Investigations of the Wild: The Development of Students' Scientific Practice and Knowledge During Ecological Fieldwork

By

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DEDICATION

For Matthew. Who always broke the trail.

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This dissertation would not have been possible without the many people who have stood beside me throughout this long labor. My family and friends. My cohort and colleagues. My advisor and mentors. This work stands as a testament to your generosity and your guidance. Thank you for speaking into my life and shaping my journey.

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INTRODUCTION

Two questions frame much of the discourse around formal K-12 education: “What should students learn?” and “How should we support students’ learning?” These questions evoke the fundamental purpose and structure of education. This dissertation examines how the discipline of science education might answer these questions. More specifically, it uses the lens of field ecology to explore what are worthwhile targets for students’ learning of science and how we can design learning environments that support student development in those targeted areas.

Throughout the dissertation I adopt a science-as-practice perspective to investigate these questions. This perspective maintains that doing, teaching, and learning science is fundamentally about participating in the various means by which scientific knowledge is constructed (Hodson, 2014; Knorr-Cetina, 2009; Osborne, 2014). Thus students should not just be memorizing the theories and models produced by science. They should also be learning how to participate in the practices by which scientists develop and use such products (Kelly, 2011; National Research Council, 2012). This involves the evolution of practice in response to evaluation and critique as students develop ways to explain nature better (Ford, 2015).

However, even if one begins with the assumption that scientific practices are worthwhile targets for student learning, this still leaves many unanswered questions (Stroupe, 2015). Which scientific practices should education focus on? What are appropriate student approximations of these professional practices? And how do specific elements of a learning environment support students’ development of these approximations of practice? This dissertation wrestles with how to answer these questions when engaging students in ecological fieldwork.

Two open areas of research motivated the design of the dissertation. The first stems from our current understanding of the discipline of science. At present, the dominant story of scientific practice under-represents field-based domains such as field ecology (Gray, 2014; Korfiatis & Tunnicliffe, 2012). Our image of science has primarily been informed by laboratory-based domains that privilege experimental evidence (e.g., Knorr-Cetina, 2009; Latour & Woolgar, 1979; Nersessian, 1984). Consequently, there is a need to detail the aspects of scientific practice that seem particularly amplified in domains like field ecology (Stroupe, 2015). The second open area of research focuses on the types of learning environments emphasized in science education. Current research in ecology education often privileges designs in which students are working with simulations, gaming technologies, or large-scale data sets rather than natural settings (Basu, Sengupta, & Biswas, 2014; Bestelmeyer et al., 2015; Hmelo-Silver, Liu, Gray, & Jordan, 2015; Stevenson, Klemow, & Gross, 2014). Though such learning environments can support students in developing sophisticated practices of data analysis and argumentation, they often focus on bounded forms of data in which pertinent variables and measures have already been established. This minimizes the learning opportunities students have to wrestle with the complexities of how scientific data is constructed (National Research Council, 2012). In contrast, ecological field research has the potential to promote the development and adaptation of students' scientific practice as they construct data from complex unbounded systems. However, there is a need to empirically tease out how to design student encounters in ecological settings so that such practice can develop.

This dissertation consists of three papers that collectively investigate how to support student learning within the domain of field ecology. Although each of these papers can stand on its own, the papers share key foci and trace a temporal progression of research and theory development. Three themes best demonstrate the unity and development across the papers. First, although the primary actors vary across the dissertation, each paper is grounded within the disciplinary context of field ecology. Thus they focus on scientists or students who are studying, under field conditions, the abundance and distribution of living organisms and the relationships within and between these organisms and their environment (Bowen & Roth, 2007; Korfiatis & Tunnicliffe, 2012; Lefkaditou, Korfiatis, & Hovardas, 2014). Second, each paper emphasizes one or more aspects of scientific practice. As described earlier, scientists form an epistemic community of practice with disciplinary specific ways to construct knowledge (Hodson, 2014; Kelly, 2011; Knorr-Cetina, 2009; Latour & Woolgar, 1979; Lave & Wenger, 1991; Nersessian, 1984; Sandoval & Reiser, 2004). Thus each paper focuses on how one or more scientific practice unfolds during ecological fieldwork. And third, when viewed collectively these three papers trace a temporal trajectory of design research in which the conjectures and learning environments iteratively build upon prior findings (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003).

The first paper, *Wild Designs: The practice of field ecology and its implications for K-12 science education*, probes the nature of the practice of field ecology and the forms of learning environments that might potentially support students in this practice. As the story of scientific practice has emerged primarily from studies of laboratory-based science (e.g., Knorr-Cetina, 2009; Latour & Woolgar, 1979; Nersessian, 1984), questions have recently been raised about whether the representations of practice dominant in science education adequately capture the full scope of scientific activity (Gray, 2014; Korfiatis & Tunnicliffe, 2012; Stroupe, 2015). Though similarities extend across all scientific disciplines, field-based domains such as field ecology privilege different elements of scientific practice than those highlighted in the laboratory. This paper expands the discussion of scientific practice by synthesizing what research studies have uncovered about how ecologists construct knowledge in field settings. The findings highlight the primary practices of field ecologists and the ways in which the nature of field settings shape these practices. The paper concludes by suggesting design principles for engaging K-12 students in these ecological practices.

This first paper uniquely focuses on the practice of professional ecologists, rather than students, and is based on a review of literature rather than empirical work. Because it presents an argument for the complex means by which ecologists construct knowledge in field settings, this paper also takes a broad view of scientific practice. Within the trajectory of the design study this paper provides the grounding for important approximations of ecological practice to target for student learning and the rationale for initial conjectures about how to design learning environments to support the development of such practice.

The second paper, *Sampling in the Wild: How attention to variation supports the development of middle school students' sampling practice*, focuses specifically on how student encounters with variation during ecological fieldwork advance their sampling practice. In ecological fieldwork variation cannot be ignored. As soon as ecologists step into the field they are confronted by different forms of variation that they must wrestle with and interpret in order to make sense of the system (Pickering, 2010). For professional ecologists this struggle has informed the disciplinary evolution of the practice of sampling (Coe, 2008). Students, however, are rarely invited to grapple with the complexities of such practice. Thus it is not yet clear what impetus might prompt students to similar shifts in sampling practice. This paper describes a design study in which two classes of sixth-grade students spent approximately three weeks investigating a local creek. The goal of this design study was to better understand how students' sampling practice develops within the context of ecological fieldwork. The analysis draws on focus student interviews, pre/post tests, student artifacts, and video recordings of classroom activity to identify and trace shifts in students' sampling practice across their investigation of the creek. The findings suggest three ways in which students' attention to variation within the context of their ecological investigations supports their development of a more sophisticated practice of sampling.

In this second paper, the focus of the dissertation shifts to understanding the ecological practice of middle school students instead of professional ecologists. The focus also narrows to an empirical investigation of one specific practice within field ecology, that of sampling. This enables the paper to advance the trajectory of the design study. It takes one of the initial design principles that emerged from the first paper's analysis of ecologists and traces how this plays out in student learning.

Finally the third paper, *Disciplining the Wild: The co-development of students' scientific knowledge and practice during ecological fieldwork*, explores how students' ecological knowledge and practice writ large develop during fieldwork. Though we sometimes frame knowledge and practice in disjointed ways, they are in fact intertwined in scientific endeavor (Ford, 2015; Ford & Forman, 2006; Latour, 1999; National Research Council, 2012). Conceptual understandings develop through participation in scientific practice, and new conceptual resources propel the refinement of practice. This paper details the second iteration of a design study in which two classes of sixth-grade students investigated the ecology of a local creek. The goal of this iteration was to better understand how students' ecological knowledge and practice co-develop. The analysis draws upon interviews, written artifacts, and video records of practice to develop a case study of student development at key moments in the instructional design. Of interest are the broad forms of scientific practice that students engage in as well as the different conceptual resources that students recruit and build across the design.

This third paper maintains the empirical focus on students that was begun with the second paper but widens the scope of research to examine more aspects of scientific practice. It also stands alone as the sole paper within the dissertation to explicitly explore the content knowledge that develops alongside practice. Within the trajectory of research, it builds on work laid out in the first and second papers by investigating refined conjectures about how to support student learning. It leverages a case study of students at the individual and team level, a form of analysis not employed in the earlier studies, to more closely detail how revised elements of the learning environment interactively support multiple aspects of ecological knowledge and practice.

As a set, these three papers contribute to current issues and trends in science education by detailing the opportunities that are made available through ecological fieldwork for engaging students in scientific practice. They offer an image of science rooted in complex systems of investigation and illustrate how students might access ecological practices. In addition, they propose ways in which the design of learning environments might be influential for student development of these practices. Science educators know that students need opportunities to develop scientific practice by planning and carrying out investigations in natural settings outside of experimental laboratories (National Research Council, 2012). However, we are not always certain how best to structure such inquiry. This dissertation explores the rich opportunities that purposefully designed engagement in ecological fieldwork can create for students to meaningfully wrestle with the construction of scientific knowledge and practice.

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CHAPTER I
WILD DESIGNS: THE PRACTICE OF FIELD ECOLOGY AND ITS IMPLICATIONS FOR K-12 SCIENCE EDUCATION

Introduction

In the past decades K-12 science education has shifted its focus from how students learn the products of science - its fundamental facts, theories, and models - to also consider how students learn to develop and use such products (Kelly, 2011; National Research Council, 2012). This new era of epistemic inquiry aims for students to approximate the authentic practice of scientists as they participate in the reasoning and discursive processes involved in making scientific knowledge (Engle & Conant, 2002; National Research Council, 2007; Sandoval & Reiser, 2004). However, an emphasis on scientific practice raises a crucial point for those designing K-12 learning environments. If the aim is to support students in productive disciplinary engagement in science, then educators must carefully consider what view of the discipline they bring students into contact with (Engle & Conant, 2002; Hodson, 2014).

Recently questions have been raised about whether current representations of disciplinary practice in science education adequately capture the full range of scientific endeavor (Gray, 2014; Korfiatis & Tunnicliffe, 2012). At the heart of this debate is the question: "Whose science practice should be privileged in learning settings?" (Stroupe, 2015, p. 1036). Historically the story of scientific practice has primarily been informed by domains of science that privilege experimental evidence, domains such as laboratory-based biology and physics (e.g., Knorr-Cetina, 2009; Latour & Woolgar, 1979; Nersessian, 1984). Although similarities of practice extend across all science, the nature of phenomena in field and historical domains such as ecology and paleontology can at times require different methods of evidence construction and thus a different epistemological basis than laboratory sciences (Dodick, Argamon, & Chase, 2009; Gray, 2014). However, the practices of field-based domains remain under-theorized and under-represented in many accounts of scientific practice. Thus there is a need to expand the discussion of disciplinary engagement and scientific practice by providing accounts of the specific practices of domains such as field ecology.

Ecology has gained increased precedence in K-12 science education as it offers a relatively accessible and compelling way for students to engage with complex systems and critical socioscientific issues (Jordan, Singer, Vaughan, & Berkowitz, 2008; Lefkaditou, Korfiatis, & Hovardas, 2014). Research has also shown that ecological contexts can be effective environments for students to develop scientific practices such as modeling, experimentation, explanation, and argumentation (e.g., Lehrer & Schauble, 2010; Lehrer, Schauble, & Lucas, 2008; Rozenszayn & Assaraf, 2011; Tomkins & Tunnicliffe, 2001). Despite this increased focus on ecology in general, the more specific domain of field ecology has often been overlooked or rendered unproblematic in the design of learning environments (Korfiatis & Tunnicliffe, 2012; Resler & Kolivras, 2009). Students are rarely invited to grapple with the complexities of the field practices that undergird the entire domain of ecology. Because of this there is also a need to better understand what might be productive approximations of practice for K-12 students studying field ecology.

This review addresses these needs by synthesizing what research studies have uncovered about how ecologists construct knowledge in field settings. In doing so, it focuses on detailing the aspects of scientific practice that seem particularly amplified in field ecology as opposed to arguing for how field ecology is definitively unique. Finally, it concludes by discussing the affordances of engaging students in the practices of field ecology and by suggesting design recommendations for implementing ecological fieldwork in K-12 science classrooms.

Theoretical Framework

Science-as-Practice

Scientists form a community of practice with specific means of legitimizing the construction of knowledge (Hodson, 2014; Kelly, 2011; Knorr-Cetina, 2009; Lave & Wenger, 1991; Sandoval & Reiser, 2004). Modeling is the defining enterprise of this community and forms the fundamental basis of knowledge claims in science (Giere, 1988; Lehrer & Schauble, 2010; Nersessian, 2008). Though many consider all epistemic practice in science to emerge from the core practice of modeling, recent frameworks in science education such as the Next Generation Science Standards have detailed practice at a slightly smaller grain size (National Research Council, 2007, 2012). These frameworks detail eight scientific practices, including modeling, that are deemed important for student understanding of science: asking questions and defining problems, developing and using models, planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking, constructing explanations and designing solutions, engaging in argument from evidence, and obtaining, evaluating, and communicating information. These eight practices highlight what members in the scientific community know and do in order to produce knowledge (Feldman, Divoll, & Rogan-Klyve, 2013). They are not just practices of the mind, but also ways of organizing the body to conduct specific forms of activity (Roth & Bowen, 2001b). The enactment of these practices by individuals and within communities legitimizes the processes and findings of scientific research (Hodson, 2014).

From a science-as-practice perspective, teaching and learning emphasizes participating within a local community in the epistemic practices that characterize the larger discipline (Ford & Forman, 2006; Osborne, 2014). This means that an effective learning environment would allow scientific content to become visible to students within the context of meaningful investigations that problematize how that knowledge is constructed (e.g., Manz, 2014). The design is for students to see, question, and make sense of the world in new ways over time. Though this approach ultimately aims to apprentice students in the norms of the larger scientific community (Duschl, 2008), it focuses on creating a local need for change in a particular practice, rather than having students simply mimic disciplinary conventions.

This focus on the evolution of practice highlights a fundamental implication of conceptualizing science as a social practice. The practices scientists use to make sense of and explain nature are stabilizations of performances that are perpetually exposed to evaluation and critique (Ford, 2015). Which forms of performance count as acceptable practice shift as members of the community find progressively better ways to explain nature. Thus although it is not unreasonable to expose students to current stabilizations of scientific practice, they should also experience the evolution of practice in response to critique. This view of practice positions science as a "constantly evolving set of value-laden public routines in which students can (and should) take an active role in developing" (Stroupe, 2015, p. 1038) and embraces the messy side of how scientific knowledge is constructed (Mody, 2015).

Field Ecology

Ecology is the study of the abundance and distribution of living organisms and the relationships within and between these organisms and their environments (Korfiatis & Tunnicliffe, 2012). Ecologists explore phenomena such as shifts in population growth, distributions of species, and the function of ecological systems. Though these phenomena can sometimes be studied in laboratory settings or theoretically modeled, field studies have traditionally formed the foundation of exploratory research and knowledge construction in this domain (Eberhardt & Thomas, 1991; Korfiatis & Tunnicliffe, 2012; Lefkaditou et al., 2014). Because ecological issues such as species extinction and the impacts of climate change are often at the core of many of today's key scientific debates, field ecology presents a significant learning target for K-12 education (Jordan et al., 2008).

Ecological fieldwork, however, is not a simple endeavor. Field settings are complex systems with processes functioning on multiple intersecting temporal and spatial scales (Underwood, 1994; Wiens, 1989). These systems change cyclically, creating seasonal variations, and directionally, creating new system states. The vast number of interconnecting variables in these systems frequently results in data sets that have substantial unexplained variance. Often it is not even initially clear which are the most important variables for ecologists to attend to (Latour, 1999). For example, one team of researchers investigating processes of pollination initially focused on the types of bees visiting each crop (Leon-Beck & Dodick, 2012). However, elements initially overlooked by the team, such as the spatial scale they were attending to and the type of habitat surrounding the crops, were actually more influential in explaining pollination patterns than the types of bees in an area. Choices about what to attend to in the field are complicated because field settings can rarely be investigated in their totality. Ecologists' understandings of system processes instead have to be refined based on the results of a subset or sample of the system (e.g., Biswas & Mallik, 2010).

Ecological arguments are often grounded in observations of uncontrolled events rather than replicated experiments (Eberhardt & Thomas, 1991). Field ecology is thus primarily an observational science in which researchers either analyze natural perturbations in the field or manipulate a few variables under field conditions (Bowen & Roth, 2007; Leon-Beck & Dodick, 2012). As in all science, these observations are heavily influenced by the underlying theories of the researcher (Bencze & Elshof, 2004). However, individual studies in field ecology are typically less replicable than laboratory-based studies as environmental conditions and organisms are variable and constantly undergoing change (Bowen & Roth, 2007; Leon-Beck & Dodick, 2012). Because much of their work is observational rather than experimental, field ecologists are often perceived as different and, at times, less sophisticated than other scientists (Bencze & Elshof, 2004; Bowen & Roth, 2002; Roth & Bowen, 2001b). Within their own community, however, fieldwork is a challenging rite of passage formative to how field ecologists interact with and represent the world. To some, these complexities and challenges of ecological field settings might preclude them as sites for K-12 learning. However, these same complexities and challenges might also be useful entry points for K-12 students to engage in meaningful evaluation and critique and could thus scaffold the evolution of students' practice (Ford, 2015).

Methodology

This review synthesizes studies that have investigated how ecologists construct knowledge while in field settings. Such studies are often referred to as social studies of field ecologists. I searched the Web of Sciences, ERIC, and PsychInfo databases for peer-reviewed papers that referenced a combination of the words "ecology, ecological, biology, biological, or environmental" and "fieldwork, field studies, or field research" in either the title, abstract, or keywords. I narrowed my focus to studies that included at least some form of first-person observational description of some aspect of field-based ecological research. In addition, I looked through issues of *Social Studies of Science* from 1998 to 2015 for appropriate studies not covered by these search terms. I also mined the reference lists of any study I included and looked for other appropriate works that had cited these studies. These searches produced sixteen core studies of the practices of field ecologists that I used for my primary analysis. (These core studies are marked in the reference list with an asterisk.) I chose to include studies that focused on graduate students in my analysis as most graduate students are active participants in the professional community of practice (Lave & Wenger, 1991) responsible for generating ecological knowledge. In addition, because graduate students are novice practitioners, their moments of trouble when conducting research can help reveal the essential elements of ecological field practices.

In my analysis of these studies I first used the constant comparative method (Strauss & Corbin, 1990) to code how the studies described the work of field ecologists. Whenever possible I drew directly on the accounts of ecologists' activities, quotes from ecologists, and samples from ecologists' journals rather than just using the authors' interpretation of these artifacts. I then used current framings of scientific practice to reorganize my initial codes across two dimensions: the practices of field ecologists and themes across practices. Finally I drew upon research articles and methodological papers written by professional ecologists to provide detail and context to my description of these practices and themes. I gave greater weight in my analysis to practices and themes that consistently appeared across multiple studies of field ecologists as well as to larger organizing principles that could unify smaller facets highlighted in individual studies. However, because some of the studies use different lenses to describe the work of the same ecologists and because the studies varied greatly in the grain-size of their descriptions of practice, I did not attempt to quantify the frequency with which any particular practice or theme emerged. Instead, I focused on developing rich holistic descriptions of practices and themes across studies.

We know that the disciplinary work of scientists is both consistent and at the same time distinctly nuanced across different domains of science (Stroupe, 2015). Consequently, any scientist reading this paper should find similarities between their work and this account of field ecology. However they should also find descriptions of practice that are less prominent in their own community. At the same time, any field ecologist reading this paper should not be surprised if some aspect of their own practice is only tangentially referenced or even omitted. Because this description of field ecology is predicated on the sampling decisions of the studies analyzed, it is not an all-inclusive account of practice. Rather it highlights the aspects of practice that seem particularly amplified within field ecology and the potential affordances of engaging K-12 students in such practice.

Findings

Two strands of findings emerged from this analysis: the individual practices ecologists engage in while working in field settings and themes characteristic across these practices (Fig. 1). The following explores each of these strands in turn.

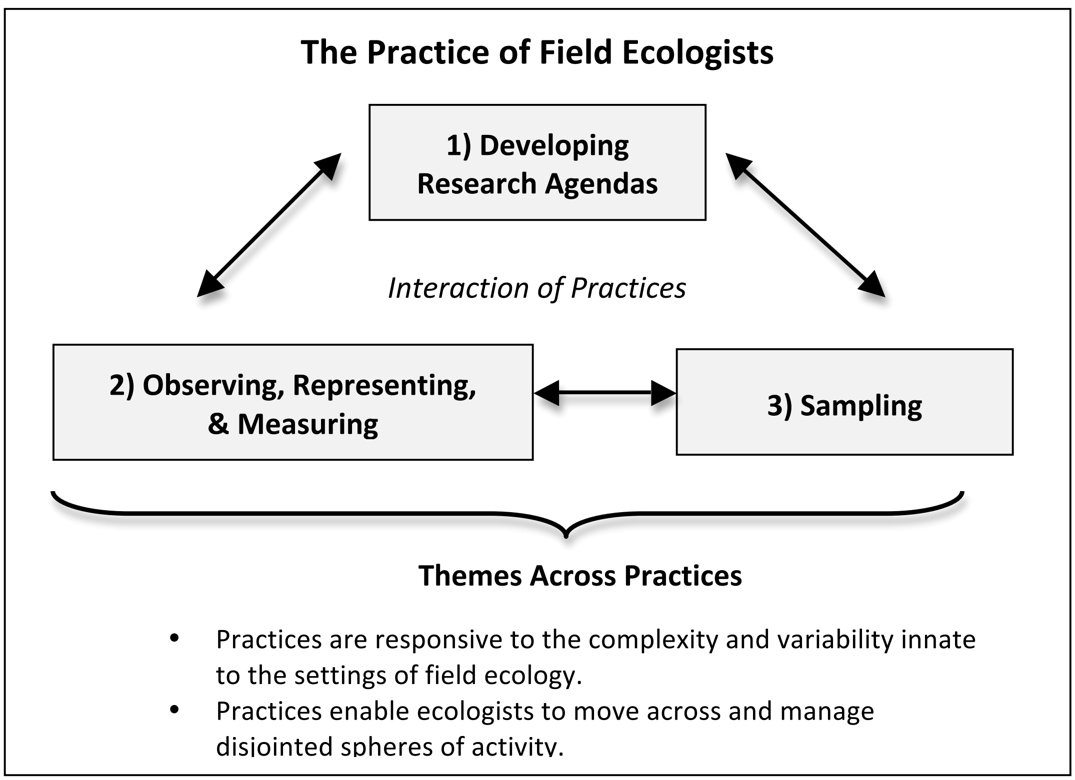

Figure 1. The practice of field ecologists

The Practices of Field Ecology

Ecologists engage in three main epistemic practices while conducting field research: the practice of *developing research agendas,* the practice of *observing, representing, and measuring*, and the practice of *sampling* (Table 1). At first glance these practices are not novel or unique.

Table 1

Summary of the practices of field ecology

Practice 1: Developing research agendas	Practice 2: Observing, representing, and measuring	Practice 3: Sampling
Ecologists develop emergent research agendas (questions, variables) while in the field. • Field ecologists often begin with questions, variables, and predictions based on prior experience or disciplinary conventions. • These initial plans can become problematized as anomalies, variation, and emergent patterns are related to initial understandings. • Often old questions and variables are adapted and new ones emerge within a single field cycle.	Ecologists transform observations into measurements and other representations that transport the field to other settings. • Field ecologists increasingly systematize and mathematize observations through inscriptions and measurement. • Representations of space are privileged as ecologists move into and out of the field. • Processes of observation, representation, and measurement adapt in response to both material and social pressure. • At times anecdotal observations can give rise to new variables.	Ecologists use sampling to focus observations and collect limited data about complex systems. • Field ecologists often begin with standardized methods appropriate to the research agenda (phenomena, question). • These initial plans can be problematized by spatial and temporal complexities and variation in the field. • Sampling evolves as a form of constraint satisfaction between material and social pushback.

This surface familiarity supports the positioning of field ecology within the discipline of science. However, it is the ways in which field ecologists enact these practices that foregrounds specific nuances which may not be as privileged in other scientific domains.

The Practice of Developing Research Agendas. Ecologists develop emergent research agendas while in the field. This practice often begins with questions, variables, and predictions based on prior experience or disciplinary conventions. These initial plans become problematized as field ecologists relate anomalies, variation, and emergent patterns in data to their initial understandings. Often old questions and variables are adapted and new ones emerge within a single field cycle. This practice of field ecology is closely tied to the NGSS description of the practice of asking questions and defining problems (National Research Council, 2012).

Ecological fieldwork seeks to advance specific aspects of theory that are often initially described by general research questions. The details of this research, however, are not always explicitly planned in advance, particularly when it is an ecologist's first time in a given field setting. Even when an ecologist arrives in the field with a rich research protocol these idealized plans often undergo substantial change as the ecologist wrestles with the realities of the field setting (Bencze & Elshof, 2004; Leon-Beck & Dodick, 2012; Nygren & Jokinen, 2013). Consequently many of the specifics of a research agenda, such as which variables are most important to attend to, develop in-situ as ecologists develop a greater sense of place (Bowen & Roth, 2002; Leon-Beck & Dodick, 2012; Lorimer, 2008; Roth & Bowen, 1999). As Bowen and Roth (2007) explain, "Lack of familiarity with a setting mediates the ability of a researcher to define variables and therefore requires prolonged periods of observation before salient dimensions can be identified" (p. 176). The sense of place an ecologist develops over time is one of their defining characteristics of practice.

