ecology, and science in general, there is no single arbiter of what knowledge claims are acceptable. Sam felt herself accountable in her practices first to her

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[1] Such a proposition may sound trite, but in our own work as teachers we have both encountered opposition from parents and administrators who did not accept that engaging in practices such as this actually constituted “science.” By illustrating that scientists such as ecologists actually engage in practices of this sort we hope to have provided teachers some material for rhetorically engaging with objections of this sort.

peers and supervisor, and then to her broader community. We can understand such a community as a community of validators in which members develop a taken-as-shared view of interpretations and knowledge claims (Cobb & Bauersfeld, 1995). Students, however, experience decisions about correctness of data in ways which do not capture this type of community, instead either relying on external authorities (such as the teacher), acceptance of all ideas, or democratic majority votes (Vellom & Anderson, 1999). For teachers to view knowledge in a manner in which they are less central requires them to relinquish some control and authority, but this would help students develop more realistic conceptions of knowledge and science.

The context of field ecology research differs from many other sciences because it involves settings about which the participants initially have little embodied knowledge. The knowledge resources found in laboratory settings (such as experienced researchers, detailed written resources, and considerable equipment) are often absent, and communication between the field setting and those knowledge resources is difficult. In many ways this resembles the settings in which teachers, especially middle-school teachers, find themselves teaching—for the settings in which they teach often lack science subject matter specialists and adequate science equipment or textual resources. The remote settings in which ecologists conduct their work explains, in part, why they interact socially to such an extent: They need to rely on the knowledge of their peers as a resource for conducting their work. In school settings providing students space (both time and physically) to discuss their research practices, such as ecologists do, would allow them the opportunity to rely on knowledge other than that gained from the two traditional knowledge resources in the classroom, the teacher and textbook. Providing students with opportunities to work on research projects that differ within and between classrooms would allow them to develop a repertoire of experiences which would foster conversations which dealt with their projects. It is not much of a leap to consider so-called off-topic conversations as the result of a lack of a diversity of experiences. Asking all students to work on the same project removes the opportunity for them to develop a social community around their scientific practices and investigations such as that found amongst ecologists.

In ecology even experienced researchers spend time observing their research settings before focusing on the specific questions they are going to address. In schools however, students are often given little time to gain any observational experiences of phenomena before they develop research questions, and all too often what questions they are to address are provided to them.

Yet, prolonged observation might well lead them to recognize that variables are developed from both disciplinary and personal interests, not that they exist transcendentally ‘in the ether’ without human influence. We described exactly these outcomes when students work only over a period of 10 weeks in the same forest developing research questions from their own interest and only under the constraint that these questions and the research has to be convincing as judged by their peers (Roth & Bowen, 1995). Similar benefits could arise when students are empowered to develop their own questions, their own variables, and their own interpretations. In this type of setting, teachers could act more as facilitators of practices than as instructors. Teachers working with students in a type of “cognitive apprenticeship” offers considerable advantages for the knowledge gains made by the students.

In particular, developing in students an understanding of how scientific claims are developed by engaging them in activities such as those that we observed among ecologists would help them understand that such claims are not irrefutable and “provable beyond a doubt using empirical data alone.” This is especially important given that they may one day be responsible for communicating the ideas of science to others (Ryder, Leach & Driver, 1999). Students seem to expect that the primary way in which consensus is reached in science is through experiments that provide unambiguous answers (Larochelle & Désautels, 1991; Ryan & Aikenhead, 1992). This makes it more difficult to teach science (successfully) whose data often contain substantial variation including animal behavior, ecology, and evolutionary biology (Rudolph & Stewart, 1998). Engaging in ecology research projects would provide students the opportunity to learn that unambiguous relationships are uncommon in many scientific settings. Students would gain if they came to understand the limitations of scientific claims, especially the variability in data that often underlies even the strongest of scientific claims in biology. Such work by students could also help them to better develop their understanding of scientific theories, since many scholars maintain that understanding scientific theories, inscriptions and claims cannot be separated from the context of their production and use.

Studies of classrooms which have been structured to encourage students to develop a micro-culture similar/congruent with that found in scientific communities are not very common (e.g., Roth, 1998; Vellom & Anderson, 1999). However the few existing studies suggest that students are capable of developing rhetorical practices and problem generating and solving practices demonstrating the generation of scientific knowledge quite different from the re-presentation of the authoritative claims of teachers or textbooks. These studies also make clear that such approaches are time consuming compared to the so-called efficiencies of regular curricular approaches but argue that the outcomes, especially with regards to implicit and explicit understanding of scientific endeavors—and thus what we would call scientific literacy—outweigh that cost.

We have already conducted one study in which we both taught and researched a unit on ecology in the way proposed here (e.g., Roth & Bowen, 1994, 1995). However, this study was conducted in a private school, which perhaps limits the transportability of our findings to other contexts. New research needs to be designed—best perhaps as "design experiments" (Brown, 1992) that we had chosen and that allows ongoing adaptation of the curriculum—to allow further descriptions of the affordances and constraints to learning and equitable participation in science. In such studies, answers to the following pressing research questions may be found. "How does 'authentic' ecology research support/constrain science learning of middle and high school students?," "What are the preferred ways in which different [e.g., gender, cultural origin] students present their research results?," "How do patterns of participation for female students change when the learning environment fosters 'feeling for the organism' and holistic understandings?"

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