For a field ecologist, new knowledge often begins as a collection of anecdotes. Anecdotal knowledge is typically scorned in formal scientific contexts, but it serves a powerful function in field practice. It builds over the course of repeated observations as ecologists begin to see variation in a previously un-described dimension of a phenomenon. If ecologists have a theoretical reason for attending to this new dimension, they often add it as a variable of interest even in the middle of an ongoing study (Bowen & Roth, 2002, 2007; Roth & Bowen, 1999). Formal reports such as journal articles rarely report on this process of emergence, as ecologists frequently re-write the logic of their investigation as if the variables had always existed. This form of repositioning through writing is not unique to field ecology and can be found in written arguments across scientific domains (e.g., Bazerman, 1988; Nersessian, 1984). However, the complexities of the systems in which field ecology is situated may make such emergence uniquely accessible and essential to practice.

The variations that lay the foundation for anecdotal knowledge often emerge as unusual or unexpected findings that problematize ecologists' initial research plans. Ecologists can arrive in the field only to find the presence of new organisms that stymie their original data collection plans and that they must account for. This happened to a research team who arrived in the field only to encounter an unexpected increase in flowering thistles at their study site (Leon-Beck & Dodick, 2012). The researchers could not ignore the thistles because they impacted the fundamental behavior of the system under investigation (and their sharp spikes also rendered the researchers' original data collection plans ineffective). Throughout ecologists' work we see that difficult field conditions often alter research methods and create variations that give salience to new research variables (Roth & Bowen, 2001b). In this way potential failures are repurposed as an important process of ecological discovery. For example, a team of ecologists studying the behavior of a small primate were once frustrated with how its elusive nature limited their observational efficiency (Madden, Grayson, Madden, Milewski, & Snyder, 2012). Because of these limitations to their observational data, the ecologists shifted their research to also focus on the types of habitats visited by the primate and in so doing developed a new theory of canopy connectivity. In other cases, the evolution of new technologies, such as remote sensors and cameras capable of recording longer scales of time-series data, enable ecologists to consider questions and variables that only become visible when implementing these technologies in the field (Mayernik, Wallis, & Borgman, 2013).

The emergent research agendas of field ecologists often develop within the middle of a single round of data collection or a single field season. This is slightly but significantly different than laboratory-based research in which questions and variables often shift across repetitions of experimental trials, but remain relatively stable during a single trial (Eberhardt & Thomas, 1991; Gooding, 1990). Field ecologists do not have precisely the same luxury of repetition in the phenomena they study, as even within a single trial the field setting is undergoing continual change. This disconnect between laboratory and field practice often frustrates novice field ecologists whose initial training is most often grounded in laboratory experiences. Novices often try to impose rigid research agendas upon a field setting only to find that their questions and variables, although informed by theory and prior research, do not account for the idiosyncrasies of their setting (Leon-Beck & Dodick, 2012). As a domain, field ecology privileges flexibility and adaptation of scientific practice and not just standardized procedures (e.g., Feldman et al., 2013; Feldman, Divoll, & Rogan-Klyve, 2009).

The Practice of Observing, Representing, and Measuring. Ecologists transform observations into measurements and other representations that enable them to interrogate and transport natural phenomena. This practice adapts in response to material and social pressures and functions in both formal and informal ways. Field ecologists increasingly systematize and mathematize their observations as they develop explanations of system processes. However, they also value and collect anecdotal observations that serve as a resource for emergent research. Elements of this practice of field ecology are closely tied to the NGSS description of the practice of planning and carrying out investigations (National Research Council, 2012).

For this holistic analysis, I have elected to treat observation, representation, and measurement holistically as a single practice because of how closely they overlap and intertwine in ecological fieldwork. A different analytical piece at a much smaller grain size might choose to explore each of these elements independently, as in Eberbach and Crowley's (2009) description of the observational practice of biologists. However, I present them as a systematic unit because although there are moments when observation, representation, or measurement might alternately take precedence in ecologists' work, it can be difficult to discriminate when one ends and another begins. For example, by definition sophisticated observational practice involves creating representations to preserve phenomena and support scientific arguments. The two are found in the same instance of work. Likewise, measurement can be considered to be a form of representation that has helped to advance scientific research by systematizing qualitative observations in quantitative patterns (e.g., Clark & Evans, 1954).

How field ecologists enact the practice of observing, representing, and measuring phenomena is contingent upon time. Ecologists often spend long periods familiarizing themselves with a field setting before beginning more formal data collection, particularly if they have limited prior experience in that setting (Bowen & Roth, 2007). This period of informal observation shifts the ecologists' frame of interpretation and supports their development of "field sense" (Bowen & Roth, 2002). In complex field settings, choosing what to focus on is not always a straightforward process (Lorimer, 2008). Novice researchers often produce little useful data in their first field season because their initial approaches to observation and measurement do not always fit their unique field setting (Bowen, 2003). In contrast, ecologists with more field experience use encounters with variation as an impetus to purposively adapt their research along meaningful directions. These new directions are supported by the expert's prior observations and a time-dependent feel for what is likely most important in that setting.

Even seemingly simple forms of observation, such as the identification of an organism, can be quite difficult in the field. Natural variation and uncertainty can make it difficult for ecologists to discern what they have just experienced even if they know what they are looking or listening for (Bowen & Roth, 2002; Lorimer, 2008). They have to learn how to alter both their body and their tools in order to rearrange physical conditions so that they can "see" a phenomena (Bowen, 2003; Roth & Bowen, 1999, 2001a). The range of means by which an ecologist makes an organism or other phenomenon visible can be difficult to translate to text because of the scope of variation inherent in nature. For example, researchers conducting a census of corncrakes, a type of bird, must become attuned not only to the most accessible form of identifying this organism, the characteristic call of the male, but also to the slight differences in similar calls of related species (Lorimer, 2008). This alignment is further complicated by the need to learn how to prioritize auditory over visual cues, how to select the most productive time and weather conditions to work in, and how to entice a silent but present bird to call.

Observation is a theory-laden enterprise as ecologists must make crucial decisions about what to attend to (Eberbach & Crowley, 2009; van Fraassen, 2008). In early stages of observation, ecologists often begin with an initial image of a phenomenon, such as the likely location of squirrel nests (Nygren & Jokinen, 2013), that they refine and expand upon over time to produce multiple lines of observational evidence. These initial images are often drawn from representations such as field guides or maps that become progressively annotated based on experience. For example, one ecologist reported having difficulty using a picture-based field guide to identify trees as the season obscured typical visual cues used for identification (Roth & Bowen, 2001a). In addition, the guide did not account for the range of variation within even a single species of tree. Because of this the ecologist developed his own approach that integrated tactile and visual identification signals. He created a new field guide comprised of a bag of twigs for each species of tree. Each contained a selection of twigs from trees he had positively identified using the original guide. He used these twigs to identify other trees by touch as well as sight. Since these bags contained samples from multiple trees, they helped the ecologist gain a sense of the variability within each species and build confidence in the accuracy of his identification. However, for a few trees, even this new representation failed to support a positive identification. In these cases, the ecologist took twigs from the remaining unidentified trees and used these remnants to consult with experts after he returned from the field. This example highlights how, over time, ecologists align themselves, their tools, and the phenomena to create a haptic feel and sense of place for their specific field setting (Lorimer, 2008).

This alignment of tree, field guide, bag of twigs, and remnants also illustrates how field ecologists integrate observational and representational activity as they create chains of representations that extend from and refer back to phenomena (Latour, 1999; Roth & Bowen, 2001b). In studying lizard length, an ecologist might use a specifically aligned set of tools to temporarily trace the overall length of the lizard onto a piece of clear plastic (Roth & Bowen, 1999). These traces might be later transferred to a permanent record, transformed into millimeter lengths, and aligned by labels to a toe clipping from the lizard and to a map denoting the capture location. Through all of this activity, the ecologist transforms their observations of individual lizards into a system of inscriptions that eventually represents a population of lizards. In their work field ecologists particularly privilege representations of space, such as maps of an overall study site or the locations of specific observations (Mauz & Granjou, 2013; Roth & Bowen, 1999, 2001a, 2001b). For example, an ecologist surveying a population of birds might plot individual observations of male bird calls on a map, draw a circle around each observation to represent typical territorial dimensions, and use the alignment of circles to arrive at a final census of the distinct males in a given area (Lorimer, 2008). As evidenced by these exemplars, much of this representational work can be highly particular to different specialties within the domain.

Lay observers or hobbyists might develop a sense of place similar to field ecologists upon repeated visits to a favorite site. However, ecologists differentiate themselves from these other specialists through their efforts to mathematize nature by translating narrative observations into measurements (Bowen, 2003; Roth & Bowen, 1999). This mathematization is important because it creates a form of standardization that enables ecologists to find patterns in observations that span spatial and temporal scales. Through measurement, ecologists can transform a set of three dimensional living organisms to a single number denoting a one dimensional feature of a population, such as typical length (Roth & Bowen, 1999). The process of transformation is typically specific to a given phenomenon. Ecologists conducting a census of bat populations might use sonar equipment outside a cave at dusk, while those studying corncrakes might rely on auditory identification of bird calls and those studying lizards might use capture and release methods (Lorimer, 2008; Mason & Hope, 2014; Roth & Bowen, 1999).

Often ecologists can meaningfully transform phenomena through their actions before they can systematically describe their actual process of measurement. For example, one ecologist could point out what did or did not constitute an official “rock pile” in the habitat she was studying, but she struggled to describe the method behind her identification (Roth & Bowen, 2001b). When a field assistant tried to replicate her process and failed, this brought the ecologist’s original notion of what constituted a rock pile into contest. Working together, the two negotiated and systematized how to operationalize and measure rock piles in their study. Secondary observers are important in developing systematic measures because multiple observers often see an instance in conflicting ways that push on and ultimately reveal tacit assumptions (Leon-Beck & Dodick, 2012). When an ecologist does not have another observer to provide this social pushback, it often emerges from the inscriptions and measures the ecologist brings into the field. These standardized approaches carry the reified weight of a community of practice, a form of disciplinary agency in action (Pickering, 2010). This can set up a dialectic of material and social pushback in which field ecologists adapt the discipline’s standardized methods within the constraints and complexities of the phenomenon they are studying.

At times, the material means and tools available for measurement can limit the type of research an ecologist can conduct in the field (Roth & Bowen, 1999). For example, although ecological theory would benefit from understanding long-term trends in many biological and behavioral parameters, ecologists have not yet been able to design sensors that could measure these variables in the same way as they trace long-term oxygen levels (Mayernik et al., 2013). Consequently, when new technologies are developed, they often open up new spatial and temporal scales of research. The way in which ecologists use even those tools that they have readily available changes out in the field (Bowen & Roth, 2007). Sometimes equipment behaves differently under field conditions then when used in a laboratory. At other times it completely breaks down. Because of this field ecologists have to often reconstruct how they use tools in measurement. This bricolage requires substantial problem solving and creativity but is essential for being able to generate data in complex and uncertain field settings (Bowen & Roth, 2007; Mayernik et al., 2013; Mody, 2015).

As field ecologists take measures they use this data to inform their process of measurement while at the same time using their process of measurement to inform how they interpret data. Ecologists reevaluate how they are measuring a phenomena if the data seems to conflict with either their prior expectations or their general field observations (Mayernik et al., 2013). Unexpected data can be a signal of problems with an ecologist's approach to measurement. The measure might be distorting the phenomenon in unproductive ways (van Fraassen, 2008), or tools might be malfunctioning. However, unexpected data can also be a signal of an interesting ecological change in the phenomenon or of a missing element in the underlying theory. Experience with the phenomenon, the tools, and the specific field setting are all important for making sense of data and determining if unusual results are due to process errors that need to corrected or if they instead signal fruitful directions for new research (Bowen, 2003; Mauz & Granjou, 2013; Nygren & Jokinen, 2013).

Despite an emphasis on measurement, informal forms of observation do not fade away with extended time in the field. Instead, they continue to persist alongside formal efforts to mathematize phenomena. Collections of informal observations are important to field ecologists because they support the emergence of new research variables and questions. For example, Bowen and Roth (2002) report on one ecologist who spent almost twenty years in a research site before identifying the key variables that led to their most significant discovery. These new variables often become visible through moments of surprise when ecologists notice something unusual or unexpected (Leon-Beck & Dodick, 2012; Nygren & Jokinen, 2013). The nature of a field setting impels ecologists to closely attend to what others might deem to be incidental because ecologists are forced to work with whatever is accessible in that setting. Given that they often have only a limited amount of time in the field, ecologists cannot simply wait around for more favorable conditions. They are under social pressure to produce some form of findings. Because of this, when their original plans break down field ecologists adapt their research to what they have at their disposal. In so doing they often arrive at disciplinary breakthroughs. For example, one ecologist whose field observations focused on bears began to notice that the areas in which he worked often had leftover salmon testes from the bears' latest meals strewn across the ground (Bowen & Roth, 2007). Though the notion of using salmon testes to study bears (or even bear-salmon interactions) had not previously occurred to the ecologist, he seized upon them because they were readily available and used them to investigate energy conservation in biotic systems. To outsiders these moments of discovery might seem serendipitous. But they are actually grounded in ecologists' deep familiarity with a field setting and backed by numerous informal observations compiled over time.

Learning new methods of measurement or ways of seeing space can be extremely challenging (Leon-Beck & Dodick, 2012). Inexperienced researchers frequently question whether they have seen what they were supposed to see or have done what they were supposed to do (Roth & Bowen, 2001a). As in other domains of science, they need support in learning how to see the world in new ways, a form of disciplined perception (Stevens & Hall, 1998). Methods of observation and measurement in ecology are often disseminated by text and then, when possible, member-checked in action as novices work in the field alongside more senior researchers (Lorimer, 2008; Mason & Hope, 2014; Mayernik et al., 2013). However, field ecologists do not always work in close physical proximity with others, and there is often a scarcity of expertise out in the field. Because of this, ecologists use formal and informal social settings both inside and outside the field to develop and discipline practice. When researchers share stories of data collection around a lunch table or campfire, they become attuned to new ways of measurement and communally evaluate, critique, and reify what counts as acceptable practice (Bowen, 2003; Ford, 2015). For example, one ecologist who had developed an emergent measure of lizard color in the field using paint chips adapted this measure upon consultation with others to a more standardized approach using a Munsell soil color chart. Concentric circles of community, beginning with the local laboratory and extending to the readers of formal reports, progressively hold each member accountable for the extent to which their observations, representations, and measurements adequately capture natural phenomena in ways that are acceptable to others (Bowen, 2003; Lorimer, 2008).

The Practice of Sampling. Ecologists use sampling to focus observations and collect data within the inexhaustibly complex systems of field settings. When sampling, ecologists often begin with standardized methods appropriate to the phenomenon or questions at hand. For example, an ecologist interested in estimating the abundance of a terrestrial organism might sample using a standardized transect line (Buckland, Anderson, Burnham, & Laake, 1993; Roth & Bowen, 2001a). In a transect line observations are gathered at prescribed intervals, such as 20 meters, along a fixed path by placing a sampling unit such as a one square meter plot at each interval and gathering data in just those plots. Though ecologists often enter the field with a set sampling protocol in mind, these initial plans are problematized by the complexities and variation they encounter as they try to enact this protocol. Consequently, their sampling practice evolves over time as a form of constraint satisfaction between material and social pushback. This practice of field ecology is only tangentially referred to in the NGSS description of the practice of planning and carrying out investigations (National Research Council, 2012).

In field settings it is impossible to collect data exhaustive of the system. Even a large research team cannot census every unit of interest. Field ecologists must therefore make decisions about where and when to measure. These methodological issues of time and space are essentially questions about sampling: where should plots be set, what size should they be, how often should they be checked, etc. (Coe, 2008; Eberhardt & Thomas, 1991; Underwood, 1994). Each of these decisions simplifies the layered complexities of the field site into distinct differences (Bencze & Elshof, 2004). In some sampling protocols this simplification can create false dichotomies out of continuous gradients. For example, ecologists might first divide a research site into patches of meadows and patches of rocky ground and then sample sections of these two areas. However, because of the variability of ground cover, some patches partitioned as meadow as well as some patches partitioned as rocky ground might be more accurately described as a hybrid of rocky-meadow. The decision about what to do with such patches is subjectively dependent on researcher preference, disciplinary precedence, theoretical assumptions about the phenomenon, and the availability of an adequate number of samples. Though sampling is related to the practice of measurement, they are different performances of activity. Sampling provides a way for ecologists to narrow the field setting into manageable units to study, such as individual organisms or square plots. Measurement deals with what ecologists will attend to about the units that they have secured access to through sampling.

Present-day field ecologists describe sophisticated methods of sampling that are highly situated and that are influenced by the nature of the problem under investigation and features of the ecological system (Coe, 2008). These standardized methods have evolved over time within the domain. Though some practices, such as measurement, have roots in domains of science that predate ecology, sampling seems to have emerged as an epistemic practice in the natural sciences only within the past century. Back in the 1800s even scientists such as Darwin frequently failed to attend to the specific locations of their field specimens. Darwin's field records are even silent as to on which of the Galapagos Islands he collected many of his famous finch specimens (Sulloway, 1979).

In the early years of the discipline, ecologists described their field settings in narrative form; however, they did not seem compelled to validate how they selected units to attend to within that setting (e.g., Hofmann, 1920; Praeger, 1920; Wherry, 1920). Those who did explain elements of a fledgling sampling practice applied a convenience approach to sample selection, using those units that were most readily accessible (e.g., Douglass, 1920; Esterly, 1920). Over time, ecologists grew to justify the timing (Byram & Doolittle, 1950; Pavan, Dobzhansky, & Burla, 1950; Schmidt-Nielsen & Schmidt-Nielsen, 1950) and location (Shotwell, 1950; Walton Smith, Williams, & Davis, 1950) of their sampling based on the purpose of the study or important features of the phenomena under investigation. This attention to timing and location emerged as a response to variations in data. In one of the earliest examples of this practice, Esterly (1920) noted that some of his anomalous findings might have stemmed from differences in where he collected different samples of organisms he studied. As the practice of sampling continued to evolve, systematic sampling in which units of study are selected by the repetition of some fixed interval such as those on a transect line became more normative (e.g., DeWoskin, 1980; Ewald, Hunt, & Warner, 1980; McClure, 1980; Rogers, 1980; Stephenson, 1980; Tobiessen & Werner, 1980). This form of sampling protocol enabled ecologists to describe patterns of distribution along a specific gradient and enact a form of replication across time at the same research site. In addition, a new methodology, randomization, began to take hold. For example, ecologists began to use random processes to select a subset of fruit from branches (Stephenson, 1980) or identify focal trees for further analyses (McClure, 1980). Randomization emerged as a way to reduce bias in sample selection, as investigations of different protocols began to show how variations in sampling propagate disparate findings about the same system. Today, field ecologists still frequently justify at least some aspects of sample selection based on either convenience or purposive consideration of the phenomenon (Alberto et al., 2010; Biswas & Mallik, 2010; Bridgeland, Beier, Kolb, & Whitham, 2010; McLellan, Serrouya, Wittmer, & Boutin, 2010; Patterson, McConnell, Fedak, Bravington, & Hindell, 2010; Ravet, Brett, & Arhonditsis, 2010). But most also apply some form of systematic approach to sample location (e.g., Alberto et al., 2010), timing (e.g., McLellan et al., 2010), or unit subdivision (e.g., Bridgeland et al., 2010). And many also apply randomization procedures at some point during sample selection (e.g., Biswas & Mallik, 2010; Patterson et al., 2010).

From these historical trends it appears that once ecologists recognized that differences in sampling could explain variability in their data, methods of purposive and systematic sampling quickly became standardized practice in field ecology. Although randomization procedures have been integrated within practice, they do not seem to be a requirement for an acceptable field study. For example, if a research question requires that sampling units account for a broad range of variability across a specific gradient, preferential sampling protocols that place units on a transect along that gradient often generate more useful data than random sampling protocols (Coe, 2008). In addition, convenience sampling, which is often theoretically disparaged for its lack of representativeness and presence of bias, has persisted even in light of the disciplinary evolution of other sampling methods. Modern forms of convenience sampling seem to be employed when access to sampling units is extremely costly (e.g., McLellan et al., 2010), in areas where systematic norms are less standardized (e.g., Alberto et al., 2010), or when the mode of sampling likely has no theoretical impact (e.g., Patterson et al., 2010). In such cases, researchers are not blindly ignoring factors that they know would likely impact their data. Rather, they are often still trying to understand what about the system is important to attend to in a sampling protocol: what size of plot captures the phenomena, what interval of spacing along a transect captures the spatial distribution, whether randomized grids are more appropriate than systematic processes, etc. As crucial factors emerge during research, ecologists would likely account for these factors in future sampling protocols, enabling them to better explain nature.

This historical account of sampling, derived from published articles of actual field research, describes the final outcomes of field ecologists' practice. But it does not readily give an account of the enactment of the practice that produced those outcomes. For that, we need to look at the social studies of field ecologists. However, although the studies of field ecologists provide evidence of sampling, most fail to adequately describe its enactment. Some studies of field ecologists even at times conflate sampling practices and measurement (e.g., Leon-Beck & Dodick, 2012). These studies may have limited descriptions of sampling because researchers were not attending to signals of it in the field. Or, researchers might have had difficulties capturing images of the practice because of its potential roots outside field settings.

What we find from the social studies is that field ecologists often begin with an attempt to adapt standardized sampling protocols used with a similar phenomenon to their local field conditions (Latour, 1999; Lorimer, 2008; Roth & Bowen, 2001a), much as was found in the historical account. These starting points are often drawn from formal accounts of others' methodology. However, common sources of methodology such as journal articles and conference presentations are typically not detailed enough for effective replication of sampling practice (Bowen & Roth, 2007). These reports treat sampling as a fairly straightforward process, but when ecologists try to replicate a prior study (even in the same location as that study) unanticipated complexities emerge. For example, when attempting to re-lay a rectangular transect belt used to study trees in a prior study, an ecologist found that he could either replicate the rectangular coordinates of the belt or he could include only those trees that had been reported to be within the belt, but he could not satisfy both conditions of the prior study (Roth & Bowen, 2001a). Thus in the field, sampling practice is not the blind implementation of standardized protocols, but a form of constraint satisfaction in response to material and social pressures.

The exact nature of these material and social pressures and their relative influences on the constraint satisfaction of sampling practice are only hinted at in the studies of field ecologists (and are largely absent in the formal accounts ecologists write). Ecologists adjust sampling protocols to the nature of the phenomena under study and to the available tools and technologies for conducting the study (Mayernik et al., 2013; Roth & Bowen, 1999). They are also forced to adapt initial idealized sampling plans in the field when they find that the resources used to develop the study, such as prior research or inscriptions like aerial maps, are no longer consistent with current field conditions (Leon-Beck & Dodick, 2012). Field sampling can also be a very subjective practice. Because of this, when sampling is distributed amongst a research team the process of arriving at some form of consistent process frequently alters the sampling protocol.

Evidence suggests that ecologists' tendencies to implement convenience sampling stems from a need to ensure adequate sample size, even if this protocol does not produce a sample that is representative of the phenomenon (Bencze & Elshof, 2004; Leon-Beck & Dodick, 2012). This optimization by convenience emerges when ecologists encounter unexpected variation, face environmental hazards, are pressured by time, or have limited manpower (e.g., Lorimer, 2008). When there are not enough sampling units that meet their initial criteria, ecologists have to choose between adjusting these criteria, being satisfied with a smaller number of samples, or changing their research foci (Leon-Beck & Dodick, 2012). However, representativeness is not completely ignored. Ecologists analyze and evaluate preliminary data in-situ while a field study is underway and use this analysis to determine if adjustments to sampling protocols are warranted because the sample does not seem to be representative of the phenomenon. While formal aspects of mathematical theory such as sample size and representativeness inform the practice of sampling in field ecology, the complexities of field settings often force ecologists to adopt less than optimal procedures that subordinate theoretical issues such as randomness to practical issues of collecting data. For example, they might exclude areas too remote or costly to access.

Sampling practice is a struggle between how to secure access to the phenomena without sacrificing the representativeness or power of the sample. However, more structured studies of field ecologists might be needed to better understand how this struggle unfolds. A better understanding of how sampling decisions develop is important because this aspect of practice seems to be distinct both from laboratory-based science and from other field-based sciences. Laboratory-based research does explicitly depend on temporal and spatial sampling. And other field-based sciences, such as geology, typically deal with phenomena that exhibit less diversity and variability than ecological systems (Mayernik et al., 2013). Because of this, sampling is potentially the most distinctive practice of field ecology, as it seems to permeate ecologists' work in ways that are largely absent from other domains.

Interactions Between Individual Practices. For the sake of clarity I have discussed these three practices of field ecology as if they were isolated, discrete elements of ecological fieldwork. However, the realities of how field ecologists perform these practices are not so distinct. As in other domains of science (Ford, 2015; National Research Council, 2012), the processes by which ecologists develop research agendas, conduct observations, and sample phenomena intersect. The discipline does not follow a strict linear progression of activity (Hodson, 2014). It is iterative and interactive. Research questions serve to focus observations, and observations can lead to new research questions (Bowen & Roth, 2007; Leon-Beck & Dodick, 2012; Lorimer, 2008). Likewise novel patterns in data can trigger changes in sampling plans, and decisions about sampling can impact what is and is not possible to measure.

In order to see how this interaction plays out, consider the practice of an ecologist whose field research investigated the life histories of lizards (Bowen & Roth, 2007; Roth & Bowen, 1999, 2001b). When the ecologist began her fieldwork, her aim was to better describe how characteristics such as weight, length, and speed impact survival rates. Because of this research agenda she designed a purposive sampling plan that focused on sampling only those locations with rock piles that, based on prior knowledge, provided the best habitat for lizards. This initial sampling plan evolved in the field as the ecologist and her assistant co-constructed what actually constituted a rock pile. These adjustments to the sampling frame helped to create a time delay between when a lizard was captured and when it was formally measured. This delay in turn impacted the values of some of the focal research variables (such as the sprinting speed of a lizard) while leaving others (such as leg length) unchanged. Initially, the ecologist did not attend to or account for these effects of the delay. However, as she struggled to make sense of unexpected data, the length of the delay emerged as an important mediating variable that was eventually written into the story of her research agenda as if it had existed all along.

We might talk about developing a research agenda, operationalizing variables through measurement, and gaining access to units through sampling as distinct decision points and practices in field ecology. But these practices actuality interact in fieldwork. In this example, the ecologist's sampling practice impacted the measures that she was gathering to answer her research question. However, this impact was invisible to the ecologist until unexpected observations prompted her to reevaluate how she was sampling and measuring the lizards. Rather than adapt her sampling and measurement process to minimize this impact, the ecologist chose to adapt her research agenda to account for the new confounding variable.

Themes Across the Practice of Field Ecology

Because individual practices intertwine in their enactment, two common themes thread across the overall practice of field ecology (Table 2). These themes are evident in how ecologists develop research agendas, observe and measure, and sample their site. Though these themes may be found in other scientific domains, they are especially salient to the domain of field ecology as they emerge from the nature of the field settings in which the practice is situated. Such settings are rife with complexity and variability that is often unexpected, uncontrollable, and at times unexplainable (Leon-Beck & Dodick, 2012; Madden et al., 2012). This sets up a dialectic of agency between nature's resistance to the actions of ecologists and ecologists' accommodation of that resistance, a dialectic that strongly influences practice (Pickering, 2010). These themes also emerge from how the practice of field ecology is disjointed in space and time as researchers move into and out of the field (Bowen & Roth, 2002; Latour, 1999; Lorimer, 2008; Roth & Bowen, 2001a, 2001b). Others might choose to pull out certain elements highlighted in these themes and position them as separate practices; however, I have addressed them in this manner as they thread throughout the practices of field ecology. Given that these themes emerge from the intricacies of working in field settings, they likely have implications for other forms of field research such as archeology (Hutchins & Renner, 2012; Mogk & Goodwin, 2012). However, this analysis does not attempt to probe these connections.

Table 2

Themes across the practices of field ecologists

Theme 1: The practices of field ecologists are responsive to the complexity and variability innate to the natural settings of their studies.	Theme 2: The practices of field ecologists enable ecologists to move across and manage disjointed spheres of activity.
Ecological field practices… • Adapt to local conditions • Emerge while in the field • Negotiate environmental stressors	Ecological field practices… • Rearrange time and space • Respond to material and social pushback • Reproduce through informal social interactions

Theme 1: The practices of field ecologists are responsive to the complexity and the variability innate to the natural settings of their studies. Field ecologists do not actively create their research settings from scratch as many laboratory-based scientists do. However, the practices of field ecologists do actively rearrange the way they make sense of their field site so that both the ecologists and the natural setting effectively change over time (Bowen, 2003; Mayernik et al., 2013; Roth & Bowen, 2001a, 2001b). This evolution of practice emerges as a response to the variations ecologists encounter as they navigate the complex systems of field settings.

Ecological field practices adapt to local conditions. Ecological field research is highly contingent on the nuances of individual field settings (Bencze & Elshof, 2004; Bowen & Roth, 2007; Nygren & Jokinen, 2013). Because field settings are both variable and complex, prior approaches cannot simply be overlaid onto new studies. Temporal variations even make replicating the same study in the same setting problematic (Roth & Bowen, 2001a). Thus research approaches must be, to a degree, redesigned for each setting. This adaptation to local conditions occurs across practices.

Though it is an important feature of practice, the process of redesign is often painted over in formal accounts of ecological work. Often what is previously published – from theory to method - does not precisely fit a specific local system (Bencze & Elshof, 2004). Furthermore, the complexity of ecological systems also makes it difficult to generalize the findings of laboratory experiments to natural conditions (Bowen & Roth, 2007). Researchers even encounter difficulties when trying to implement standardized measurement or sampling practices common to other field studies (Bowen & Roth, 2007; Lorimer, 2008; Roth & Bowen, 2001b).

Experience with a specific setting is important for successful local adaptation of practice (Roth & Bowen, 2001b). This sense of place helps discipline what an ecologist attends to and helps illuminate what had once been invisible (Bowen & Roth, 2002, 2007; Leon-Beck & Dodick, 2012; Lorimer, 2008; Roth & Bowen, 1999). Extended time in a site is important in highlighting and giving meaning to small variations (Madden et al., 2012). Though ecologists of all skill levels typically need extended time in the field to adequately adapt their field practices, novice researchers often need extra time to even notice that specific research approaches are not working in a given location (Leon-Beck & Dodick, 2012).

Ecological field practices emerge while in the field. Ecologists' practice is a constantly evolving endeavor that, although at times momentarily stabilizes within a research study, continues to adapt as new opportunities or challenges alter research conditions. This emergence extends to the questions ecologists ask, the variables they attend to, the representations they create, and the way they sample (Bowen, 2003; Nygren & Jokinen, 2013; Roth & Bowen, 1999, 2001a, 2001b). Although similar to the concept of local adaptation of practice, emergence privileges the temporal dimension of evolving practice. Ecologists do not just adjust practice when planning or beginning an investigation. They also do so throughout their research. Laboratory-based scientists might also make adjustments mid-experiment; however, they also have more flexibility to postpone such changes until the next round of experiments. In contrast, the settings in which field ecologists work prioritize responsive adaptation in the moment.

Emergence is important in ecological field practices because of the temporal bounding of their phenomena (Bowen & Roth, 2007; Leon-Beck & Dodick, 2012; Madden et al., 2012). Field ecologists typically work in field seasons with limited durations fixed by the phenomena under investigation and their extent of funding. During a field season both the ecologists and the phenomena they are studying are changing. The ecologist is becoming more expert, and the field setting is evolving as organisms grow and seasons change. This forces the ecologist to confront unpredicted variations and complexities that problematize practice in the moment as they emerge. As one novice ecologist questioned, "Can we really investigate bees and how they change in time and space as a result of agriculture during the period of a doctorate when it is known that this is a group (of bees) which is commonly scattered in patches and changes from year to year for reasons we are not aware of?" (Leon-Beck & Dodick, 2012, p. 2465).

Field conditions mediate what a researcher can do on any one day, stymie initial sampling plans when suitable plots are unavailable, and create delays or alterations in data collection that impact findings (Bowen & Roth, 2007; Madden et al., 2012). Tools fail to perform as intended and break down (Mayernik et al., 2013). Such events can be frustrating and even catastrophic if an ecologist is not flexible. Novice researches often struggle with emergent, adaptive practice as they typically approach research as standardized, predetermined, and inviolable (Bowen & Roth, 2002; Leon-Beck & Dodick, 2012). Such inflexible approaches often fail under the variation and complexity of field settings (Madden et al., 2012). On the other hand, expert ecologists comfortable with emergent practice can transform potential moments of failure in the field into new opportunities for research.

Ecological field practices negotiate environmental stressors. Though ecologists conduct their work in some of the most breathtaking landscapes on the planet, ecological field research is not always a glorious and uplifting endeavor. On the contrary, it can be repetitive, boring, and fraught with danger (Roth & Bowen, 2001b). Field ecologists often endure extended isolation in harsh environmental conditions that push both their body and mind to the edge of exhaustion (Bowen & Roth, 2007; Leon-Beck & Dodick, 2012). This is a discipline where issues of safety are legitimately issues of life and death and where it is not unusual to only have only one good week of weather for data collection in a given month (Bowen & Roth, 2007; Lorimer, 2008). Ecological field practices must negotiate these environmental stressors.

In the field, ecologists make in-the-moment adjustments from what is ideal to what is possible given their personal physical and mental limitations. This might involve altering anything from the types of measures taken to research questions or sampling plans (Bowen & Roth, 2007; Leon-Beck & Dodick, 2012; Lorimer, 2008). Once safely back at camp, informal social interactions provide a mechanism by which to test the disciplinary legitimacy of their choices and develop a bank of alternative approaches (Bowen & Roth, 2002; Mayernik et al., 2013). Community support, personal interest, and an acceptance of the normalcy of frustration all serve to sustain researchers during difficult field seasons (Bowen & Roth, 2002, 2007; Leon-Beck & Dodick, 2012; Lorimer, 2008).

The ability to adapt practice to negotiate environmental stressors seems to invoke aspects of identity in a much more powerful and tangible way than the prior themes of local adaptation and emergence. In informal gatherings of field ecologists stories of extreme survival (and at times stupidity) are bantered about as symbols of honor and badges of membership (Bowen & Roth, 2002). They mark that a researcher has survived the initiation into a privileged community. The inability to deal with the mental and physical rigors of field conditions is one of the most frequently cited reasons for a researcher to abandon the domain (Leon-Beck & Dodick, 2012).

Theme 2: The practices of field ecologists enable them to move across and manage disjointed spheres of activity. Field settings require ecologists to manage multiple spatiotemporal dimensions as their interactions with phenomena are typically divorced from their interactions with the disciplinary community (Bowen & Roth, 2002; Latour, 1999; Lorimer, 2008; Roth & Bowen, 2001a, 2001b). The representational infrastructure and discourse norms embedded within the practices of ecologists support this transformation of time and space.

Ecological field practices rearrange time and space. Natural settings are the laboratories of field ecology. However, they are only temporary laboratories. Ecologists must find ways to fix phenomena in time and space so that they can reproduce the present state at a future time and can transport their field experiences to places where others can interrogate their work. To do this, ecologists generate series of inscriptions and other forms of representation that serve as immutable mobiles and enable ecologists to make connections across research settings or across time in the same setting (Latour, 1999). Effective representations create a traceable and reversible chain of reference for phenomena. Often recorded in field notebooks, inscriptions create a stable mobile record of momentary and often incoherent events (Lorimer, 2008; Roth & Bowen, 1999, 2001a). Inscriptional records of field research have played a fundamental role in the development of ecological theory from the foundation of the discipline. Today, technological advances continue to expand the potential tools and forms of representational activity available in the field. For example, advancement in photographic identification has enabled ecologists to individually identify and then trace the life histories of organisms for which other forms of field tracking are not feasible (Nutch, 2006).

Representations serve multiple functions across the practices of field ecology. First, they extend the responsive adaptation of field practice to settings outside the field and beyond the spatial and temporal extent of the phenomenon (Roth & Bowen, 2001a). In such a way a series of sounds from different birds on different days in different locations can become a comprehensive account of a population (Lorimer, 2008) and forest surveys from the 1700s can be used to inform modern day environmental impact studies (Black & Abrams, 2001). Second, they allow ecologists to amplify and reduce key aspects of the phenomena they are studying (Hall, Lehrer, Lucas, & Schauble, 2004; Latour, 1999). This is important both in seeing the phenomena in new ways and also in crafting an argument for a preferred interpretation of ecological events (Rees, 2001). And third, they provide a means by which other ecologists who were not present in the field can collaborate on the construction of research.

The representational work of field ecologists can be viewed as a vital element within the practices of field ecology, as I have treated it here. Likewise, the NGSS threads its discussion of representation across the practices of science, from modeling to using mathematics and computational data (National Research Council, 2012). Alternatively, representational activity can be positioned as its own social practice (e.g., Roth & McGinn, 1998).

Ecological field practices respond to material and social pushback. Field settings often force ecologists to individually struggle with phenomenon. For example, an ecologist studying a population of crayfish might be successful in her first few sampling attempts, but as she continues the creek will respond to and push back on her activity. Perhaps her boots will begin to stir up murky water, reducing the visibility needed for her measures. Or the crayfish might fundamentally alter their behavior in response to her presence. Often field ecologists work in isolation and thus encounter and must respond to material pushback on their own, developing their own unique ways of operationalizing, measuring, or sampling phenomena (Pickering, 2010). However, as they develop these novel responses, other ecologists are also disciplining their practice - even when there is no one else with them in the field. This sets up a dialectic of material and social pushback. Ecologists must adaptively respond to the phenomena they are studying, but they must do so within the social constraints of what counts as an acceptable performance of practice (Ford, 2015).

Ecologists are acutely aware that they must take what is meaningful to them in the field setting and convince the broader community of what they found (Bowen & Roth, 2007; Roth & Bowen, 1999, 2001b). While out in the field they often wonder if the specific ways that they have addressed challenges of material pushback will be acceptable to others (Leon-Beck & Dodick, 2012). Because of this, if they think an observation, measure, or sampling approach might be deemed too novel by the community, they will either reject the approach or else validate their method by collecting more data than originally planned (Roth & Bowen, 1999).

Informal settings are important in providing initial mechanisms by which field ecologists can test the social acceptability of their choices before immortalizing them in formal research reports (Bowen & Roth, 2007). At times researchers can be tempted to adjust their measures and sampling practices if their initial data substantively differs with prior research, even if this borders on falsifying their findings (Roth & Bowen, 2001a). In short, field ecologists often question the social acceptance of their data, which complicates and adds stress to working in the field (Roth & Bowen, 2001b). Though common across scientific domains, this questioning is likely exacerbated in field ecology by the isolation of field research and the spatial and temporal disconnect between the phenomena and the broader community of practice.

Ecological field practices reproduce through informal social interactions. Informal social interactions, both within and out of the field, are important for establishing and circulating knowledge within the community of field ecologists (Roth & Bowen, 2001b). In the field, ecologists often recruit and rely on less-experienced community members whenever possible in order to achieve the scale of data collection needed for a successful research project (Madden et al., 2012). Field-based interactions between community members are important for reproducing ways of orienting to specific phenomena and how to use tools to make key processes visible (Leon-Beck & Dodick, 2012; Mason & Hope, 2014). However, such interactions are not automatically assured in the domain. When field-based research groups are loosely organized, there is a risk that members may not become full-fledged participants in the epistemic community in the way that laboratory-based or close-knit field-based research groups do, where the proximity of space supports the apprenticeship (Feldman et al., 2013, 2009).

Outside of the field informal storytelling promotes social cohesion and communicates knowledge and practices within the community of field ecologists (Bowen & Roth, 2002, 2007).

These narratives extend one's sense of the field through the experiences of others and are used to explain how to be safe in the field, what constitutes a typical field experience, and how to appropriately conduct research. Often these informal interactions provide a new context for anecdotal observations by connecting the experiences of disparate researchers and research studies. For example, one ecologist's story of maternal care in snakes once led another to consider a similar question in her research of lizards. During another moment of storytelling, an ecologist's observations of salmon was related to another's data about porpoise movement and enabled the two researchers to co-construct an explanation of predator avoidance in aquatic environments. The discourse norms of informal, anecdotal storytelling do not fit the formal structure of research reports. But they offer a mechanism for field ecologists to develop a repertoire of practice that is crucial in working in complex field settings.

Limitations of the Analysis

The practices and themes highlighted in this analysis help describe how ecologists transform natural objects to scientific knowledge while working in settings that are laced with uncertainty (Roth & Bowen, 1999). They offer a useful way to characterize this epistemic work. However, they are not the only way one could do so. They also do not necessarily address the full scope of the practice of field ecology.

A Partiality for the Investigative Sphere of Scientific Activity. Scientific activity is often subdivided into three spheres that describe the work of scientists and engineers: investigating, evaluating, and developing explanations and solutions (National Research Council, 2012). The epistemic practices in this account of field ecology primarily fall into the investigative sphere of activity (although the choices made during such investigations also impact other activities such as evaluation and explanation). This imbalance is not necessarily a disparity in the overall practice of field ecology, but instead likely stems from how and why social scientists have researched and reported on the practice.

The impetus for many of the social studies of field ecologists reviewed in this analysis was a need to provide a counter-narrative to the account of experimentation that has dominated the discussion of scientific practice (Bowen & Roth, 2007; Korfiatis & Tunnicliffe, 2012). Understanding how ecologists construct data during field investigations forms the foundation for this counter-narrative. Therefore the research studies used to ground this analysis primarily focused on investigative work done in the field (e.g., Bencze & Elshof, 2004; Leon-Beck & Dodick, 2012; Mayernik et al., 2013). An analytic focus on what happens out in the field likely produces a biased snapshot of overall practice because, as discussed earlier, the work of ecologists extends across time and space as they move into and out of the field. Therefore, this account of practice (though consistent with the available studies of knowledge production in field ecology) is not necessarily comprehensive of all practice across the domain.

The "Hidden" Practice of Modeling. In particular, a discussion of modeling, what is widely considered to be the foundational practice of science (Giere, 1988; Lehrer & Schauble, 2010; Nersessian, 2008), is largely absent from these studies. We know from reports written by ecologists and studies outside of field contexts that field ecologists do engage in modeling (Hall, Stevens, & Torralba, 2002; Lorimer, 2008; Mauz & Granjou, 2013). However, it may be that modeling is not a focus while in the field and primarily takes place in other settings. It may also be that, in the field, modeling is more tacit than other practices and thus less directly observable.

The representational choices ecologists make in documenting and analyzing their observations are crucial for how they are able to model the phenomena they study. In Latour's (1999) description of field research at the forest-savannah boundary, it is the spatial representation of that boundary that enables the mechanism of earthworm activity to possess explanatory power for the system. Other studies also hint at how representational infrastructure is vital in supporting explanatory modeling outside of the field setting (Griesemer, 1990; Hall et al., 2004; Lorimer, 2008). However, most of the studies in this analysis did not follow the ecologists once they moved out of the field. This truncated their account of ecologists' larger system of practice and likely contributed to the lack of description of the practice of modeling in these studies.

Within the larger discipline of ecology there is also a divide between the field and the laboratory that goes beyond a simple division of physical space. Studies of what different ecologists value in their community suggest a disconnect between those whose primary work involves field observations and those whose primary work involves forms of modeling (Mauz & Granjou, 2013; Reiners, Reiners, & Lockwood, 2013). Thus there is a need for an explanation of knowledge production in the entire discipline of ecology that traces ecologists' work across the field and the laboratory and accounts for these multiple perspectives of the domain. Such a comprehensive description of the larger discipline is beyond the scope of this analysis.

Implications for the Design of K-12 Science Learning Environments

The practice of field ecology is a story of how scientists flexibly negotiate complexity and variation to uncover meaning in natural settings. This story has unique affordances for highlighting certain aspects of the nature and practice of science. These aspects of scientific practice are not necessarily unique to the field ecology, but they may prove more effectively employed in learning environments structured around field ecology (Bowen & Roth, 2007). The specific affordances of field ecology for the design of K-12 science learning environments arise from how the characteristics of field settings problematize practices so that they are functionally emergent in response to a local need (Engle & Conant, 2002; Ford, 2015; Hodson, 2014; Manz, 2014).

The Affordances of Field Ecology for K-12 Learning

Field research foregrounds the situated nature of scientific knowledge and practice and how these co-develop across time (e.g., Bencze & Elshof, 2004). This evolution of practice can highlight how data is not "found" in science, but is actively constructed by scientists' (or students') actions (Bowen, 2003; Ford, 2015; Mayernik et al., 2013; Roth & Bowen, 2001a, 2001b). This underscores how scientists actively arrange conditions for seeing phenomena and is in stark contrast to the way students typically experience scientific investigations - as activities in which phenomena have been previously arranged by others (Lehrer & Schauble, 2010).

Students need opportunities to develop scientific practice and perspectives by planning and carrying out investigations in natural settings outside of experimental laboratories (National Research Council, 2012). However, current trends in ecology education tend to disconnect students from the complexities of data construction in favor of designs that privilege data analysis and argumentation. Most current research into K-12 learning environments for ecology utilize simulations, gaming technologies, or large-scale data sets to promote student learning about complex systems (e.g. Basu, Sengupta, & Biswas, 2014; Bestelmeyer et al., 2015; Hmelo-Silver, Liu, Gray, & Jordan, 2015; Stevenson, Klemow, & Gross, 2014). Though these are effective at simplifying complex ecological systems so that students can use data patterns to uncover causal processes, the designs often restrict students to analyzing and modeling bounded forms of data in which pertinent variables and measures have already been established. In contrast, ecological field research has the potential to promote the development and adaptation of students' practice as they construct data from broader systems.

The complexity and variability of field settings can be harnessed to create a need for students to wrestle with question development, selecting and operationalizing variables, and sampling - aspects of science that K-12 students rarely experience as a stable construct let alone as an emergent practice (Bowen & Roth, 2002). Such learning opportunities, however, are not guaranteed. Even learning environments situated within field settings, such as EcoMOBILE's innovative curriculum integrating augmented reality (Kamarainen et al., 2013), at times subordinate opportunities for students to make decisions about data collection to opportunities for them to engage in data analysis and explanation. However, well-crafted learning environments in field ecology can support students in meaningfully encountering issues of uncertainty around data construction. In addition, because students have to find ways to transport the field back to the classroom, field settings can encourage inventive and adaptive tool use and the construction of representational systems. Finally, field research can create a need for students to develop and rely on a local community of practice.

Because it privileges local knowledge, flexible practice, creative tool development, and a collaborative community, some have suggested that experiences with field ecology might make the discipline of science more amenable to a broader range of students (Armstrong, Berkowitz, Dyer, & Taylor, 2007; Bowen & Roth, 2007). I would argue, however, that the power of field ecology does not just lie in its ability to inspire traditionally marginalized students, but also in its ability to inspire the use of traditionally marginalized scientific practices for all students. As such, it can alter how educators bring students into contact with science, which in turn may alter students' perspective of the discipline (Engle & Conant, 2002; Hodson, 2014; Stroupe, 2015). Field ecology seems to have particular promise as a venue to develop K-12 students' sampling practice. This aspect of data collection is alluded to, but not developed, within the NGSS framework (National Research Council, 2012). A better understanding of sampling could not only help students in critiquing ecological arguments but it could also help students make more informed decisions about the number of trials or the conditions to control within experimental studies.

At the same time, not every aspect of the practice of field ecology is amenable to K-12 learning environments. In particular, although the negotiation of environmental stressors functions in creating a community of professional ecologists and sustaining research in hostile settings (Bowen & Roth, 2002; Leon-Beck & Dodick, 2012), the legitimacy of this theme in the practice of K-12 students is questionable. Most learning environments in K-12 education are not intended to immediately induct students into the professional community. Consequently, the function of environmental stressors in establishing the identity of ecologists is not warranted. In addition, K-12 learning environments must privilege student safety even to the expense of authentic practice. This is not to say that students will be able avoid environmental stressors altogether. Students studying even a fairly benign creek in fair weather will likely return with their own version of survival stories of spotting a water snake from a distance or slipping on a wet stone. These stories can create powerful bonds that mark a community of student-ecologists. Those absent during fieldwork might even be jealous of these experiences. However, the design of K-12 learning environments should seek to minimize the mental and physical environmental stressors of field settings rather than emphasize them.

General Principles for Designing K-12 Learning Environments in Field Ecology

Given these affordances, questions still remain about how to support students in the practice of field ecology. The prior analysis does not validate specific approaches to teaching and learning. However, it does suggest potential design principles that may prove effective in constructing K-12 learning environments in field ecology. These principles have emerged from studies of how ecologists construct knowledge while in field settings. However they are also supported by studies of learning environments that productively engage students in scientific modeling (Lehrer & Schauble, 2012). These design principles suggest potentially fruitful directions for future research into the design of K-12 learning environments in field ecology.

Design Principle 1: Foster repeat experiences within the same ecological setting.

The studies of field ecologists repeatedly show that familiarity with a specific setting is important for the evolution of practice and development of theory, particularly for novice researchers (Bowen & Roth, 2002, 2007; Leon-Beck & Dodick, 2012; Lorimer, 2008; Roth & Bowen, 1999, 2001b). Likewise, K-12 students need opportunities to build personal local knowledge over time at a field setting. This experience is important for supporting them in developing emergent and adaptive practices. Students logically have less time to devote to fieldwork than the typical field season of an ecologist. However, designers can amplify the effectiveness of students' limited time by selecting field sites that are spatially bounded and that are familiar within the local community. These criteria serve to minimize the overall complexity of the system and support an initial sense of place. Designers should also allow for repeated observational experiences in the field before pressuring students to take sophisticated interpretive stances (Tomkins & Tunnicliffe, 2001).

Design Principle 2: Problematize variation as a lever for emergent and adaptive epistemic practices. As students conduct their own field research, their initial approaches and interests might not always be conducive to productive practice. Students need designed opportunities and reasons to adapt their practice. In field ecology, variation often provides the impetus to refine research agendas, observations and measures, or sampling protocols (Bencze &

Elshof, 2004; Bowen & Roth, 2007; Leon-Beck & Dodick, 2012; Nygren & Jokinen, 2013). Designers can purposively draw attention to productive forms of variation that students encounter and use this variation to problematize students' practice (Engle & Conant, 2002). In order to accomplish this, students will need guided support in what types of questions might be accessible in this field setting, how difficult variables might be measured, and what types of variation might be worth attending to. For example, questions about organism behaviors might be less productive for short-term research than questions that connect an organism to habitat conditions (Madden et al., 2012). Designers might also encourage students to initially focus on ecosystem features, such as water depth or speed, for which students likely have rich initial resources for measuring, self-monitoring through coarse observation, and making sense of. Features that exhibit strong patterns of co-variation with other observable system processes are also rich targets for initial student study as this can be used to compel the evolution of research questions and sampling practice.

Design Principle 3: Support students in developing tools and inscriptions to rearrange conditions for seeing. The representational infrastructure threaded throughout ecologists' practices enable them to see phenomena in new ways and make sense of observations scattered across research settings or across time in the same setting (Latour, 1999; Lorimer, 2008; Roth & Bowen, 1999, 2001a). As they learn to wrestle with the materiality of field settings, students need support in using tools and inscriptions to create their own new language of observation (Lehrer, 2009; Tomkins & Tunnicliffe, 2001). Material means such as tools and representational practices such as inscriptions enable ecologists to transform natural phenomena into ecological arguments. Whether they are developed or appropriated by students, it is essential that these tools and inscriptions have meaning for students and meet an epistemic need in the design. For example, designers do not have to make students develop their own way of testing nitrate levels in a pond. Students can appropriate the use of standard test trips for this purpose. However, designers should craft opportunities for students to understand why and how such strips change color and have students negotiate when and where the use of such strips might support their investigations.

Design Principle 4: Create an opportunity and a need for a local community of practice. Students need support in working collaboratively to understand a system. In field ecology, collective work emphasizes the social construction of knowledge, supports tangential members in becoming active knowledge-producers, legitimizes forms of practice, and spreads research findings across the community (Feldman et al., 2013, 2009; Richard & Bader, 2010; Rozenszayn & Assaraf, 2011). Designers can create a need for a local community of practice by situating student work in a field system that is large enough or complex enough that individual students must rely on the work of others to help answer their research questions. Opportunities for collaborative work can also be built into the design by simply having students work in structured groups in the field.

Once the need to learn from others is established, class research meetings can be used to spread research findings across the student community and can be an effective means to refine what counts as good practice (Lehrer et al., 2008). These meetings can be designed to foreground many aspects of scientific practice, including the modes and means of disciplinary argument, evaluation, and critique (Ford, 2015; Lehrer, 2009; Manz, 2014; National Research Council, 2007, 2012). They can also provide rich opportunities to use different student experiences to draw attention to variability within a system and to meaningfully problematize issues of uncertainty. Finally, as a classroom is primarily a community of novices, designers can leverage the material pushback within different activities, the voice of the teacher, and declarative exemplars of disciplinary practice as additional sources students can draw upon to evaluate, critique, and reach new stabilizations of practice.

Conclusion

For scientific practices to be meaningful for K-12 students, science educators need to design learning environments that support the development of practices in response to epistemic needs. Learning experiences grounded in field ecology have the potential to promote such evolution of practice. Field settings compel both ecologists and students to wrestle with variation and complexity and manage multiple spatiotemporal dimensions as they move into and out of the field. This can provoke the emergent evolution of practices such as designing research agendas, observation and measurement, and sampling. In the struggle to master the materiality of nature, ecologists and students must recruit tools, inscriptions, and the broader disciplinary community as they move across and manage disjointed spheres of activity. All of these aspects of the practice of field ecology present potential levers that designers can use to create a tangible need for students to develop their own meaningful approximations of scientific practice.

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CHAPTER II
SAMPLING IN THE WILD: HOW ATTENTION TO VARIATION SUPPORTS MIDDLE SCHOOL STUDENTS' SAMPLING PRACTICE

Introduction

In science, claims are made and evaluated in light of how data are constructed. This focus on how data is built has led many scientific disciplines, including that of field ecology, to develop sophisticated practices for collecting data - practices of observation, representation, measure construction and sampling (Coe, 2008; Eberhardt & Thomas, 1991; Kenkel, Juhász-Nagy, & Podani, 1990). Current frameworks for science education advocate for K-12 students to learn science by engaging in these investigative scientific practices (National Research Council, 2012). However, students are rarely invited to grapple with the complexities of practices such as sampling. This paper reports on a design study in which middle school students sought to understand the ecology of a local creek and in the process advanced their scientific practice. In particular, it focuses on how ideas about variation, a fundamental facet of ecological research, played out in students' sampling practice.

Theoretical Framework

Science (and Science Education) – as - Practice

For the past decade, science education has increasingly advocated for student participation in the practice of science (Ford, 2015; Mody, 2015; Stroupe, 2015). This new construct of practice has primarily been informed by studies of how scientists conduct their own work. These studies have elucidated how scientists form an epistemic community of practice with specific means of legitimizing how knowledge is constructed (Knorr-Cetina, 2009; Latour & Woolgar, 1979; Lave & Wenger, 1991; Nersessian, 2008). The activity within this community is orchestrated by historically developed social norms and arrangements of performances that shape both the individual and the communal scientific search for a better explanation of nature (Ford, 2015). Within this community, practices emerge as stabilized interactions of these performances that have been evaluated, critiqued, and reified as appropriate means, at least for the present, to conduct this search. As knowledge and norms evolve, what the community counts as appropriate scientific practice also shifts. Currently, science education has specified eight practices that are important for student understanding of science: asking questions and defining problems, developing and using models, planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking, constructing explanations and designing solutions, engaging in argument from evidence, and obtaining, evaluating, and communicating information (National Research Council, 2012). These distinctions provide the science education community a common language for discussing practice; however, because practices are grounded in interactive performances, the bounds of any individual scientific practice can be fluid.

The practice shift in science education emphasizes engaging K-12 students in meaningful approximations of the disciplinary work of scientists within a local community (Ford & Forman, 2006; Kelly, 2011; Osborne, 2014; Richard & Bader, 2010). However, the goal is not for students to learn how to replicate current stabilizations of disciplinary performances. Nor is it for practices to merely serve as a means of promoting the development of core content knowledge. Rather, the objective is for students to learn how to progressively refine both their explanations of nature and the ways in which they develop those explanations. In order to achieve this, students need opportunities to participate in their own progressive stabilization and evolution of scientific practices over time (Ford, 2015; Stroupe, 2015). From this perspective, an effective learning environment for science would be one that supports the co-development of students' knowledge and practice in ways that promote students' own critique of that process (e.g., Manz, 2012, 2014). Though this evolution of practice can be informed by the norms of how the larger scientific community has itself stabilized practice (Duschl, 2008), it privileges student agency by leveraging students' ideas and questions, the materiality of the system, and community dynamics to create a local need for change in a particular practice, rather than presenting disciplinary conventions a priori to students.

All of the sciences engage in similar disciplinary work; however, the different domains of science are also characterized by subject-specific forms of practice. Because of this, science educators have to make decisions about which forms of scientific practice to emphasize in K-12 learning (Stroupe, 2015). Education has historically privileged the practices and experimental methodologies of lab-based domains over field-based naturalistic studies (Gray, 2014). In addition, most of the research on how to support the scientific practice of students has focused on the practices of modeling, explanation, and argumentation (e.g., Berland et al., 2015; Manz, 2014; Nielsen, 2011; Sandoval & Reiser, 2004; Schwarz et al., 2009; Svoboda & Passmore, 2011). Because of this, there are many practices influential to the construction of scientific knowledge that are often overlooked within science education. One such practice is the practice of sampling.

The Ecological Practice of Sampling

One of the dilemmas scientists face when conducting research in field settings is that it is impossible to collect data exhaustive of the system. Scientists must therefore make decisions about where and when to measure. These methodological issues of time and space are essentially questions about the epistemic practice of sampling: where should plots be set, what size should they be, how often should they be checked, etc. (Coe, 2008; Eberhardt & Thomas, 1991).

Though sampling is related to the practice of measurement, they are stabilizations of different forms of activity and have emerged in response to different questions about research. Sampling provides a way for scientists to narrow the field setting into manageable units to study while measurement deals with what scientists attend to about the units that they have secured access to through sampling. Sampling is a practice inherent to many field sciences, including geology and paleontology. This paper, however, centers on how sampling is enacted within the domain of ecology. Ecology is the study of the characteristics, abundance, and distribution of living organisms and the relationships within and between these organisms and their environments (Korfiatis & Tunnicliffe, 2012). Like many scientists, ecologists utilize laboratory experiments and modeling environments in their work; however a preponderance of ecological research is conducted in field settings (Eberhardt & Thomas, 1991; Korfiatis & Tunnicliffe, 2012; Lefkaditou, Korfiatis, & Hovardas, 2014).

Mörsdorf et al. (2015) articulated the feelings of many of their ecological colleagues when they bluntly stated, “Sampling in ecology can be challenging” (p.1). This difficulty stems in part from the inherent complexities of field settings and in part from how ecological studies at times diverge from the objectives emphasized in classical statistical sampling theory (Kenkel et al., 1990). Some ecological investigations are concerned with estimating parameters of populations with discrete sampling units, such as the mean tree height. These studies are similar to those that ground sampling theory in statistics. However, other ecological investigations focus on uncovering patterns of distribution or variation in continuous settings, such as clumped patterns of floral diversity. In these studies, ecologists often make methodological decisions that purposefully maximize variation between samples or create arbitrarily defined sampling units, issues not readily addressed in classical sampling theory. Though ecologists have to struggle to manage and interpret variation in each type of investigation (Pickering, 1985), their response to that struggle can differ from study to study. Thus the appropriateness of any one sampling procedure depends on the context: the study objectives, variables measured, and characteristics of the specific ecological setting.

The struggle with variation has been influential in the disciplinary evolution of the ecological practice of sampling. In the early 1900's ecologists described their field settings in narrative form, but they either did not detail how they selected units to measure within that setting (e.g., Hofmann, 1920; Praeger, 1920; Wherry, 1920) or else they used a convenience approach and selected the most readily accessible units (e.g., Douglass, 1920; Esterly, 1920). As the discipline evolved, ecologists began to justify decisions about when and where they collected their measures based on the purpose of the study or characteristics of the phenomena (e.g., Byram & Doolittle, 1950; Pavan, Dobzhansky, & Burla, 1950; Schmidt-Nielsen & Schmidt-Nielsen, 1950; Shotwell, 1950; Walton Smith, Williams, & Davis, 1950). Ecologists' attention to how they were selecting units for analysis emerged as a response to the conflicting knowledge claims that resulted from unexpected variations in data. Foreshadowing this emergence of practice, Esterly (1920) briefly noted that some of the anomalies in his findings might have stemmed from what he had originally thought to be inconsequential differences in how he collected his samples. Over time, the need to manage the bias in data caused by variations across known gradients gave rise to systematic forms of dividing up space and time (e.g., DeWoskin, 1980; Ewald, Hunt, & Warner, 1980; McClure, 1980; Rogers, 1980; Stephenson, 1980; Tobiessen & Werner, 1980). In addition, randomization began to take hold as a way to reduce bias from unknown, and thus unpredictable, gradients of variability. Though contemporary ecologists still justify aspects of sample selection based on either convenience or purposive consideration of the phenomenon, most also apply some form of systematic or randomized approach to location, timing, or unit subdivision when sampling (Alberto et al., 2010; Biswas & Mallik, 2010; Bridgeland, Beier, Kolb, & Whitham, 2010; McLellan, Serrouya, Wittmer, & Boutin, 2010; Patterson, McConnell, Fedak, Bravington, & Hindell, 2010; Ravet, Brett, & Arhonditsis, 2010).

Today's field ecologists describe sophisticated methods of sampling that are highly situated and influenced by the nature of the problem under investigation, features of the ecological system, and characteristics of the relevant sampling unit (Coe, 2008; Eberhardt & Thomas, 1991; Kenkel et al., 1990). These methods permeate the ecological literature, offering general procedures for sampling everything from fuel loading in forests to plant diversity (Bacaro et al., 2015; Sikkink & Keane, 2008). This literature serves as a key social resource ecologists use to construct initial sampling plans. However, when ecologists try to enact these initial sampling plans in the field, they become problematized by unforeseen complexities and spatial and temporal variation (Latour, 1999; Lorimer, 2008; Roth & Bowen, 2001). As their initially fixed protocols become more nuanced and flexible, ecologists struggle to balance the need to adapt sampling protocols to the local context with the need to preserve the social normality and universality of their approach. This sets up a dialectic of constraint satisfaction between material and social critique, even when ecologists are working alone in the field.

Although it is often enacted at the individual level, sampling is a social practice as the ultimate aim of the ecological community, their ability to explain nature better, hinges on being able to compare and validate individual knowledge claims (Ford, 2015; Mörsdorf et al., 2015). These claims in turn are dependent on ecologists' sampling decisions. Because of this, when ecologists want to shift the normalized disciplinary approach to sampling, they often design studies that specifically argue how different sampling protocols generate different findings (e.g., Bacaro et al., 2015; Kenkel et al., 1990; Mörsdorf et al., 2015; Schweiger, Irl, Steinbauer, Dengler, & Beierkuhnlein, 2016; Sikkink & Keane, 2008). Social distribution and discussion of these methodological studies in formal and informal settings allows for the practice of sampling to evolve in the larger disciplinary community through progressive evaluation and critique. The impetus for this evolution of practice comes from the competing knowledge claims that emerge when researchers use different sampling protocols to investigate similar phenomena and arrive at conflicting results (Bacaro et al., 2015).

Students, Sampling, and Field Ecology

Sampling is a potentially powerful practice for supporting students' broader understanding of the endeavor of science because it foregrounds how data is constructed. It touches on how different scientific studies might produce different findings, how clear forms of communication are essential within the scientific community, and how the objectives of scientific research permeate investigative and interpretive decisions (Kenkel et al., 1990; Mörsdorf et al., 2015). On the other hand, sampling is also a complex and contingent practice for even professional ecologists. Because of this, some might question whether it is an appropriate practice to explore with students. However, the educational goal is not for K-12 students to replicate current disciplinary stabilizations of sampling, which would indeed be an inappropriate learning target. Instead, the objective is to engage students in the meaningful local evolution of an appropriate approximation of the practice.

Curriculum designs, however, rarely invite K-12 students to wrestle with the complexities of how the practice of sampling ecological systems impacts the data collected and the claims that can be drawn from that data. Rather, typical pedagogical approaches often dictate sampling methods or allow students to arbitrarily choose protocols with little reflective activity (e.g., Council for Environmental Education, 2006). Many of these approaches undermine the complexity of the practice by assuming the reliability of small samples and overlooking issues of variability. Even the more sophisticated curricular designs tend to simply promote randomization procedures rather than explore the relationship between the study's question, context, and sampling design (Stier, 2010).

The practice of sampling has similarly been overlooked in most science education research. However, a few studies have begun to elucidate how to potentially support students' sampling practice. Lehrer and Schauble (2012) found that when middle school students engage in ecological field investigations they most often initially focus on collecting as much of something as possible, no matter their research question. In this hunt to count and measure things, students often think they are working to find the one right answer. If they mime any complex sampling practice, such as replication, it is to "double-check" their answer or ensure that they have not missed anything. Students rarely invoke other elements of sampling, such as differentiating space, except as a way to ensure that they have not missed counting something. When Metz (1999) explored sampling with elementary and middle school students who had conducted their own research projects on plant growth and animal behavior, 41% of students exhibited at least a limited understanding of the influence of sampling on their research. During post-interviews about their research, these students recruited ideas such as sample size, replication, stratification, and trends in data to critique their studies. However, most still insisted that they needed to test every member of a population to be confident of their findings, particularly in contexts with variability. Neither of these studies, however, specifically explored shifts in students' sampling practice as they conducted their investigations.

Research in statistics education can shed additional light on how students reason about sampling, though this research primarily focuses on students' understanding of probabilistic reasoning and randomization in situations such as selecting candy or flipping coins. Studies indicate that middle and high school students often treat all possible outcomes in a likely range as equally probable, rarely reason proportionally about distributions in sampling situations, and frequently search for a causal mechanism to explain random variation (Reading & Shaughnessy, 2000, 2004; Sharma, 2000; Shaughnessy, Ciancetta, & Canada, 2004; Torok & Watson, 2000; Wroughton, McGowan, Weiss, & Cope, 2013). As with the elementary science students (Metz, 1999), these statistics students often struggled because they did not have an adequate feel for either the scope or the source of variation likely to be encountered in different sampling situations.

For professional ecologists, encounters with variation have been influential in the disciplinary evolution of the practice of sampling. It may be that similar encounters with variation could be productively leveraged to provoke the development of students' sampling practice. Variation is an inherent part of ecological fieldwork. As soon as students step into the field, they will be confronted by variation - even if they only perceive it on a gross level. One area of a field might be in shade while another area is in the sun. Wildflowers might clump in one area and grasses in another. Or the currents in a creek might be constantly shifting. Students can easily notice these differences. Uncovering the sources of variation contributing to these differences, however, is more complicated. Consider a student who observes that some clumps of grass in a field are taller than others. Both random natural variation and directed causal processes such as the amount of sunlight have contributed to this variability in perceived height. Should the student choose to explore this phenomenon by measuring the height of the grass, this would introduce another source of variation as natural variation, causal processes, and now measurement error would all be contributing to variability in the measured height of the grass clumps.

Despite this complexity, students do have rich resources for thinking about variation. Studies have shown that middle school students can successfully reason about distributions of variation due to repeated measures as well as causal forms of variation (Lehrer & Kim, 2009; Lehrer & Schauble, 2004; Petrosino, Lehrer, & Schauble, 2003). These ideas about variation have the potential to support students in making sense of ecosystem processes. However, students seem to need substantial familiarity with data patterns in the specific context in order to recruit these resources. Without this, students often struggle to negotiate multiple sources of variation and relate these sources to the sampling context (Metz, 1999; Pfannkuch, 2008; Watson & Kelly, 2002; Wroughton et al., 2013). In such instances they often construct causal stories to explain away random variation, especially in contexts that highlight natural variation or about which they have strong beliefs. In addition, students' ideas about variation often remain disconnected from their approaches to collecting data and are thus not translated into action when designing scientific investigations. These open questions about how students might approach sampling in complex contexts such as ecological field settings and how one might support the meaningful local evolution of this practice have provoked the development of this study.

Research Question

Because of the relatively small research base on students' sampling practice, I began this exploratory study with the broad research question: How does middle school students' scientific practice develop within the context of ecological fieldwork? This broad focus was systematically refined through the process of analysis, as will be described later. Thus this paper reports more specifically on the question: How can attention to variation support middle school students' development of a more sophisticated sampling practice?

Methods

In order to better understand the development of students' sampling practice, I conducted a design study (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003) with middle school students in which they worked to better understand the ecology of a local creek. This creek was superficially familiar to the students as it flowed through the center of their small rural town (Fig. 1). Most passed by it on a daily basis, and many had explored it recreationally at some point in their life. However, none reported ever investigating the creek from a scientific perspective or substantially thinking about how the different parts of the creek might work together to form an ecosystem. The overarching questions "What type of place is the creek?" and "How do different parts of the creek ecosystem interact?" guided our investigation.

Figure 1. "The Creek" study site

Study Participants and Context

Two classes of sixth-grade students from a rural public middle school in the southern United States participated in this study. These two classes were taught by the same math/science and literacy/history teaching team. A total of 48 students (94%) consented to participate in the study, although all students joined in the learning activities. In each class I also followed a focus group of four students in more detail. The math/science teacher selected these eight focus students to be representative of the demographics of the two classes and span a diverse range of initial competency in science.

The middle school in which this study took place served a student population that identified as 87.1% White, 9.4% Hispanic or Latin@, and 3.4% other races or ethnicities. Most of the students (61%) qualified for free or reduced student lunch, and only a few (7%) had limited English proficiency. In the year of this study, 77% of the sixth-grade students tested proficient or advanced on their state mathematics assessment. The prior year, 62% of this same population of students tested proficient or advanced on their fifth-grade state science assessment.

Instructional Design

The study took place over the equivalent of three weeks of science class (three class periods in December and ten class periods in May). Each class period lasted 35-40 minutes for a total of approximately 8.5 hours of instruction. During the study the students conducted three mini-cycles of investigation (Table 1) in which they formulated research questions and hypotheses, designed data collection plans, grappled with the materiality of the creek, and analyzed their findings. Each investigation cycle incorporated opportunities for students to iteratively refine their practice based upon personal and collective experiences. These cycles culminated with students constructing informal inferences about ecosystem relationships within the creek based on computer models of their data. The overall learning environment for this design study was structured to account for various elements conjectured to support the development of students' scientific practice, including prior work investigating repeated measures, multiple inscriptions of the creek, tools to collectively present and contest findings, and general opportunities to attend to variation. As this form of instruction was novel to the math/science teacher, I served as the primary instructor during these class periods. However, the math/science teacher freely interacted with students throughout the investigations and often posed questions during small group work and whole class discussions.

Table 1.

Summary of Instructional Design for Students' Creek Investigation

Cycle 1 December (2 hrs)	Cycle 2 May (3.25 hrs)	Cycle 3 May (3.25 hrs)
Day 1: Class Discussion – What type of place is the creek? Day 2: Small Group Planning Day 3: Creek Visit 1	Day 4: Class Discussion – How do the different parts of the creek interact? Day 5: Small Group Planning Day 6: Creek Visit 2 Day 7: Small Group Data Analysis Day 8: Class Research Meeting	Day 9: Small Group Planning Day 10: Creek Visit 3 Day 11: Class Data Exploration Day 12: Small Group Data Analysis Day 13: Class Discussion – Could patterns we see be due to chance?

The instructional design integrated balanced learning goals across what Hodson (2014) has called learning science, doing science, and learning about science. Many of the class discussions focused on "learning science" and aimed to build students' conceptual understanding of interdependent relationships in ecosystems, cycles of matter and energy transfer, and ecosystem dynamics and functioning. These discussions, however, were also grounded within students’ experiences “doing science” as they planned and collected data during their creek investigations. In addition, meta-conversations for “learning about science” were threaded throughout the instruction to support students in making sense of the characteristics of good research questions, ways to productively critique the inquiry of others, and conventions for visualizing and exploring data. As will be detailed in the description of each cycle, the instructional design supported the co-development of multiple aspects of students’ scientific practice and ecological content knowledge. However because of the need to expand the research base on sampling, the findings of this study focus specifically on the emergence and evolution of students’ sampling practice.

In my role as the researcher, I formulated the initial plans and made the final decisions regarding the instructional design. However, many of the specifics of each day’s enactment were flexibly negotiated with the math/science teacher of the two classes in this study as well as the math/science teachers of four other sixth grade classes with which I was working at the same time. Because of this collective decision-making, I will often purposively use plural pronouns when discussing different details of the instructional design.

Summary of Cycle 1: Days 1-3. The first cycle of investigation focused on familiarizing students with the setting of the creek, with participating in guided scientific inquiry, and with myself as an instructor/researcher. Following a brief introduction by the classroom teacher, I began our first day with a discussion framed around the question “What type of a place is the creek?” We blended partner and whole class discussions to generate class lists of what we might see at the creek, what we might want to investigate, and what observations we might want to record during our first visit. The aim of this discussion was to leverage students’ initial ideas about the creek to first broaden the scope of what might be important to attend to and then narrow this to questions that might be possible to empirically explore. Students began by focusing on the living things, such as fish, frogs, and crawdads, that they expected to see at the creek. With my support they broadened this list to also include nonliving elements, such as the substrate and water. When discussing what we might want to learn about the creek, students initially focused on "what" questions about the biotic life, such as "what types of fish are in the creek". With guided questioning, students once again broadened their ideas to different dimensions of the biotic life (e.g., size or number), different dimensions of the abiotic environment (e.g., water depth and speed), and relationships between different elements (e.g., whether different organisms might be found in areas with different water depths). I also drew student attention to how some of the questions they were interested, such as "where does the creek begin", could not be answered by gathering data in the section of the creek we were going to explore. We ended class with a firm discussion about responsible behavior and safety when conducting field investigations. This day was characterized by many "firsts" for all participants. We were collectively interacting for the first time around a form of scientific inquiry that most students had rarely experienced using a discussion format that broke the norms of students' typical science classes within an instructional design that was novel even for myself.

On the second day, the class broke into teams of 3-4 students each and began planning their first visit to the creek. Teams were selected by the math/science teacher to maximize the diversity of ability within each team and minimize the likelihood of personality conflicts. Each team developed their own research question about the creek and plans for how they would collect data to answer that question. Though it was scaffolded by worksheet prompts (Table 2), this planning process proved a struggle for many teams. As students did not yet have a rich sense of what type of a place the creek even was, they fixated on fairly simple questions: "how deep is the water", "how many fish is there", "are there rocks we've never seen", or "how fast it flows". These questions interrogate the basic status of a number of different biotic and abiotic variables, but they do not position the variables in relation to each other or explore patterns across space. Students also became frustrated when trying to figure out how to collect their data because they did not have a sense of what they could and could not do with the variety of equipment that I had provided. In retrospect, the design likely asked too much too fast of the students. As they had not yet "messed around" with either the creek or the equipment, many had limited resources with which to construct research possibilities. Instead, they had to work off of a less productive imagined space.

Table 2.
Summary of Key Worksheet Prompts for Creek Visit 1

Day 2 - Small Group Planning	Day 3 - At the Creek
Developing a Question • Individually, make a list of questions you want to answer about the creek or things you might want to measure • Working together, pick one question to focus on when you are at the creek. • What do you predict you will find out about this question? Designing Data Collection Plans • Plan what you might want to measure to help answer this question • Describe a way to measure that variable • Describe a different way to measure the same variable • Pick one of the two ways of measuring to try first. Why did you choose this method?	General Observations • List three things you notice or observe about the creek • Make a quick rough sketch of the creek Specific Observations • Location #1 – Describe or indicate in some way where this location is. • Look closely, list two specific things you notice about this location. • Take your measurements. Record what you measure, how you measure it, and what your results (data) are. • *Prompts repeated for location #2*

On the third day the students headed out for their first visit to the creek. I gave the class a quick safety briefing when they arrived at the creek, and then the teams set off to conduct their investigations. Each team had access to a personalized selection of tools and equipment tailored to their own data collection plans. For example, a team exploring water speed might have tape measures, flags, ping pong balls, timers, and boots while a team exploring the minnow population might have buckets, dip nets, plastic scoops, and boots. Extra tools were on hand for students to flexibly adjust their measurement protocols when needed. After taking general observations to familiarize themselves with the creek, the teams worked independently to collect data in different self-selected locations of the creek. At times frustrations emerged when teams had difficulty wresting the equipment (and the creek) to their desired purposes. However, excitement also bubbled up when new organisms were discovered or unexpected variation encountered. The math/science teacher and I floated from team to team and monitored safety, helped troubleshoot equipment use, and encouraged students to record what they were discovering. Each class had approximately 25 minutes at the creek for data collection not counting time spent distributing and returning equipment.

We had initially intended to conclude this first cycle of investigation with two days in which students would analyze what they had discovered at the creek and present their findings to others in the class. (The design would have been similar to the research meeting format that will be detailed in the summary of cycle 2). However, we had to end this cycle of investigation prematurely as an ice storm closed the local schools for an extended period of time.

Summary of Cycle 2: Days 4-8. Five months later I returned to the school for our second cycle of investigation. This extended delay was not a purposive element of the instructional design, but rather the result of scheduling limitations. This second cycle focused on supporting students in thinking about how different parts of the creek ecosystem, including the living organisms and abiotic features, might interact with each other. This emphasis on relationships between elements in ecosystems privileges forms of data collection that reveal patterns of covariation.

Because of the length of this break, we chose to once again launch this cycle with a whole class discussion on the fourth day. (Note: I chose to number the days across cycles rather than within cycles in order to better preserve the progression of time.) Since the ice storm had forced us to cancel our research meeting at the end of the first cycle, I structured this discussion so that it would serve a similar function in helping students reflect on what they had discovered and learn from the discoveries of other groups. We began by sharing what we remembered about our observations at the creek, including what we found that seemed surprising, and discussed how different teams had gathered their measures. I then shifted the conversation to focus on whether students thought the creek was a uniform space whether it seemed different in different places. While facilitating this discussion, I purposively brought into contact the findings of different teams who had investigated similar variables in different sections of the creek. As we talked, students often found it difficult to envision where each of the teams had gathered their measures. When this frustration emerged, I proposed using a map as a tool to share and compare our data. When the students reached agreement on this, I pulled out a whiteboard sized hand-drawn map of the creek that I had prepared in advance. If we had had more time, I would have had students generate this inscription themselves. However, I compromised by positioning it in response to a need that had been recognized by the classroom community. We used this map to begin discussing the different relationships that might exist between different elements of the creek. For example, one team thought that the number of crayfish might be related to type of substrate at the bottom of the creek because crayfish seemed to prefer habitats with large rocks. We discussed both a direction (e.g., areas with larger rocks would have more crayfish than areas with smaller rocks) and a rationale (e.g., large rocks might provide more areas for crayfish to hide and ambush their food sources) for each relationship that students proposed. I then shifted the discussion to focus on variation and asked the students whether when we measured a variable in the creek, such as the depth of the water or the number of crayfish, we always arrived at the same value. Students responded that there seemed to be lot of variation in the creek, and they tied this variation to differences in measurement (e.g., one student scooped near the middle of the water while another scooped near the bottom) and causal forces (e.g., one area of the creek might have more food or a better habitat than another area). I added an alternative idea to our list of possible sources of variation - that some of the variation might also be due to chance. I might scoop in the same way in areas that are functioning the same way and randomly get different values. However, we did not delve deeply into this idea at this time, and we concluded by laying out an overview for the week ahead.

On the next day, students once again broke into their teams and began planning their next creek investigations. Because of shifts in the student population as well as student personalities, the math/science teacher elected to assign some students to different teams than the ones they had been a member of back in December. Once again, students' discussions were guided by a worksheet that scaffolded their development of a research question and data collection plan (Table 3). This worksheet prompted students to design an investigation that explored patterns of covariation within two sections of creek. For example, one team decided to investigate whether there were more minnows in areas with higher dissolved oxygen levels. This team designed a plan that compared the minnow population near an island that had lots of plants and thus a potentially high dissolved oxygen level with the minnow population in an area with less plant life and thus a potentially lower dissolved oxygen level.

Table 3.

Summary of Key Worksheet Prompts for Creek Visit 2

<table>
<tr><th>Day 5 - Small Group Planning</th><th>Day 6 - At the Creek</th><th>Days 7 & 8 – Research Meeting</th></tr>
<tr>
<td>
Developing a Question

As a team, pick two variables in the creek that you want to investigate
Write a research question for what your team wants to find out about the relationship between these variables
Describes what your team thinks the relationship is between these two variables

Designing Data Collection Plans

Pick at least two locations in the creek where your team will measure these variables and mark these locations on the map.
Plan how your team will collect data for each variable. In your plan, include how to measure, where to measure, and what to measure with, how many times to measure (samples to take), and what to sample with.

</td>
<td>
Data Collection Table
<table>
<tr><th></th><th>Variable 1: ________</th><th>Variable 2: ________</th></tr>
<tr><td rowspan="2">Location 1</td><td>• Sample 1 –
• Sample 2 -
• Sample 3 –
•
•
•
•
•
•</td><td>• Sample 1 –
• Sample 2 -
• Sample 3 –
•
•
•
•
•
•</td></tr>
<tr><td>Median:
IQR:</td><td>Median:
IQR:</td></tr>
<tr><td rowspan="2">Location 2</td><td>• Sample 1 –
• Sample 2 -
• Sample 3 –
•
•
•
•
•
•</td><td>• Sample 1 –
• Sample 2 -
• Sample 3 –
•
•
•
•
•
•</td></tr>
<tr><td>Median:
IQR:</td><td>Median:
IQR:</td></tr>
</table>
Extra writing space

For more variable, samples, locations, interesting observations, and calculations.

</td>
<td>
Team Presentation Planner

Member #1 - Explains your research question and what you thought the relationship between the two variables might be
Member #2 - Explains where you took your measurements how you measured, and how you sampled each variable
Member #3 - Summarizes the data you collected and puts a post-it note with a measure of center and measure of spread for each variable on map
Member #4 – Describes what you currently think is the answer to your research question, what you need to more confidently answer your research question, and what difficulties you are having or what help you need

Listening Notes
<table>
<tr><td>Team #</td><td>(Circle One)
• I have a question…
• I have a suggestion…
• It surprised me that…</td><td></td></tr>
<tr><td>Team #</td><td>(Circle One)
• I have a question…
• I have a suggestion…
• It surprised me that…</td><td></td></tr>
</table>
</td>
</tr>
</table>

On day six we headed back to the creek for our second visit. The overall protocol for this day mirrored our first creek visit. We began with a safety briefing. Then each team picked up the equipment specific to the variables they were measuring and headed off to the first section of the creek they had decided to investigate. After taking their measures in this first section, the team was to move to the second section that they had selected. Because many students had struggled with organizing their data during the first creek visit and as our time at the creek was limited, we chose to scaffold students' data recording of their two variables of interest at the two locations with a preformatted data table, as was shown in Table 3. This table explicitly prompted students to record the results of each of their samples. Though this form of inscription compelled students to attend to repeated sampling, it was introduced only after students had uncovered a need for collecting more than one sample during the class discussion on day four. Thus it was scaffolding their implementation of an aspect of sampling practice that they collectively valued. Students worked diligently throughout the 25-30 minutes that they had for data collection at the creek. However, many teams ran out of time to collect all the data on both variables at both locations that they needed to answer their research question.

During the last two days of this cycle the class participated in a research meeting in which they analyzed, shared, and compared both what different teams had discovered about the creek and how they had gone about conducting their investigations. The structure of this class research meeting was adapted from the format described by Lehrer, Schauble, and Lucas (2008). On day seven, students worked in their teams to summarize their data and prepare what they wanted to present to the class. Teams were asked to share about their research question, their data collection methods, their findings, and their difficulties (Table 3). Near the end of class we began the first team's presentation. When it was a team's turn to present, the students came to the front of the class and posted their data summary on the class map of the creek on the location they had investigated. Then each team member shared a portion of what they had prepared. Students from teams that were not presenting filled in a listening notes worksheet on which they recorded either a question for the team, something that surprised them, or a suggestion for improving the investigation. When the team members finished presenting, I opened the floor to the whole class for these questions and comments. Some students would share how they were surprised at what a team found, particularly if it was different from what they had noticed in their own investigations. Others would ask for clarification about how the team had taken a particular measure or about the number of samples on which a summary value was based. Many productive exchanges between students bubbled up during these sections of the research meeting. We often had to cut these conversations short in order to ensure that even team would have adequate time to present. I also stepped into the discussion from time to time to ask questions or make comments that compared the findings or methodologies of different teams. On day eight we wrapped up the remaining team presentations. Then, in the final minutes of class we looked holistically at the data summaries that had been posted on the class map and discussed patterns of abundance, variation, and uniformity within the creek.

Summary of Cycle 3: Days 9-13. We began our third cycle of investigation immediately following the second cycle. The focus of this cycle was to empirically determine how different elements of the creek seem to be related and then figure out if these patterns could be explained by chance or if they uncovered ecological relationships and patterns of distribution. In the second cycle a single team often did not have enough time at the creek to gather all the data needed to explore a potential pattern. So in this cycle we would have to pool our collective efforts. We began class on day nine with a short discussion that reviewed what students thought should be included in data collection plans. We also used our class map and what we had learned from each other in the research meeting to spatially divide the creek into four sections for comparison. During this discussion the students primarily used gross difference in water speed and depth in determining where they wanted to draw these divisions. Students then split into their teams and began constructing data collection plans for the next day (Table 4). Each team was assigned a single variable in which that had previously developed expertise (e.g., dissolved oxygen, water depth, number of minnows or length of crayfish) and a single section of the creek in which to work. Each team would bear the sole responsibility for collecting data on this specific variable in this specific section. Teams would then share data with each other in order to answer their research questions. This design served two primary functions. First, it divided the labor so that we could collectively measure all variables of interest to students in all sections of the creek within the limited time that we had in the field. Second, it prompted students to think about and resolve differences in how teams were collecting data on the same variable. After the teams had spent some time individually brainstorming their data collection plans, they joined with the other teams in the class who had been assigned the same variable. The teams shared their different approaches, discussed why it was necessary to collect their data in similar ways, and collectively constructed a joint data collection plan for that variable.

On day ten the students headed off for their last visit to the creek. Once again, we followed a protocol similar to the previous two creek visits. After being briefed on the day's safety concerns and gathering their equipment, each team headed off to their assigned section. Since teams were spread out across the creek, there were fewer instances in which one team's

Table 4.

Summary of Key Worksheet Prompts for Creek Visit 3

<table>
<tr>
<th>Day 9 - Small Group Planning</th>
<th>Day 10 - At the Creek</th>
<th>Day 12 – Small Group Data Analysis</th>
</tr>
<tr>
<td>Background
• Circle which variable your team is responsible for
• Circle which location your team is responsible for
• Based on our previous trips to the creek, we know that our measurements are not always exactly the same each time we repeat them. Describe some of the reasons why the measurements of your variable might be different from time to time

Designing Data Collection Plans
• Plan how your team will collect data for your variable. In your plan, include how to measure, where to measure, and what to measure with, how many times to measure (samples to take), and what to sample with</td>
<td>Data Collection Table
<table>
<tr><td>Our Variable:____________
Our Location: _____________

Team Leader:_____________
Equipment Manager:_______
Data Recorder:____________
Methods Recorder:_________</td></tr>
<tr><td>Sample 1 –</td></tr>
<tr><td>Sample 2 –</td></tr>
<tr><td>Sample 3 –</td></tr>
<tr><td>Sample 4 –</td></tr>
<tr><td>Sample 5 –</td></tr>
<tr><td>Sample 6 –</td></tr>
<tr><td></td></tr>
<tr><td></td></tr>
<tr><td></td></tr>
<tr><td></td></tr>
<tr><td>Mean:
Range:</td></tr>
</table></td>
<td>Research Question
• Pick two variables in the creek that you want to investigate and write a research question
• Describe what you think the relationship is between these two variables

Data Visualization
• Create a graph comparing the mean values of the two variables at two locations
• What is the relationship between these two variables?
• Look at your primary variable. Describe the difference (if any) between the mean values of this variable at the two locations.

Data Exploration
• Compare the two graphs of all the data for your primary variable at the two locations. Do you think there is an actual difference in the variable between the two locations, or do you think this amount of difference could just be due to chance?
• Run the model for your variable in TinkerPlots™. How many of the 100 samples by chance had a difference equal to or greater than the one we found at the creek?
• Based on this model, do you think there is an actual difference in the variable between the two locations, or do you think this amount of difference could just be due to chance?</td>
</tr>
</table>

work interrupted that of another. In addition, since they were only focused on one variable and had by then gained experience in working with the equipment, each team had ample time to complete their observations. Occasionally students were frustrated when they perceived that the section of the creek that they were assigned to was not as interesting as the locations that they had self-selected in cycle one and two. So after a team had collected their part of the communal data, they were encouraged to continue to make their own self-directed comparisons within and across creek sections of their choice. At the end of the day I used all of the teams' data to compile a table summarizing the mean and range for each variable in each section of the creek. Each student received a copy of this data summary sheet.

On the eleventh day the class collectively reviewed and discussed what they and what teams from other classes had discovered during the third visit to the creek. We searched first for patterns within a single variable by looking across the data to see if there were instances, such as with pollution, where the variable seemed to have similar mean values across all creek sections or if there were instances in which a variable, such as the number of water striders, seemed to have different mean values in different locations. Once students were familiar with interpreting the table, I connected the data to various research questions the students had constructed. For example, we considered what the data might tell us about which location might have the best habitat for crayfish. Some students suggested that the third section of the creek had the best habitat because it seemed to have more crayfish, while others suggested that the first section of the creek was the best because it had the largest crayfish. This led to a debate about what might have contributed to these patterns (e.g., competition, smaller crayfish being dislodged by water currents, eggs traveling downstream and then hatching) and about how the way in which we operationalize a variable impacts our findings. I wrapped up the day by modeling how teams would use this data to explore their own research questions about relationships between different variables within the creek. Each team then selected their own question to analyze using the collective data. For example, one team chose to explore whether crayfish prefer colder water temperatures. Another examined whether areas with slower water speeds had fewer water striders than those with faster water speeds. To simplify the analysis, each team focused on comparing their selected variables across only two creek locations.

On day twelve each team worked to analyze the data related to their specific research question. They constructed a scatter plot of the mean values of their selected variables across the two locations, described any relationship they saw between these variables, and calculated the difference between the means of their primary variable of interest at each location (e.g., the difference between the mean number of water striders in the area with slower water and the mean number of water striders in the area with faster water). I then provided each team with bar graphs and box plots based on all of the data points for their primary variable for each of the two locations. Teams used these descriptions of the data to think about whether they thought there was an actual ecological difference between the two locations or if this degree of difference could be due to the role chance plays in sample variation. The teams then used a resampling model that I had created for them in the data visualization tool Tinkerplots™ to further explore the likelihood that a difference of this magnitude could occur by chance. This model pooled the data from the two locations, randomly assigned half to one group and half to another, and then calculated the difference between the means that could occur by chance assignment. Students ran this model 100 times and looked at how often the model produced a difference that was equal to or greater than the difference that we had found in the creek. The teams used the results of all these analyses to draw conclusions about the relationship, if any, between their two variables.

On the thirteenth and final day of our investigation, the students shared what they had discovered in their analysis, and we generated a class concept map (Fig. 2) of the relationships between different parts of the creek. Some of these relationships came directly from the students' analyses (e.g., one team had determined that we could be fairly confident that areas with faster water speeds had fewer minnows), and some of these relationships came from other experiences in the creek or from outside knowledge the students applied to the creek (e.g., the connection between the death of minnows, decomposition, and nitrate levels). To wrap up our investigations, we opportunistically used the exemplar of a young snapping turtle that one group had observed at the creek to trace how changes to one element of the creek might create cascading impacts on other elements.

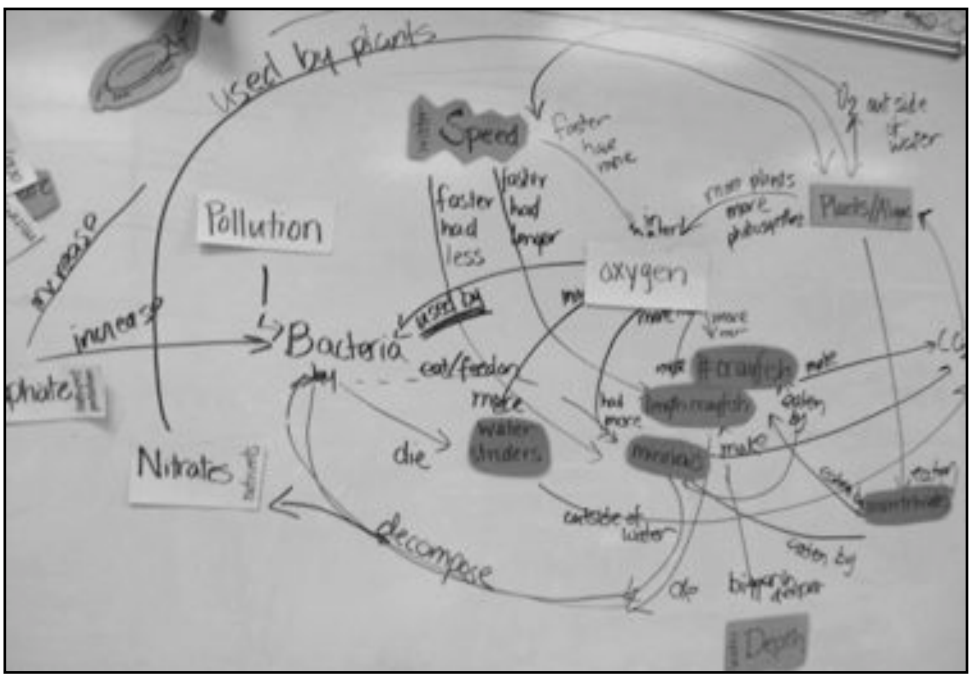

Figure 2. Class concept map of the creek

Data Collection and Analysis

Throughout the study I collected data on students' sampling practice from a variety of sources including focus student pre- and post-interviews, pre- and post-tests, student written artifacts, and video records of student activities both in class and at the creek. I began my analysis by focusing on the source that captured the most detail about students' sampling decisions - the focus student interviews. From these interviews I isolated three key shifts in students' sampling practice. I then analyzed students' pre- and post-tests to see to what extent these shifts were also revealed in this work. Finally, I used students' written artifacts and the video record of students' activities to describe when and how these shifts emerged in students' practice. Details of each data source are provided below.

Focus student interviews. I conducted individual semi-structured initial and final interviews around a variety of hypothetical scenarios involving measurement, sampling, and variation with each of the focus students (Appendix A). For example, students were probed about their thinking around the following scenario:

> Benson decided to use a net to sample once in the morning and once in the afternoon. He counted four butterflies in the morning and nine in the afternoon. Given his findings, can Benson be confident that there are usually more butterflies in the park in the afternoon? Why or why not? Suppose it's true that there really are usually more butterflies in the park in the afternoon. If that's right, do you think that Benson will always catch more butterflies in the afternoon than in the morning? Why or Why not?

Because interviews could only be administered outside of students' instructional time, initial interviews were conducted opportunistically throughout the first five days of the study. Thus some students were interviewed before their first visit to the creek while others were interviewed before their second visit. All final interviews were conducted after the last instructional day. Each interview lasted approximately 20 minutes. During the final interview, I also asked students to describe various elements of their creek investigations, such as what question they were trying to answer, what they found out, and how their group had made decisions about sampling. Interview findings are reported for the seven focus students for which there are paired initial and final interviews.

I looked holistically at each interview and used a grounded theory approach and the constant comparative method to code the various ways students were talking about samples and sampling (Strauss & Corbin, 1990). I then compared the codes from the initial and final interviews to identify themes about how students' decisions about sampling had changed over the course of the investigation. These themes highlighted three key shifts in students' sampling practice. Coding exemplars of each shift are included in the findings.

Student pre/post-tests. Each student completed an individual pre-test at the start of cycle 2 and a post-test after the last instructional day of cycle 3. The math/science instructor had advised that, as the students had very limited experience in designing their own scientific investigations, many of them would likely leave the pre-test blank if it was given before we had done any work together. Because I was interested in tracing the emergence of sampling practice, having the students complete the pre-test on day four of our investigation would still enable me to capture students' practice at an early stage. Findings are reported for the 37 students (74%) with paired pre/post-tests.

The pre/post-tests present an imaginary scenario in which students design an investigation to determine whether the number of grasshoppers in an area is related to the soil temperature (Table 5). Though the scenario was designed to be similar to the types of investigations the students conducted in the creek, it is situated in an unfamiliar ecological context and focuses on different variables than those with which students were familiar. I added a few additional exploratory questions to the end of the post-test. These questions were informed by aspects of measurement and sampling that had emerged throughout the study. I coded the pre/post-tests for how students addressed the three themes about sampling that had emerged from my prior analysis of the focus student interviews.

Table 5.

Summary of Student Pre/Post-Test

Pre/Post-test scenario: Where are the grasshoppers?
Imagine you are studying the ecology of a field near your school. You decide to investigate the question: "Is the number of grasshoppers in an area related to the soil temperature?" Explain what you could do to find out an answer to your question. Write about… • What to measure and how to measure • Where to measure and how many times to measure • And how to use the data from your measurements to answer your question You can use both words and pictures in your explanation. Just try to give enough detail that someone else could follow your instructions to collect their own data.
Additional post-test questions: Collecting data at the creek
1) At the creek, our measurements were often different when we repeated them. Explain why our measurements of crayfish length might vary. 2) If you are studying the invertebrates in the creek and in your first scoop you find no invertebrates, do you count that scoop as a sample and write zero on your data sheet? (Circle one) a. Yes   Explain why you circled that answer… b. No c. It depends

Student written artifacts. I collected all of the student worksheets from across the investigation and examined each artifact for the presence/absence of the three themes about sampling. I elected to code the planning phase of each cycle separately from the observational phase at the creek so that I could document when in the investigation process students attended to sampling. For many of the teams one student served as the primary recorder, particularly when at the creek. Because of this I coded the investigation plans and data reports at the team level and looked holistically across all of the team members' written work to assign a team code. However, as students individually completed their own listening notes during the cycle 2 research meeting presentations, I coded these notes at the student level.

Video records of student activity. Throughout the study I collected video records of each whole class discussion as well as the focus groups' small group work both in the class and at the creek. As with the pre/post-test and written artifacts, I used the themes highlighted from my coding of the focus students' interviews as a lens to analyze these records. I looked across the video record for evidence of when and how these themes emerged in students' practice and use this to add depth and context to the findings from other data sources.

Findings

This study was designed to uncover how students' sampling practice develops within the context of ecological fieldwork. The analysis of the focus students' initial and final interviews revealed three key shifts students' sampling practice. These shifts emerged as students' attention to variation problematized the need for repeated sampling, the need to variablize data by attending to absence as well as presence, and the need to differentiate space. For each of these findings I begin by explaining the nature of the change in students' sampling practice as revealed by the focus student interviews. I then examine the evidence for similar shifts in sampling within the pre/post-tests. I conclude by detailing the emergence of the aspect of sampling practice over the course of the investigation as documented by students' written artifacts and the video record.

Finding 1: Attention to variation highlights patterns, not points, of data and creates a need for repeated sampling.

At the start of the investigation most of the focus students were confident that a single data point could adequately characterize a phenomenon of interest. For example, I asked Mary during her initial interview whether she could be confident that there are usually more butterflies in the afternoon if in the morning she went out and took a single sweep of a net and caught four butterflies and then in the afternoon she did the same thing and found nine butterflies. Mary replied, “Yeah, I think so. Because there where more.” When probed whether or not it would be good to take more than one sample each time, she continued, “Um, yeah, because you could always double-check yourself.” This idea of double-checking that they had found the right answer and not made a mistake during measuring was the primary reason students would assent at this stage to any form of repeated sampling. In other words, repetition could improve data collection by fixing the problems that might cause variation from the “true” answer. Only one student, Gary, suggested during the initial interview that he would need to take multiple sweeps because each sweep would likely have different numbers of butterflies. In his words, “Because if you’re just doing one scoop, there might be a place behind you that has a whole bunch of them and you only saw that one spot that has just a few of them.” However, Gary’s reasoning still privileged more of a “catching” mentality rather than a true sampling perspective, as it primarily emphasized the location where you would find the most butterflies.

In contrast, by the end of the creek investigations students’ notions about repeated sampling had undergone a dramatic shift, although they were still fairly simplistic by disciplinary standards (Fig. 3). During the final interviews every focus student considered a single sample to be insufficient to have confidence in one’s findings. This epistemic commitment was consistent across students’ descriptions of their creek investigations as well as their critiques of hypothesized scenarios. However, students still struggled to make sense about the extent to which they should repeatedly sample. More than once was essential. But the question remained as to how much more. In trying to decide how much to sample, students would often talk about needing to sample until you are able to see the "main part" or "clump" in your data. This shift from privileging data points to privileging data patterns seems to lie at the core of students' practice of repeated sampling.

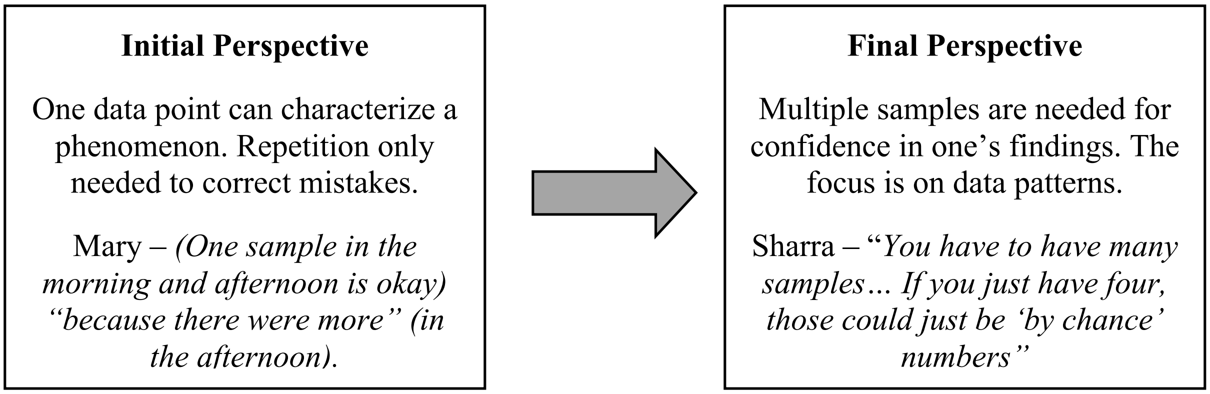

Figure 3. Shift in students' perspective of repeated sampling

Students' ideas about chance also seemed to play out in their ideas about repeated sampling, even though these students had not received much formal mathematical training in probability and chance outside of the brief computer modeling that we had done at the end of cycle 3. In the final interview, two students suggested that repeated sampling might help them account for random variation in their measures. For example, in describing her group's decisions about how much to sample in the creek one student, Sharra, explained that taking a small number like four samples would not always be enough to uncover the underlying pattern in the data because "if you just have four, those could just be 'by chance' numbers". Here Sharra is referencing the idea that it is possible that the first measurements you take may, just by chance, not be indicative of the broader pattern of data that would emerge after taking more measurements.

Pre/Post-Test findings. This strong shift in attention to repeated sampling was not as evident in students' pre/post-test responses (Table 6). On their pre-tests, completed after the first investigation cycle, a plurality of students (43%) either did not describe the number of times they intended to sample or planned to sample only once in each condition. A few (16%) suggested sampling “many times” or to “repeat” their measurement process, while many (35%) suggested sampling two to six times. (Sampling two to six times was collapsed into a single category because these were the values where at least one student explicitly referenced using repeated sampling to “double-check” that they had gotten the right answer.) Only one student (3%) planned to sample 10 or more times. On their post-tests, completed after the third investigation cycle, a plurality of students (38%) still did not describe the number of times they intended to sample or planned to sample only once in each condition. However, the number of students who planned to sample 10 or more times did increase to ten (27%).

Table 6.

Students’ Attention to Repeated Sampling in Pre/Post-Test Data Collection Plans

	Pre-Test n students (%)	Post-Test n students (%)
Not described *or* sample only once	16 (43%)	14 (38%)
Sample “many times” or “repeat”	7 (19%)	3 (8%)
Sample 2-6 times	13 (35%)	10 (27%)
Sample 10 or more times	1 (3%)	10 (27%)

The emergence of repeated sampling. In tracing back how repeated sampling emerged in students’ practice, it was evident that in their first visit to the creek most of the teams, like the focus students, considered a single data point to be sufficient for characterizing what they were measuring. None of the teams included repeated sampling in their data collection plans (day 2), and only 23% of the teams included multiple values for a variable in their results (day 3). From these plans and these quantitative results, one would think that the creek was a single uniform entity. For example, it was not unusual for a team exploring the depth of the creek to write a single value, such as 12 inches, on their results page as if this stood in for the depth of the whole creek.

However, what made it into the written record was only part of the story of students' first visit to the creek. As seen in the video record, students were frequently surprised by the amount of variation found when trying to gather data in the creek. A student measuring depth would stand in the same spot and dip the yardstick in the creek multiple times with the water rising to different level each time. A team would take turns dropping a ping-pong ball in the creek to measure the water speed and the ball would take a different amount of time to float the same distance. A student would scoop one time with a net and catch four small crayfish, and the student next to them would scoop one time and catch one large crayfish. One team would find lots of minnows, another lots of water striders. Because students were working in teams and because teams were working side-by-side, news of these differences would travel up and down the creek. Thus students, in unplanned and unstructured ways, were experiencing repeated sampling in the creek. This experience of variability helped call into question the reliability of a single measurement.

In a sense, these students seemed primed to attend to variation. During the initial interviews, the focus students had suggested that you could be more confident of your estimate of an attribute by gathering more measures, particularly if there was not yet a discernable "clump" in the data display. This was likely related to experiences in their math class earlier throughout the year in which students had invented data displays, measures of center, and measures of spread using data from repeated measures of an attribute such as the perimeter of a table. However, although students reasoned about patterns and clumps when prompted with collected data, they were still struggling to invoke this reasoning when critiquing or designing data collection plans. This first visit to the creek seemed to create a shared experience around variation that supported students in bringing this reasoning to the foreground.

Consequently, repeated sampling began to emerge as an essential aspect of sampling practice during the second investigation cycle. We began this cycle by discussing what students had seen during the first visit to the creek (day 4). As a student or team shared what they had observed about different variables, I would call on others to compare the findings to what they had noticed. These comparisons highlighted the degree of variation within the creek. I also probed students about the consistency of their experiences. For example, I asked one team if the ball they had used to measure speed always floated down the creek in the same way. By this time most students were outright laughing at the suggestion that they could get precisely the same value each time they took a measure in the creek, even if they stayed in the same location. I asked students how they could be confident that one part of the creek was deeper than another or one area had a better habitat for crayfish of they expected their measures to always be different. Multiple students suggested that we could take more than one sample in each location and either look at differences in the pattern across each location or compare some form of measure of center.

In their worksheets for the second creek visit, 86% of the teams included specifics in their data plans about the number of samples that they intended to collect (day 5) and reported on multiple samples in their findings (day 6). For example, one team wrote, "Use a net or a hula hoop to check the amount of fish in the area. Do each (area) five times." As was described in the instructional design and shown in Table 3, the worksheet for this second visit did provide inscriptional support for repeated sampling. However, this was introduced only after the students had highlighted the need for multiple samples in the whole class discussion.

This disposition towards the practice of repeated sampling was later reified when teams reported on their findings from the second visit during the research meeting (days 7-8). Students often asked teams how many samples their findings were based on when they failed to share this detail in their report. When teams had not collected what others considered to be a sufficient number of samples, they were encouraged by their peers to increase this number during the next cycle of data collection. Of the forty-four students present for the research meeting, sixteen (36%) included a question or comment about repeated sampling in their listening notes. For example, one student suggested that a team should "take more samples to have more confidence" in their findings.

This emphasis on repeated sampling carried over to the third cycle of investigation, though once again the inscriptional tools were designed to support this. Eighty-six percent of the teams included specifics in their data plans about the number of samples that they intended to take on the third visit to the creek (day 9), and all of the teams reported findings from multiple samples (day 10). For example, one team planned to "measure 10 to 20 times in the middle of location 2 and near the edge." In their data report, this team ended up including findings from 30 samples. I asked one member of the team if she though this was a good number of samples or if she would suggest a different number the next time. The student replied that the team had taken extra samples because they had extra time at the creek and that she didn't think that they had needed all of them because they could see the pattern of where most of the numbers would be after taking only twenty samples.

Finding 2: Attention to variation highlights absence as well as presence and creates a need to variablize data.

What students counted as a sample also shifted over the course of their creek investigations. During the initial interview, most of the focus students only highlighted the material aspect of sampling. All but one talked explicitly about a sample as a piece of something that they had cut from nature's complexity. It was the actual minnows caught in a scoop or the actual polluted cup of water pulled from the creek's edge. However, by the end of their investigations, all of the students were also talking about a sample as the data they collected to help answer their questions. Thus in the final interview the students' conception of a sample encompassed the chain of transformation (Latour, 1999) from the actual minnows caught in a scoop to the numbers recorded for that scoop.

This shift in students' view of the nature of a sample was paralleled by a shift in how students attended to absence in their data (Fig. 4). This was most evident in how students talked about constructing counts of different living organisms. Initially, students viewed an empty sweep of a net or a scoop of water with no organisms as a failure. They had not sampled the crayfish because they had not caught a crayfish. Absence was not a signal of the organism, it was a signal of your competence. To rectify this, you had to change where you were sampling or how you were using the equipment so that you would be successfully in catching something. However, by the end of their investigation students had created a need for variable-like dimensionality in their measures. A "scoop of zero", as students called it, was meaningful. Absence as well as presence could be used to infer relationships between organisms and their environment. Mary highlighted this connection in her final interview when explaining why recording samples of zero was important in their creek investigations. She said that if you don't record zero you "overestimate, because that would say that every time you go down there, you would catch something." By the end of the investigation, students in both focus groups had spontaneously referenced the importance of recording "zero" in either their research meeting notes, their data collection plans for the third creek visit, or their final interviews.

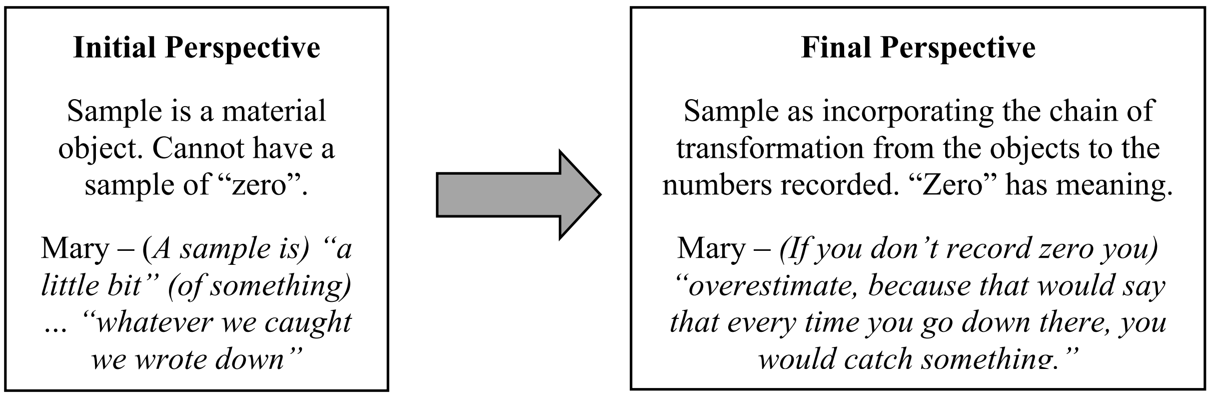

Figure 4. Shift in students' perspective of absence and the nature of a sample

Pre/Post-Test findings. Students' responses on the pre/post-test scenario failed to reveal their perspective of the nature of a sample or the function of absence in ecological investigations. No student addressed absence on either the pre- or the post-test. However, this is not surprising given the nature of the pre/post-test question. When writing a data collection plan, ecologists do not explicitly state that if they don't happen to catch any organisms that they'll be sure to record that to. Rather, their treatment of absence is revealed by their actions in collecting data. Similarly, students' actions in collecting data (and their critique of others actions) would likely reveal more about this perspective than their data collection plans.

On the post-test, students were asked an additional question: If you are studying the invertebrates in the creek and in your first scoop you find no invertebrates, do you count that scoop as a sample and write zero on your data sheet? In this case, all but one of the students (97%) said yes they would. In explaining their reasoning, students wrote that the scoop counted because it was a part of the data, or because you had taken action to do something, or because it would change the value of your mean if you didn't include it.

The emergence of "scoops of zero". The shift in what counted as a sample seemed to emerge as students began to value absence – a notion highlighted though students' experiences with variation in the creek. In their initial investigations, students frequently wandered the creek in an attempt to capture some organism, such as a crayfish. In some areas they could catch a crayfish virtually every time they scooped a net into the creek. However, in other areas students would have to scoop over twenty times before they caught a single crayfish. Initially, students only recorded the organisms that they successfully caught, without accounting for any scoops that came up empty. None of the teams recorded information about zero or the absence of an organism in the data from the first creek visit (day 3). Rather, students recorded lists, total counts, or comparisons (more/less) of organisms.

However, this approach began to lead to dissonance between how some students were experiencing the creek and how they were representing it. Students would be recording similar counts for areas in which they had dramatically different material experiences. This dissonance did not sit well with students who either noticed it on their own or who had it called to their attention. It was at that moment that all of those previously ignored empty scoops offered students a way to resolve their dilemma. During the middle of their second visit to the creek (day 6), some students began to document every scoop they took – not just those with organisms. In their data records from this trip, 55% of the teams who were taking measures where they had to make a decision about absence recorded at least one "scoop of zero". However, during the research meeting the next day (days 7-8) none of the students asked other teams about absence or wrote about attending to zero in their research meeting listening notes.

At the beginning of third cycle, I brought the issue of scoops of zero up in our class discussion (day 9). It turned out that students had been primed for this discussion by their teacher who had drawn a connection between zero in a scoop at the creek and what you would do if you were calculating your average grade and you had a zero on an assignment. So when I presented the students with a scenario in which two teams had each found the same number of crayfish but one team had taken more scoops than the other, all of the teams agreed that the number of scoops made a difference. The empty scoops mattered if you wanted to be able to make a comparison. As these students planned the next round of data collection, the importance of "recording scoops of zero" became a reified aspect of collective sampling practice. In their final data records, all but one of the teams attended to absence as well as presence and recorded samples of zero if they were investigating organism abundance.

As can be seen in this narrative, attention to absence did not emerge as readily as repeated sampling in students' practice. It was never included in a team's plans for data collection, and it was not highlighted during the research meeting presentation. A variety of factors might have contributed to these patterns. It may be that absence is simply more abstract and thus more difficult to talk about than repetition. Or it could be that, unlike repetition, absence impacts only some of the variable students measured. Many aspects of the creek, such as water speed, depth, crayfish length, and dissolved oxygen were already variablized for students. Issues of absence only impacted students' measures of organism abundance. Students' difficulty with absence might also reflect how they typically engage with natural spaces outside of school. Most students this age explore a creek to catch things. In such cases, absence is always a signal of failure. But in science, absence can be a signal of both success and failure. You may get a scoop of zero because that is a valid representation of the ecological functioning of that location. Or you may get a scoop of zero because you had a momentary problem with wielding the net that you were using to take that sample. The first scoop of zero would need to be attended to. But the second scoop might be legitimately discounted.

Finding 3: Attention to variation highlights differentiated space and creates a need to attend to sample location.

The way in which students talked about space also shifted over the course of the investigation. During the initial interviews, only three focus students referenced location in any way when describing sampling or critiquing data collection plans. These students primarily focused on choosing a location that secured access to the phenomena of interest. For example, Sharra explained that someone deciding how to sample a field for butterflies needed to "find a certain location because in some places there won't be any butterflies". She suggested that the sample should be taken in a cool location because that's where there would be the most butterflies. As described in earlier findings, this form of attention to space illustrates how students initially privileged the hunt for organisms in their investigations. The only location to attend to when sampling was the one where you could sweep and catch the most organisms.

However, in the final interviews students talked about space in a very different way. Here every focus student talked in some way about the need to differentiate space and about how sample location can impact the interpretation of one's findings (Fig. 5). For example, Mary described how "if the other people that were doing minnows and we wanted to compare...if we just did it in the middle and all of them just did it on the sides and the middle, they might have way different results." Decisions about sample location were no longer only about catching an organism (though of course securing access to the phenomenon was still important). Decisions were about preserving the ability to make comparisons across data sets. Though the ways in which students attended to space were still relatively crude approximations of the systematic approaches of professionals, students had begun to recognize that the locations in which they sampled did not just impact their access to the phenomena of interest, but the locations also impacted what they could do with their data.

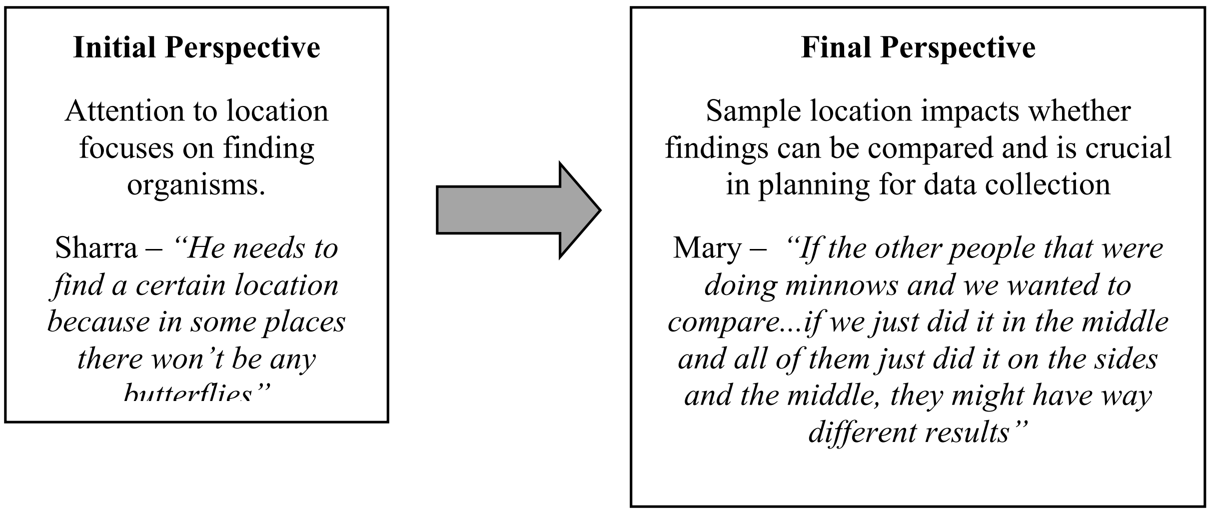

Figure 5. Shift in students' perspective of sample location

Pre/Post-Test findings. The shift in attention to sample location was also not as strongly evidenced in students' pre/post-test responses (Table 7). On their pre-tests, the majority of students (57%) did not describe where they intended to take their measures, even though the question prompted them to do so. Those who did attend to location tended to use general proxies for the variables of interest (temperature and grasshopper abundance) to stratify space. For example, one student suggested measuring under the rock where it is shady and out in the sun. This would likely ensure a temperature difference between locations. In addition, a few chose their sample location by stratifying the spatial structure of the field so that areas in the middle and edge were both included. On the post-tests, fewer students (38%) completely ignored sample location, although this still represented a plurality. However, students still did not attend to space in sophisticated ways, with the largest increase being in the number of students (16%) who suggested the general approach of sampling "different locations". No student described plans to spatially locate individual samples within a form of stratified space.

Table 7.

Students' Attention to Space in Pre/Post-Test Data Collection Plans

	Pre-Test n students (%)	Post-Test n students (%)
Not described	21 (57%)	15 (38%)
Sample "different locations"	2 (5%)	6 (16%)
Stratified by proxy for temperature or grasshoppers	7 (19%)	8 (22%)
Stratified by spatial structure such as middle or edge	3 (8%)	2 (5%)
Other descriptions of space	4 (11%)	4 (11%)

In the interviews, the focus students described their stratification of space in the creek (e.g., middle vs. sides) in relation to their specific experiences with finding different organisms in those different areas. However, the students did not have such experiences with the ecosystem in which the pre/post-test scenario was situated. Because of this, it may have been difficult for them to imagine what factors might potentially influence organism abundance and would thus need to be accounted for in decisions about sample location.

The emergence of attention to space. Our earlier accounts of how students attended to variation have already suggested how variation in a measure can create a need to see space from a new perspective. In the beginning students viewed the creek as a singular entity. In our first discussion (day 1) and their first data collection plans (day 2), they asked questions such as "how deep is the creek" and "how many fish are there". However, as students began to see differences between repeated measures of the same variable, they began to partition the creek at a gross level. For example, the area by the car wash had fast moving water. The area by Granny's bridge had lots of water striders. These gross differences emerged in students' observational records from the first visit to the creek (day 3) and supported the development of our map of creek at the start of cycle 2 (day 4).

Over time, this differentiation of space supported new observations about variation, which in turn led to the development of new research questions. For example, during cycle 2 one focus group started exploring whether the average number of crayfish was related to water speed (days 5-6). However because their observations of crayfish seemed to vary even at a single location with relatively slow water, they further stratified that location to test an emergent hypothesis relating crayfish and shallow habitats. In the research meeting after this second visit (days 7-8), students began to ask the other teams about where they had sampled and how they had made these decisions. In their research meeting notes, 41% of the students included an observation or suggestion about where teams should sample.

Although students began to differentiate spaces in the creek based on variation after their very first visit to the creek, the need to attend to sample location with data collection plans did not emerge until planning for the third visit (day 9). Prior to this day, none of the teams' data collection plans described where they would collect their data within the two general locations they had selected. In planning for the third visit, teams were told that they would be responsible for collecting data about one variable in one of four general locations in the creek. Students would then share their findings to look for patterns of covariation in variables across locations. This comparison helped create a need for students to make their implicit notions of sampling location finally explicit in their plans. In this, students often chose sampling locations that accounted for the breath of spatial variation in their location and incorporated some aspect of stratification. For example, one team decided to distribute the 10 samples they intended to take so that three were equally spaced out along the far bank, four were spaced through the middle of the creek, and the last three were spaced across the near bank. Though all teams talked about where they would sample when planning their investigation, only 21% of the teams detailed these decisions in their written data collection plans. All of these teams included hand-drawn diagrams of where they would take each sample. These inscriptions were not the final products of the teams' decisions, but rather emerged as students negotiated different options for data collection.

Students' Views about Sources of Variation

These three findings suggest that attention to variation is important in the evolution of students' sampling practice. Given this, it is important to consider what students think contributes to the variation in their data. One of the additional probes on the post-test examined this very question. Students were asked, "At the creek, our measurements were often different when we repeated them. Explain why our measurements of crayfish length might vary." This context was selected because of the ubiquity of crayfish in students' experiences in the creek and our class discussions. Student responses were analyzed for evidence of causal variation, variation due to measurement error, and natural variation. These categories were not mutually exclusive as students could include multiple potential sources of variation in their response.

Approximately two-thirds of the students referenced some form of causal variation. Eleven of these students (30%) described a general cause, such as measuring crayfish from different locations of the creek, while fourteen (38%) described a specific cause, such as measuring crayfish from locations with different levels of pollution. In addition, eight students (22%) described ways differences or errors in measurement could have contributed to variation. For example, one student explained, "Some could fold the tail in and others don't. Or they could have gaps" (in measuring crayfish). Only three students (8%) alluded to some form of natural variation without attributing a cause. For example, one student stated, “Crayfish are all different sizes”. Although some students described how both causal variation and measurement error could contribute to differences in measures, none coupled natural variation with a second source.

Discussion

This paper has made a case for how attention to variation supported the development of students’ sampling practice. It has shown how key shifts in how students perceive and engage in sampling emerged from moments in which they were wrestling with some form of variation. As such, variation seems important in supporting students in creating a need for and valuing more sophisticated aspects of sampling practice, including repeated sampling, attending to sample location, and sampling absence as well as presence. Though students did not approach the complexity of practice seen in professionals, they began to attend to many of the same issues and problems within sampling that ecologists consider (Coe, 2008; Eberhardt & Thomas, 1991). They also began to connect how their methods of collecting data had implications for what they could (or could not) say about that data. These are sophisticated developments for middle school students. In addition, they lay a meaningful foundation for students to explore more advanced aspects of sampling, such as sampling saturation and random assignment, in the future.

The students’ practice of sampling followed a trajectory of emergence that seemed informed in part by the instructional design and in part by the nature of ecological fieldwork (Table 10). Students’ attention was drawn first to the need for repeated sampling. The early emergence of this aspect of practice was likely reflective of the degree of variation present in the ecosystem we studied. If students were investigating a system with weaker gradients of variability, it might have proven more difficult to create a need for repeated sampling. Students attended next to the role of absence in their investigation, as indicated by “scoops of zero”. This element of sampling practice seemed tied to students' experiences making comparisons between locations. It also required students to be working with a feature of the ecosystem, such as organism abundance, that had a need to be variablized. If students had solely been focusing on measures such as dissolved oxygen or crayfish length that have a built-in zero point, the importance of attending to absence might have taken longer to develop. The final aspect of practice to emerge in students' activity was their attention to sample location within differentiated space. This emergence seemed tied to the instructional move to have teams collaboratively plan and rely on each other's work. It is possible that similar moves at an earlier stage of the investigation could potentially shift students' attention to space to an earlier point, particularly if students' inscriptional work in mapping their decisions about space were given more explicit support.

Table 8.

Summary of Students' Emergent Sampling Practice Across the Creek Investigations

Cycle 1	• Data collection plans focus on tools. No evidence of attention to repeated sampling, samples of zero, or sample location
Cycle 2	• Initial whole class discussion highlights variability within data • Data collection plans include some attention to repeated sampling • Some groups begin to attend to samples of zero while at the creek • Research meeting discussion highlights repeated sampling and samples with zero organisms
Cycle 3	• Data collection plans include attention to repeated sampling and, for some, sample location. Samples of zero are more consistently recorded while at the creek

Limitations

In streamlining this argument for how students' sampling practice developed I have had to strip away some of the nuanced complexities inherent in this work. Because of this I do not want to give the false impression that a more sophisticated sampling practice will spontaneously arise from merely engaging students in ecological fieldwork. Rather, students' evolution of practice was fundamentally intertwined with the overall design of the learning environment. Key elements of the design, from my discourse moves during class discussions to the inscriptional tools available to students and the organization of creek teams, were not inconsequential for how students were able to see and make sense of variation in this study. Even the field site was purposively selected in part for the range of natural variation in that section of the creek. I have attempted to include in this analysis how such elements of the learning environment likely influenced students' actions and reasoning about sampling. However, there may be crucial aspects of the design that I have overlooked.

Nor do I consider attention to variation to be the sole impetus for advancing students' sampling practice. By its very nature, ecological fieldwork is messy (in addition to being muddy). It is fraught with failure and often requires redesign in situ (Bowen & Roth, 2007). As students wrestle to develop their own measures and data collection plans, personal frustration and need can sometimes be productive stimuli for changes in practice. Likewise, it would be remiss to overlook that students' sampling practice evolved within the social context of nested, intersecting communities of learners (Lehrer et al., 2008). As has been found with professional field ecologists (Bowen & Roth, 2002, 2007; Feldman, Divoll, & Rogan-Klyve, 2013, 2009; Leon-Beck & Dodick, 2012; Madden, Grayson, Madden, Milewski, & Snyder, 2012; Mason & Hope, 2014; Roth & Bowen, 2001), social interactions both within and out of the field were important for establishing and circulating knowledge within this community. An individual student's practice was refined through negotiating with their own group members, observing and jostling with other groups in the creek, reporting out to their science class, and finally sharing findings and anecdotes across the entire sixth grade. Though I have tried to emphasize the importance of bringing students' investigations into contact with each through class discussion, research meetings, and collective planning, I do not feel like I have done justice in this paper to how individual and collective practice co-develop in such moments.

In addition, this paper details the development of two classes of students from one rural community as they investigated one aquatic ecosystem. Though it is likely that attention to variation could support similar development in students from other communities studying other ecosystems, it is also likely that some elements of the timing and trajectory of development are locally contingent on students' lived experiences and the specifics of the ecosystem they are studying. Experience with a specific variable and with a specific setting mediates the practice of even professional ecologists (Bowen & Roth, 2002, 2007; Leon-Beck & Dodick, 2012; Lorimer, 2008; Madden et al., 2012; Roth & Bowen, 1999, 2001). Similarly, a student's sense of place likely influences their own sampling practice.

Finally, I found tracing and interpreting the sampling practice of middle school students to be a tricky endeavor. Many of the students exhibited difficulties with writing that impacted what they were able to convey in their data collection plans and on the pre/post-test. Others struggled with how to express their rationale behind sampling decisions, even during low-key conversations. The richest signals of students' practice were found in the interviews and video records of the creek investigations and research meetings. These moments captured students' actions while sampling and their critique of the actions of others. As was highlighted in the findings, the pre/post-test in particular failed to offer much insight into the evolution of students' sampling practice. This may have been because the post-day was given on the second-to-last day of the school year. But it may also have been because it focused on students' construction of data collection plans. Adapting the pre/post-test so that it includes scenarios in which students are asked to critique the sampling decisions of others might reveal more of the nuances in students' sampling practice.

Implications for Future Studies

The findings of this exploratory design study suggest numerous means by which future iterations can build on the instructional design. First, it may be useful to streamline the planning phase of the first cycle and anchor students' initial investigations in accessible features of the ecosystem that often exhibit substantial variation, specifically water depth and water speed. These are features of the abiotic environment in which students often have initial interest, strong resources for measuring, and the ability to self-monitor quantitative measures through qualitative observation. Second, the creek investigations seemed to provide opportunities for students to make sense of variation due to causal processes or measurement error. However, students still struggled with issues of natural variation due to random processes. As has been seen in other studies (Metz, 1999; Torok & Watson, 2000), experientially based causal reasoning had explanatory precedence over chance. Students might benefit from new classroom-based experiences that could help tease apart these different sources of variation and ground their perspective of the degree of difference that chance processes can produce. Third, the design should capitalize on the emergence of additional dimensions of sampling, such as sampling saturation. Many of the students in this study seemed poised to more deeply explore how to use the degree of variation in a measure to make decisions about what counts as a satisfactory number of samples. Finally, as this study focused narrowly on the practice of sampling, future studies might consider how the design supports the co-development of students' knowledge and practice at a broader scale. In particular, it would be useful to better understand how students' sampling practice interacts with their performance of other scientific practices, such as those involved in analyzing data, and with their development of ecological content knowledge.

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Appendix A
Interview Protocol

Question 1 - Creek Investigation (Post-Interview Only, All Students)

Question 1a – What research question are you investigating in the creek?

- Prompt – What are you doing to answer this question? Why did you decide to do *x*?

Question 1b - What are you looking at to see if *(question construct)?*

- Prompt – How are you measuring *x*? How did you decide to measure *x* the way you did?
- Prompt – What difficulties are you having in trying to measure *x*? What are you doing to fix those problems?
- Prompt – Have you noticed any differences in your measurements of *x*?
    - Prompt - When or where have you noticed these differences?
    - Prompt – What do you think might be creating these differences?
    - Prompt – Have those differences affected the way you are thinking about your question? If so, how? If not, why not?

Question 1c – In science, we talk sometimes about taking a sample. What do we mean by sample?

- Prompt - Are you taking any samples as part of your study?
    - *If yes* – What are you doing to sample the creek? Why did you decide to do *x*?
    - *If no* - Are you taking measurements at more than one time or in more than one place?
- Prompt - Where in the creek are you measuring *x?*
    - Prompt – How did you decide where to measure?
    - Prompt – How do you keep track of where you measure?
    - Prompt – Are you having any difficulties with figuring out where to measure *x*? What are you doing to fix those problems?
- Prompt - How many times are you measuring *x*?
    - Prompt – How did you decide how many times are enough?
    - Prompt – Are you having any problems when trying to figure out how many times you should measure *x*? What are you doing to fix those problems?
- Prompt – What are you using to collect (your samples) of *y*?
    - Prompt – How did you decide to use *z* to collect (your sample)?
    - Prompt – How did you decide what size *z* to use?
    - Prompt – Are you having any problems when trying to figure out what to use to collect (your samples)? What are you doing to fix those problems?

Question 1d – What have you found out about your question? What are your results?

- Prompt – If you repeated what you did the last time at the creek, do you think you would get the same results? Why or why not?
- Prompt – Do you think *(any difference mentioned)* could be due to chance and there not really be *(difference mentioned)*? Why or why not?
- Prompt – Has your question about the creek changed over time? If so, why?
- Prompt – Have you learned anything about the creek from hearing or watching other people's investigations? What have you learned? How did you learn that?

Question 2 – Sampling Benson's Butterflies (Pre- and Post-Interview, All Students)

Setup: Benson thinks there are usually more butterflies in the park in the morning. His friend Enoch thinks there are more in the afternoon. Benson decides to find out who is right.

Question 2a - Benson decides to take a sample of the butterflies in the park, once in the morning and once in the afternoon. In science, what do we mean by sample?

- Prompt – What are some things Benson needs to think about when he is making a plan to get a sample of butterflies in the park?
- Prompt – In your own work in science class, have you ever had to find a way to get a sample of something?
    - *If yes* – Prompt – Can you describe what you did to get a sample? What are some of the things you thought about when you made your plan to get your sample?

Question 2b – Remember Benson wants to learn whether there are usually more butterflies in the morning or in the afternoon. Does he need to count every butterfly in the park to answer his question?

- *If yes* – Prompt – Why does he need to count every butterfly?
- *If no* – Prompt – Why is it okay to only count some of the butterflies?
    - Probe – What do you think he should do? How will he decide how much to count?
    - Probe (If not mentioned) – Does it matter where he counts? Why or why not?

Question 2c - Benson decided to use a net to sample once in the morning and once in the afternoon. He counted four butterflies in the morning and nine in the afternoon. Given his findings, can Benson be confident that there are usually more butterflies in the park in the afternoon? Why or why not?

- *If no* – Prompt – What could Benson do to increase his confidence that there are usually more butterflies in the afternoon? Why would (*doing x)* help?
- *If repeated sampling not mentioned* – Benson's friend thinks that he needs to take more than one sample. Do you agree that Benson should take more than one sample? Why or why not?
    - *If yes* - Prompt – How many more samples should Benson take? Why is that a good number?
- Prompt - If Benson goes back every day for a week and samples each morning and afternoon, do you think his samples will have the same number of butterflies every day? Why or Why not?
    - Probe – Suppose it's true that there really are usually more butterflies in the park in the afternoon. If that's right, do you think that Benson will always catch more butterflies in the afternoon than in the morning? Why or Why not?

Question 3 – Measure (Pre- and Post-Interview, 2 students from each focus group)

Question 3a - George and Gina are growing grass in cups to see how sunlight, water, and nutrients affect how the grass grows. To find out, every day George measures how tall the grass is. Gina uses a different measure to determine how the grass is growing. Every day she measures the weight of the grass. Who do you think has a better method of measuring the growth of the grass? Is George's method better? Is Gina's method better? Or are they both equally good? Why?

- Prompt – What would George have to think about when measuring how tall the grass is
  - Probe (If not mentioned) – What is useful about George's method? What might be some problems George might have?
- Prompt – What would Gina have to think about when measuring how much the grass weights?
  - Probe (If not mentioned) – What is useful about Gina's method? What might be some problems Gina might have?

Student Visual for Question 3

George and Gina are growing grass in cups to see how sunlight, water, and nutrients affect how the grass grows

Every day George measures how tall the grass is.
Every day Gina measures the weight of the grass.

Question 4 – Variation as a Signal of Ecological Difference (Pre- and Post-Interview, 2 students from each focus group)

Setup: Sarah wants to know if there is a difference between the wildflowers in the field behind her house here in Arkansas and the wildflowers in the field behind her grandma's house in Tennessee. So she designs an investigation to help her answer this question.

1. She puts 20 hula-hoops in random locations in her field and counts the number of different wildflowers found in each hoop.
2. When she visits her grandma, she does the same thing. She puts the same 20 hula-hoops in random locations in her grandma's field and counts the number of different wildflowers found in each hoop.

Question 4a – When I say that Sarah put the hula-hoops in random locations, what does the word random mean to you? (Note – if students have trouble with the idea of random, explain that Sarah tossed the hula-hoop in different locations without looking)

Question 4b – Here is a display Sarah made of the data she collected from the 20 hula-hoops in each of the two fields. What does this display tell you about the number of different kinds of wildflowers in Sarah's field and in her grandma's field?

- Prompt – Is there anything you could do to the data display to help you better compare Sarah's field and her grandma's field?
- *If yes* – How will the change help you better compare the two fields?

Question 4c – Here I have separated the data from Sarah's field and her grandma's field and found the median and the IQR. What does this data tell you about the wildflowers in the two fields?

- Probe (If needed) – What is similar about the data in the two fields? What is different about the data in the two fields?
- Prompt – The data from Sara's field has a smaller inter-quartile range. How do you think this happened?
- Prompt – How might this larger inter-quartile range in grandma's field have happened?

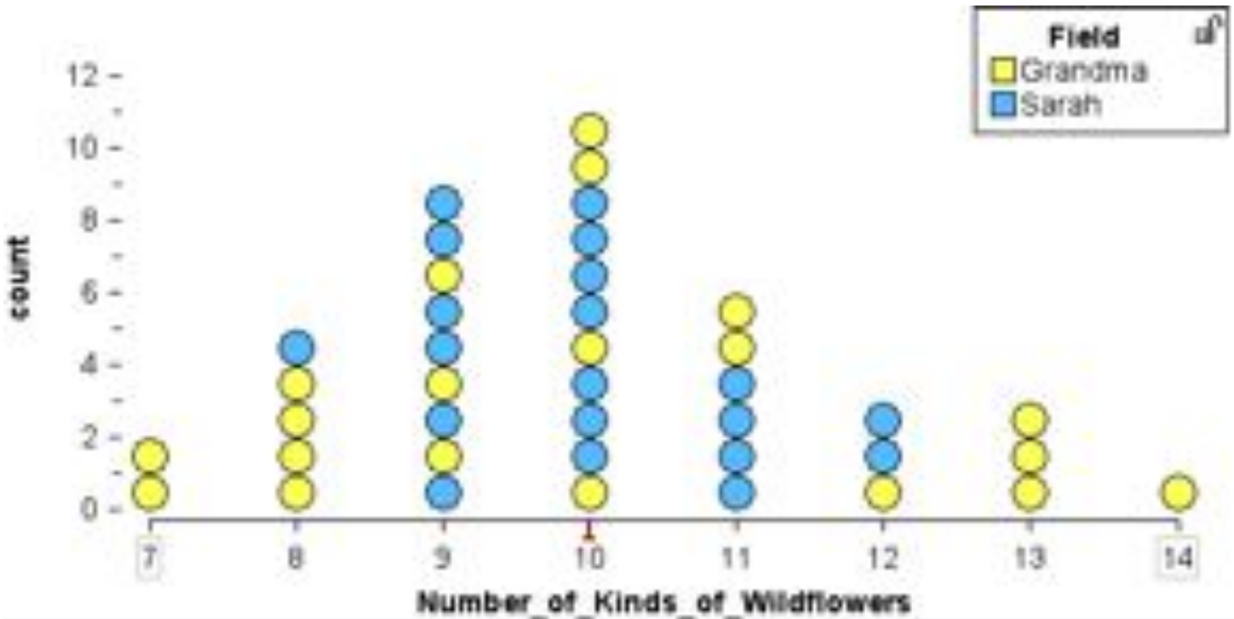
Question 4d – If I gave you pictures of three different fields, what would you look for to pick out Sarah's field?

- Prompt – How could you tell from the data to look for that?
- Prompt – What would you look for to pick out grandma's field?
- Prompt – How could you tell from the data to look for that?

Student Visuals for Question 4

Sarah wants to know if there is a difference between the wildflowers in the field behind her house here in Arkansas and the wildflowers in the field behind her grandma's house in Tennessee

Here is a display Sarah made of the data she collected from the 20 hula-hoops in each of the two fields:



Here I have separated the data from Sarah's field and her grandma's field and found the median and the IQR.

	Median	Inter-quartile Range (IQR)
Sarah's Field	**10**	**2**
Grandma's Field	**10**	**3.5**

Question 5 – Variation and Sampling Saturation (Pre- and Post-Interview, 2 students from each focus group)

Setup: Maria and Mark's class is studying the average height of different plants in the field behind their school. They want to compare their data to what field guides say about the typical height of these plants. Maria and Mark have sampled the height of 10 Purple Nutsedge plants and 10 Yellow Nutsedge plants so far and have made a display of their data. They have time to take 20 more measurements, but they can't agree what to measure next.

Question 5a – Here is Maria and Mark's display of the heights of the 10 Purple Nutsedge plants. Do Maria and Mark need to measure more Purple Nutsedge plants in order to be fairly certain they can describe the average height of this plant in their field? Why?

If yes – How many more plants should they measure? Why?

Question 5b – Here is Maria and Mark's display of the heights of the 10 Yellow Nutsedge plants. Do Maria and Mark need to measure more Yellow Nutsedge plants in order to be fairly certain they can describe the average height of this plant in their field? Why?

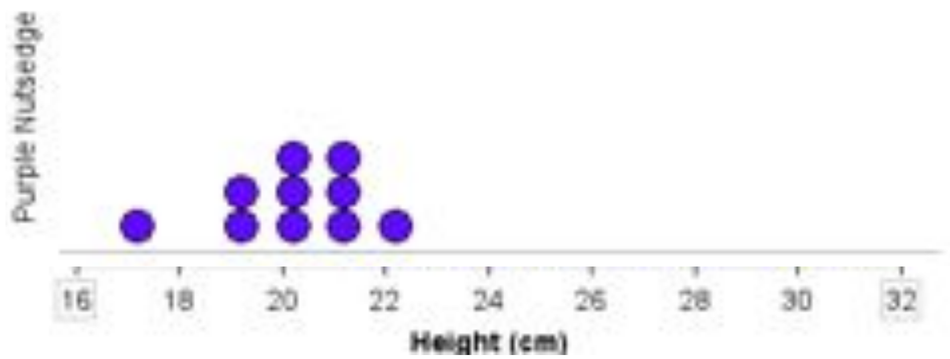
If yes – How many more plants should they measure? Why?

Question 5c – If Maria and Mark only have the time to take 20 more measurements, how many of each type of plant should they measure in order to be able to accurately describe the average height of each type of plant? Why?

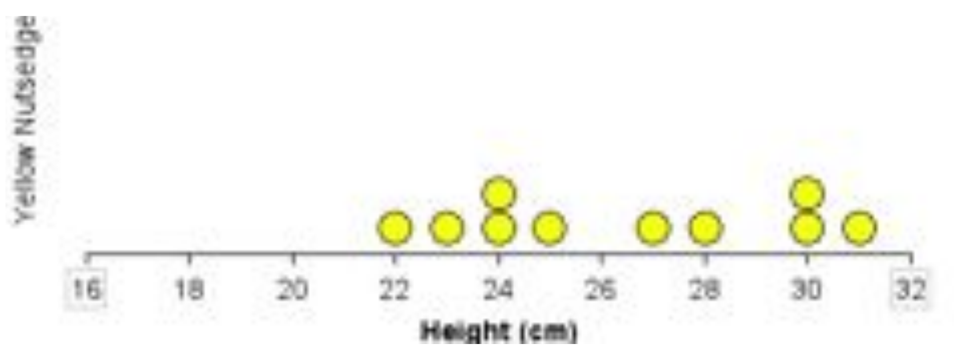
Student Visuals for Question 5

Maria and Mark's class is studying the average height of different plants in the field behind their school.

Here is Maria and Mark's display of the heights of the 10 Purple Nutsedge plants:



Here is Maria and Mark's display of the heights of the 10 Yellow Nutsedge plants



Question 6 - Sample Size & Chance (Pre- and Post-Interview, 2 students from each focus group)

Setup: A team of scientists has been studying creekshells – a type of freshwater mussel or clam – in Arkansas rivers. Across all rivers, about 45% of adult creekshells mussels are male. This fall, when the scientists conducted their study, they found two rivers in which 60% of the creekshell mussels were male. In River A, they had sampled 50 creekshells. And In River B, they had sampled 12 creekshells.

Question 6a – Here are two statements about Rivers A and B. Let's look at statement one first. Do you agree with this statement? Statement 1) Both rivers are very unusual because the rate of male creekshells is 45%. Why or why not?

- Prompt - Now let's look at statement two. Statement 2) The rate of male creekshells in River A is more unusual than the rate of male creekshells in River B, even though it is 60% for each. Do you agree with this statement? Why or why not?

Setup: Now let's look at another study about creekshells. The scientists also want to know if the average size of the creekshell mussels is decreasing over time. If the mussels are smaller, this might be an indicator that something is wrong with their habitat. They measured a sample of 60 creekshell mussels in 2008 and 30 mussels 2013. In 2008, the median length was 42mm. In 2013, the median length was 38mm.

Question 6b - Some of the scientists say that the results show that the mussels are decreasing in length. Others say the results likely happened by chance. Who do you think is right? Explain your reasoning.

Student Visuals for Question 6

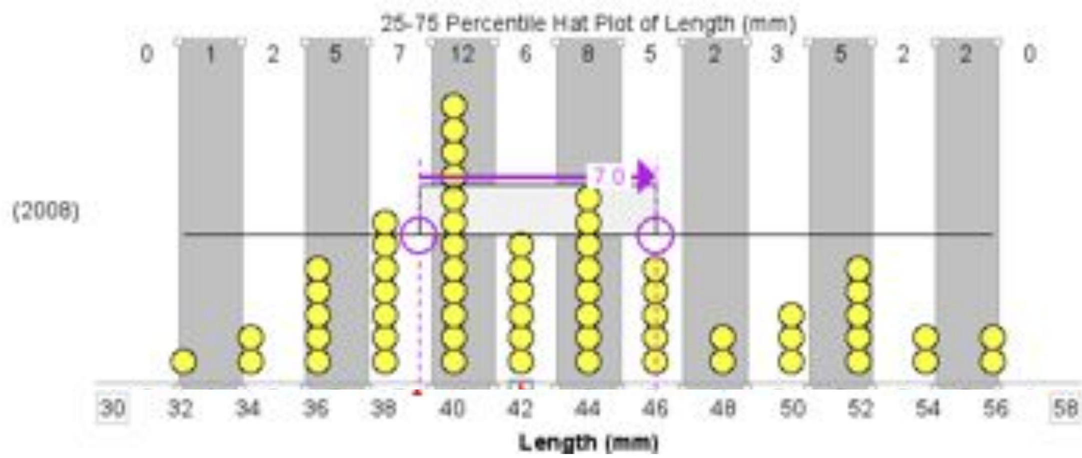
Creekshell mussels

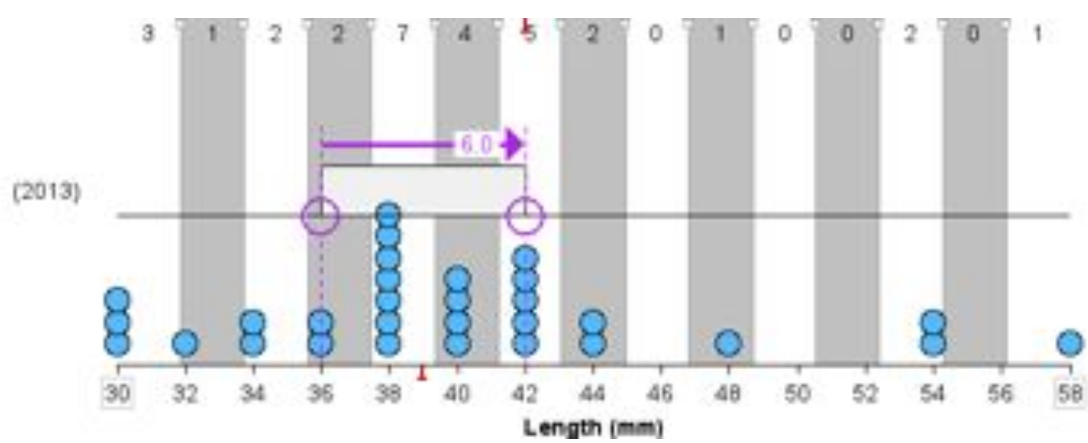
- Across all rivers, 45% of adult creekshells are males
- Scientists found two rivers in which 60% of the creekshells were male
    - River A – They had sampled 50 creekshells
    - River B – They had sampled 12 creekshells

Statement 1) Both rivers are very unusual because the rate of male creekshells is 45%

Statement 2) The rate of male creekshells in River A is more unusual than the rate of male creekshells in River B, even though it is 60% for each.

The scientists also want to know if the average size of the creekshell mussels is decreasing over time.





CHAPTER III
DISCIPLINING THE WILD: THE CO-DEVELOPMENT OF STUDENTS' SCIENTIFIC KNOWLEDGE AND PRACTICE DURING ECOLOGICAL FIELDWORK

Introduction

Since the development of the *Next Generation Science Standards* (*NGSS*), K-12 science education has positioned student learning of science as participation in the practices of science (Achieve, Inc., 2013; National Research Council, 2012). This framing has been informed by our understanding of how scientists construct knowledge in communities of practice and emphasizes the integration of knowledge and practice in scientific endeavor (Ford, 2015; Ford & Forman, 2006; Knorr-Cetina, 2009; Latour, 1999; Latour & Woolgar, 1979; Lave & Wenger, 1991; National Research Council, 2012; Nersessian, 2008). However, the communities of practice in science classrooms do not function in the same way or for the same purpose as those in science laboratories. These differences present meaningful challenges for how science education conceptualizes and designs for student learning of the practice of science (Mody, 2015; Stroupe, 2015). Though the field has substantially advanced the ways in which supports students' scientific practice, much is still unclear about how the practices of science interact in students' activity and how students' practice co-develops alongside their understanding of core ideas.

This paper addresses these needs by tracing the co-development of students' scientific practice and content knowledge during ecological fieldwork. It reports on a case study of one team of four middle students as they and their classmates investigated the ecological relationships and dynamics of a local creek.

Theoretical Framework

Science Education – as - Practice

For the past decade, science education has increasingly advocated for student participation in scientific practice (Ford, 2015; Mody, 2015; Stroupe, 2015). Social studies have detailed how scientists form an epistemic community of practice with specific means of constructing and critiquing knowledge (Knorr-Cetina, 2009; Latour & Woolgar, 1979; Lave & Wenger, 1991; Nersessian, 2008). Activity within this community is orchestrated by historically developed systems of performances that characterize both the individual and the communal search for a better explanation of nature (Ford, 2015). In its simplest form, a scientific practice can be understood as a temporarily stabilized arrangement of these performances that serves to help scientists advance this explanation. As new understandings and norms emerge and evolve, what the community considers to be appropriate scientific practice also shifts. As a result, both a scientist's explanations of how nature works and the means by which those explanations are developed are open to constant critique by the community. This critique helps drive scientific progress by creating space for new possibilities and problematizing areas that had been previously overlooked. Although scientific knowledge and practice are typically described independently, their development is interlaced in this endeavor (Ford, 2015; Ford & Forman, 2006; Latour, 1999; National Research Council, 2012).

The *NGSS* highlighted eight practices that the field of science education has deemed important for student learning of science. These practices included asking questions and defining problems, developing and using models, planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking, constructing explanations and designing solutions, engaging in argument from evidence, and obtaining, evaluating, and communicating information (Achieve, Inc., 2013; National Research Council, 2012). Though science educators often focus one of these practices at a time (e.g., the emphasis on argumentation), these practices are grounded in integrated performances that are not always characterized by distinct boundaries (Ford, 2015).

The Complexities of Positioning Classrooms as Communities of Scientific Practice

The reframing of student learning as participation in meaningful approximations of the disciplinary work of scientists within local classroom communities of practice necessitates a parallel shift in the design of instruction (Ford & Forman, 2006; Kelly, 2011; Osborne, 2014; Richard & Bader, 2010). From this perspective, the design of learning environments should support the co-development of students' knowledge and practice in ways that promote students' own critique and progressive stabilization of that knowledge and practice (Ford, 2015; Manz, 2012, 2014; Stroupe, 2015). This process can be informed by how the larger scientific community has itself stabilized practice (Duschl, 2008), but it also must support the evolution of practice in response to local needs and questions. However, how do such needs become visible in a classroom community, and how can a community comprised of novice students respond productively to these opportunities?

Communities of practice in schools do not function in the same way or for the same purpose as those in laboratories. These differences present meaningful challenges when designing learning environments to support the evolution of scientific practice in a classroom community (Mody, 2015; Stroupe, 2015). In professional communities, the development of scientific knowledge actively pushes on the boundaries of the unknown. Even apprentices on the periphery of the community (e.g., graduate students in university labs) are often working on advancing new theories or methodologies. Though this knowledge builds on and connects to what has come before, it does not advance in a pre-determined direction. In contrast, students are not expected to make new scientific discoveries, but rather they are expected to make scientific discoveries that are new to them. Thus K-12 learning environments are often designed for a form of directed evolution of knowledge and practice. In addition, profession and classroom communities of science also function on different timescales. Social studies of scientists have traced how the emergence, critique, and stabilization of knowledge and practice at times take months and years of intense investigation (Latour, 1999; Latour & Woolgar, 1979; Lave & Wenger, 1991; Nersessian, 2008). In contrast, common approaches to student science learning often measure development in terms of days and weeks. Finally, the bounds of a scientific community of practice often begin with a local research team and extend out through informal and formal social interactions to reach a global scale. Within this disciplinary community there are multiple means by which novices can identify and interact with more expert members and multiple modes of evaluation and critique. In contrast, in a classroom community of novices (including sometimes the teacher), the members often lack experts from which to learn via peripheral participation. If problematization and critique are foundational to scientific practice (Ford, 2015), how do students come to question whether their current ideas or stabilizations of performances are the best means by which they can explain a phenomenon, and what sources do they draw upon to evaluate and adapt their practice?

These issues do not contradict how science education positions student learning as participation in the practices of science (Achieve, Inc., 2013; National Research Council, 2012). However, they do complicate this positioning. As such, the field needs to develop rich descriptions of how, in classroom communities, conceptual knowledge and forms of practice emerge and evolve, both individually and in relation to each other.

The Domain of Field Ecology

Though these questions about classroom communities of scientific practice could be examined in any scientific context, this study focuses on the practice of students who are investigating the ecological relationships and dynamics of a local creek. The discipline of ecology focuses on understanding the characteristics, abundance, and distribution of living organisms and the relationships within and between these organisms and their environments (Korfiatis & Tunnicliffe, 2012). Ecologists investigate these questions by conducting experiments and creating models of ecological processes in laboratory settings (Eberhardt & Thomas, 1991; Hall, Stevens, & Torralba, 2002; Lorimer, 2008; Mauz & Granjou, 2013). However, they also conduct much of their research in the field (Eberhardt & Thomas, 1991; Korfiatis & Tunnicliffe, 2012; Lefkaditou, Korfiatis, & Hovardas, 2014). Field settings are complex natural systems that function on multiple temporal and spatial scales (Underwood, 1994; Wiens, 1989). These settings can rarely be investigated in their totality. Rather, scientists' understandings of ecosystems have to be refined based on the results of a subset or sample of the system. These challenges serve to problematize and advance new stabilizations of ecological practice.

As ecological issues such as the health of watersheds or changes in species distributions are often at the core of many socio-scientific debates, field ecology presents important learning targets for K-12 education (Jordan, Singer, Vaughan, & Berkowitz, 2008). Though the uncertainty and variation inherent in ecological systems can present challenges for K-12 student learning in field settings, they can also create potentially useful entry points for students to engage in the meaningful evolution of practice by generating moments where students' existing conceptions and arrangements of performances no longer suffice to explain what they have just experienced. As students develop increasing expertise in a field setting, the types of questions that they have been asking or they types of data that they have been collecting might no longer encompass all of the features they now consider to be relevant to the system. Such moments can provoke students to critique their current stabilizations of practice and to potentially generate new forms of evidence (Ford, 2015). In turn, students' new approaches to practice might make new elements or new relationships in the system visible and trigger a new round of critique.

Ecologists engage in many epistemic practices while conducting field research, including the practice of developing research agendas, the practice of observing, representing, and measuring, and the practice of sampling. These practices are responsive to the nuances of individual field settings and evolve as ecologists respond to variability within these settings (Bencze & Elshof, 2004; Bowen & Roth, 2007; Nygren & Jokinen, 2013). Over time, ecologists develop a sense of place that helps them understand previously overlooked features of the system (Bowen & Roth, 2002, 2007; Leon-Beck & Dodick, 2012; Lorimer, 2008; Roth & Bowen, 1999). In field settings, local conditions mediate what a researcher can do on any one day and often stymie initial data collection plans (Bowen & Roth, 2007; Madden, Grayson, Madden, Milewski, & Snyder, 2012). Such moments, though at times frustrating, help create a need for ecologists to critique and adapt practice in emergent and often unforeseen ways. This feature of ecological fieldwork can be leveraged within the design of K-12 learning environments to help support students in positioning their own practice as subject to ongoing critique and adaptation. Although ecologists often work alone or in small teams in the field, they must be able to convince the broader scientific community of the validity of their discoveries in order to advance the discipline (Bowen & Roth, 2007; Roth & Bowen, 1999, 2001). Ecologists often test the social acceptability of their methodological decisions or theories in informal settings before offering them for more formal communal critique at conferences or in research reports. These informal social interactions, both within and out of the field, are important for establishing and circulating knowledge within the community.

Research Question

This paper examines how middle school students' scientific knowledge and practice evolve during ecological fieldwork. As such, the analysis focuses on two research questions: How do new ideas and arrangements of performances emerge, develop, and stabilize in students' individual and collective practice? And how do students' ecological knowledge and practice(s) co-develop across time?

Methods

In order to better understand this integration of knowledge and practice, I conducted a design study (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003) in which middle school students advanced their ecological knowledge and scientific practice while investigating a local creek. This paper presents a case study of one team of four students from the second iteration of this design.

Study Context and Participants

Classroom context. This study was conducted within a small rural school system in the south. The student population of this school system identified primarily as White/Caucasian (90%) or Hispanic/Latin@ (8%). Over half of the students qualified for free or reduced student lunch, and less than 10% had limited English proficiency. Many of the students' families had lived in the region for generations. However, local jobs in food production had also attracted new families into the community. The school system had a single middle school, which served all of the 6th-8th grade students. For this study I partnered with all three of the 6th grade math/science teachers. Each math/science teacher was paired with an English/social studies teacher and taught two classes of students.

Though I had worked with these teachers during the year prior to this study, they did not yet feel comfortable with taking the lead during classroom instruction. Each was a veteran middle school teacher with decades of combined experience; however, each had also been primarily trained in and felt more comfortable with teaching mathematics. They most often taught their science classes using a traditional lecture format with occasional elements of structured inquiry. Both the more open guided-inquiry format and the ecological context of this instructional design were less familiar to them. Because of this, I served as the primary instructor for the science classes during this study. However, I encouraged the teachers to engage in the instruction at any time. The focal class selected for this case study had a teacher who actively participated in whole class discussions, team planning meetings, and the creek investigations. This participation by the teacher helped lend credence to the new classroom norms we were establishing and helped in my efforts to draw out a variety of student voices. As the instructor/researcher, I designed the instructional sequence. However, some elements of the enactment were flexibly negotiated with the teachers.

Study participants. All of the 6^{th} grade students participated in these instructional activities. However, this paper presents a case study of one team of four students from one class. This team included two girls, Mychel and Christine, and two boys, Dennis and Matthew *(all names are pseudonyms)*. These four focus students were selected by the math/science teacher to be representative of the class demographics and span a range of traditional competency in science. Though the teacher did not want to reveal each student's specific level of competency, the team included one student from the lower third of the class, two from the middle third, and one from the upper third. In selecting this team, the teacher also took into consideration parent consent, the student's openness to being repeatedly interviewed and closely video recorded, and the likelihood that the student would remain in the community for the full school year.

The creek study site. Our collective work centered on investigating the ecosystem of a creek that flowed through the center of the students' small rural town (Fig. 1). This site was outwardly familiar to most students because it ran behind the town's local diner. Many had visited the site before in order to eat in the diner or play in the creek, and most of their school buses routes passed by it every day. However, the creek had never been positioned for the students as a tool for scientific investigation. I selected this site because it was close to the school, had an open layout with easy access for large groups, presented minimal safety concerns, and had a diverse ecosystem with substantial spatial variation.

Figure 1. "The creek" study site

Instructional Design

This study took place over the equivalent of four weeks of science class (four class periods in December, five in February, four in March/April, and six in May). Each class period lasted 35-40 minutes for a total of approximately 11 hours of instruction. We used the guiding questions “What type of place is the creek?” and “How do different parts of the creek ecosystem interact?” to frame students’ activity and sequenced the instructional design around four mini-cycles of investigation that included three visits to the creek (Table 1).

Each cycle of investigation was designed to progressively support the coordination of new aspects of students’ knowledge and practice. An overview of the intentions behind the design of each cycle is provided below and highlights the intended trajectory for students across this study. This trajectory was informed both by Lehrer and Schauble’s (2012) learning progression for ecology and by a previous iteration of this design. Additional details of the design are included within the narrative of the case study to provide important context in parallel with the analysis. In keeping with the perspective of the classroom as a community of practice, the design of each cycle included ways to bring different students’ ideas and practice into contact with each other so that the students could iteratively refine their knowledge and practice based upon both personal and collective experiences.

Table 1.

Summary of instructional design and data collection

	Interviews	Written Artifacts	Video	Other
Cycle 1 – What type of place is the creek? (2.3 hrs November)				
• Day 1: Class Discussion & Team Planning		Investigation Plans	Class & Team	
• Day 2: Creek Visit 1		Creek Observations	Individual Focus Students	Team photos
• Day 3 & 4: Research Meeting	Creek Interview	Presentation & Listening Notes	Class & Team	Pre-Test
Cycle 2 – What's in the water?/Modeling the creek/Exploring variation (2.9 hrs February)				
• Day 5: Abiotic Measures		Abiotic Worksheets	Class & Team	
• Day 6, & 7: Microcosm models of the creek		Microcosm Worksheets	Class & Team	
• Day 8 & 9: Snail Variation	Microcosm Interview	Snail Worksheets	Class & Team	
Cycle 3: How do the different parts of the creek interact? (2.3 hrs March/April)				
• Day 10: Class Discussion & Team Planning		Investigation Plans	Class & Team	
• Day 11: Creek Visit 2		Creek Observations	Individual Focus Students	Team photos
• Day 12 & 13: Class Research Meeting	Creek Interview	Presentation & Listening Notes	Class & Team	
Cycle 4 - Could patterns we see be due to chance? - (3.5 hrs May)				
• Day 14: Class Discussion			Class & Team	
• Day 15: Team Planning		Investigation Plans	Class & Team	
• Day 16/17: Creek Visit 3		Creek Observations	Individual Focus Students	Team photos
• Day 17/16: Snail Data Analysis			Class & Team	
• Day 18: Creek Data Analysis			Class & Team	
• Day 19: Class Discussion			Class & Team	Post-Test

The first cycle of investigation aimed to expand students' awareness of the different components within the creek and challenge their perception of the creek as a singular space. We opened the study with a whole class discussion designed to help students recruit what they already knew about places such as the creek as they considered what might important to investigate. The class then broke into their creek teams to prepare for their first creek investigation. The design called for students to ask questions and develop data collection plans around what lives at the creek as well their choice of either water depth or water speed. I selected these foci because I conjectured that students would be most engaged and intrigued by the animal life at the creek. However, I also wanted them to gain some initial experience with factors of the physical environment that would likely be related to the spatial distribution of those animals. On the second day the students visited the creek for the first time. The design of this visit focused on establishing safety protocols, building familiarity with our tools, and developing a sense of what could be seen the creek. Finally, the last two days of this adopted a research meeting format similar to that designed by Lehrer, Schauble, and Lucas (2008). Students first planned their presentations as a team. Then each team came to the front of the class and shared what they had focused on, how they collected their data, what they had discovered, and what they still wanted to find out. During each presentation, the rest of the class would write down a question, a suggestion, or something that surprised them. Afterwards, the presenting team would field questions and comments from the audience. These meetings provided students with experience in the collective form of generative critique that Ford (2015) suggested is vital for the evolution of scientific practice. I conjectured that this design would help students generate new ideas about the elements and relationships within the creek and highlight patterns of distribution across the creek.

The second cycle of investigation introduced students to hitherto invisible abiotic factors within the ecosystem and used microcosm investigations to support students in expecting and responding to variation in their scientific practice. The specific microcosms used in this study were one-gallon mini aquatic ecosystems that I designed to model key ecological principles and relationships of the creek ecosystem. I set the microcosm jars up in advance and left them running as self-contained systems for two weeks before bringing them into the classroom. The designs were intended to lead to contrasting pH, hardness, nitrate, phosphate, and dissolved oxygen levels so that students could connect these measures to how the components of each jar functioned. In addition, I created three replicates of each jar so that students could experience variability within even the same set-up. The three "A" jars contained dead leaves, snails, and fish. This set of jars was designed to induce a low level of dissolved oxygen (and a potentially anomalous pH level) to highlight the role of bacterial decomposition in the oxygen cycle. The three "B" jars contained plants, algae, and fish, and the three "C" jars contained plants, algae, snails, fish, and were under a light box. These two sets were designed to present contrasting cases that highlighted elements of the oxygen and nitrogen cycle. The light in the "C" jars induced plant growth, which was likely to decrease nitrate levels as the plants used up those resources and increase dissolved oxygen levels through photosynthesis. In contrast, the "B" jars would likely begin to experience plant die-off, which would decrease dissolved oxygen levels and increase nitrate levels due to continued inputs from animal waste. Finally, the three "D" jars contained plants, algae, snails, fertilizer, and were under a light box. The design of these jars emphasized the cascading impact of fertilizer on measures of phosphate, nitrates, and hardness, and the biotic components of the system. The fertilizer load was purposively set high enough to potentially trigger an algae bloom, which could then be connected to the impacts of decomposition highlighted by the "A" jars. (See Lehrer, Schauble, and Lucas (2008) for similar work, but with student-designed microcosms.)

Our investigations during the second cycle were split into two classroom-based sequences of activity that were positioned as being able to offer general insight into how ecosystems function and the ways we can investigate them. In the first sequence, students used the aquatic microcosm jars to explore the abiotic resources within the water. These resources are often referred to as the water chemistry. This sequence was designed to expand students' understanding of the different abiotic factors, how to measure them, and how they interact with other elements of the ecosystem. I conjectured that this microcosm work would provoke students in expanding their creek investigations to also include abiotic resources and support them in integrating abiotic factors in their explanations of how the creek functions as a system. In addition, the design aimed to expand students' data practices by highlighting how measure and quantity can be used to characterize ecosystems. In the second sequence of activity, the students examined potential sources of variation in measures of ecological phenomena by measuring the shell thickness of a variety of snails from the same population. This activity was designed to shift students' perspective of differences in their data and help them differentiate differences due to measurement and natural forms of variability from those that suggest causal shifts in the ecosystem. This design aimed to support students in expanding their approaches to collecting and analyzing data as they began to attend to issues of variability.

The third cycle of investigation supported students in researching their own questions about ecological relationships and patterns of distribution within the creek. The design of this cycle closely paralleled that of the first. The intent was for students to build on their familiarity with the established activity structures as they continued to advance their knowledge and practice. Its prime aim was to support students in integrating what they held learned studying the microcosms cycle 2 with what they had discovered about the creek back in cycle 1. We began this cycle with a brief discussion about how we could improve the ways in which we collect data at the creek. The students then split into their teams and planned for their second visit to the creek. Because the students were already on their own beginning to pose questions about the relationships between different elements of aquatic ecosystems, I chose to validate this shift in practice and frame their research this cycle around the question, “What does your team want to find out about how the parts of the creek work together?” This created space for teams to investigate, if they so chose, any of their new water chemistry measures. After planning, we took our second visit to creek to collect data. Finally, the last two days were once again structured around the same research meeting format as in the first cycle so that students could continue to learn from the findings and practice of their classmates. During this meeting, I explicitly drew comparisons across the findings and the observational practices of different teams so as to highlight variability within measures and patterns of distribution across the creek.

Finally, the fourth cycle of investigation urged students to consider whether the patterns in the creek revealed underlying ecological functions or whether the degree of difference that they found could be attributed to measurement error and sources of natural variation. During this cycle I chose to assign each team a specific variable based on their research interests to attend to and two locations in the creek in which to collect data. This was a significant shift in the design as teams were no longer carrying out full investigations on their own. However, the students’ questions had evolved to the point that it was impossible for a single team gather the data they needed in the time we had at the creek. Rather, teams would need to pool their data in order to be able to explore patterns of covariation within the creek. We spent the first day preparing for these collective investigations by partitioning the creek into meaningful sections, developing questions that probed the relationships between variables of interest, and constructing a class list of what to include in a good data collection plan. We next spent a whole day planning for our third (and last) visit to the creek. I purposively allotted more time to planning during this cycle because teams were now working together and negotiating a collective plan. I conjectured that this would encourage students to make some of the formerly implicit elements of their data collection procedures more explicit and that it would support students in systematizing their decisions about the number of measurements to take and the locations of those measurements. Next, we headed to the creek for our third and final visit to the creek. And finally, we spent the last three days exploring how to distinguish differences due to measurement error and sources of natural variability from differences due to direct ecological causes and shifts in ecosystem functioning. As students had never approached data in this way (They had previously made causal claims based upon any detectable difference), I chose to conduct most of the analysis as a class. We began our data analysis by first looking at their data students had collected on snail shell thickness back in cycle two. As the snails had all came from the same colony, working with this system eliminated ecosystem differences as a potential source of variation and highlighted the degree of difference due to measurement error and natural variation. We compared the data displays from all seven teams and used this comparison to develop heuristics for how to look at different samples of a measure and determine if the samples came, like the snails, from areas with similar ecological processes. On the next day I gave students computer-generated data displays of all of the data, broken down by variable and section, collected during our last visit to the creek. We then applied the heuristics that we had developed by looking at the snail data to these displays. For each variable we determined if there was likely an ecological difference in that variable across the sections of the creek or if the sections seemed to be functioning under similar ecological process. We then color-coded a table of the mean value of each variable for each section of the creek based on this analysis. Similar colors across the sections signified that that variable seemed to functioning similarly in those areas. Different colors signified a different ecological process. I purposively designed this table so that students could sweep their eye across the colors and use them to highlight patterns of covariation between different variables. On the last day we used this table to develop and test conjectures about relationships between different variables in the creek.

These four cycles of investigation were designed to support students' knowledge of the creek ecosystem across three dimensions: their understanding of the organisms at the creek, their understanding of the physical environment, and their understanding of the abiotic resources in the water, also known as the water chemistry. In addition, the design was intended to encourage students to progressively connect these dimensions in their explanations of how the creek functions as a system. I developed these conceptual categories based on key properties of the ecological system. For example, the separation of the non-living dimensions of the creek into two categories distinguishes between what is readily observable by the senses, the physical environment, and what is invisible without special tools and means of measure, the water chemistry. However, the three categories were also informed by the retrospective analysis of how students perceived the elements of the creek. The cycles of investigation were also designed to progressively support four aspects of students' practice: asking questions, planning and carrying out investigations (which includes observation and measurement), analyzing data and developing explanations, and communicating information. These divisions of practice were informed by the sequencing of activities within the design as well as how the *NGSS* (Achieve, Inc., 2013; National Research Council, 2012) generically distinguishes between the practices of science.

Data Collection and Analysis

Sources of data. Throughout the study I collected data on the focus students' ecological knowledge and practice from a variety of sources including retrospective interviews, pre- and post-tests, student written artifacts, and video records of activities both in class and at the creek. Each source of data is briefly described below. In addition, key questions, writing prompts, and other pertinent details about these sources are woven throughout the narrative of the case study. Table 1, which was introduced above, details the forms of data that were collected on each day of instruction.

Video records of student activity. I collected video records of each whole class discussion as well as the focus team's work both in the class and at the creek. When we were in the classroom the students arranged their desks in groups and sat with their creek teams. I positioned one video camera at the back of the room to capture the full scope of class activity and one video camera on the focus team to capture their individual reactions and small group discussions. I also wore a portable video camera while leading instruction, both in the classroom and at the creek. This enabled me to capture my interactions with the students while preserving my mobility and ability to focus on instruction and safety. While at the creek each student in the focus group, as well as one student from each of the other teams, also wore a waterproof portable video camera. These overlapping video records provided multiple traces of the focus students' activity at the creek and allowed me to track the activity of individual students as well as the activity of the team as a whole.

Student written artifacts. I collected all of the student worksheets from across our investigations. However, sometimes one student would serve as the primary recorder for the whole team, particularly when at the creek. At other times students would accidentally fill in another student's worksheet. Because of this, I relied on the video record as much as possible to attribute specific inscriptions to specific students. In addition, I treated what students wrote during times of collective planning or analysis to be the general product of the team unless a student's writing contradicted those of the other students. I then used the video record to trace which student initiated a specific idea and how it made it into the written record.

Student interviews. I conducted individual retrospective interviews with each focus student at the end of cycle 1, cycle 2, and cycle 3. These interviews asked students to reflect on what they noticed or found out about the creek, what surprised them the most, and what they learned from others during our investigations. They also opportunistically probed student ideas about key topics such as variation or ecosystems relationships that emerged during a given cycle. These interviews lasted approximately 5-15 minutes and were audiorecorded.

Student pre/post-tests. Each student completed an individual pre-test at the end of cycle 1 (day 4) and a post-test after the last instructional day of cycle 4 (day 19). We originally planned to administer the pre-test the week before I arrived to work with the school in November, but the math/science teacher accidentally forgot to do this. So, we decided to have students complete the pre-test at the end of the first cycle. Because I was interested in tracing the emergence of students' knowledge and practice, having students complete the pre-test at this time still allowed me to capture students' ideas at an early stage in the overall investigation. These pre/post-tests asked students to use words or drawings to describe how the parts of a creek work together to make a functioning ecosystem.

Data analysis. I primarily drew upon methods of video-based interaction analysis (Hall & Stevens, 2015; Jordan & Henderson, 1995) in analyzing this data. This allowed me to cohesively explore students' talk, action, and inscriptional traces within microgenetic interactions. Many of these interactions happened between individuals or within small groups (e.g., student-student or student-instructor), but they also played out at larger scales (e.g., when a student responded to a collective action). In addition, students frequently interacted with non-human agents (e.g., the water, dip nets, and crayfish) as they wrestled to gain a material grasp on the natural world during their creek investigations (Pickering, 1985). I supplemented this interaction analysis with open coding (Strauss & Corbin, 1990) of the students' written pre/post-tests and audio-recorded interviews. These two data sources often helped highlight what was most relevant to individual students.

I analyzed the corpus of data from each day in chronological order and looked specifically for moments of interaction around ecological ideas or scientific practices. In particular, I paid attention to instances when a focus student introduced a new idea (e.g., bacteria break down dead fish) or arrangement of performances (e.g., marking the location they took a sample on a map) and traced the evolution of (or indifference towards) these ideas and performances within individuals and the community. I also looked for how the focus students responded to the ideas and performances of others and how these idea and performances interconnected in students' activity. In order to detail how new ideas and forms of practice emerge, I initially focused my analysis at the microgenetic level of activity (Saxe, 2002). However, I also traced the development of the four individual students across the four cycles of investigation in order to describe how their knowledge and practice evolved over the course of the study. In accordance with the recommendations of Hall & Stevens (2015), I focused on what was directly traceable in students' activity and adopted the students' perspective of what was happening during instruction, even if that contradicted the intended design. However, within the case study I also detail the key elements and the intent of the instructional design, including my actions as the instructor/researcher, so as to better understand student activity in relation to the learning environment. This retrospective analysis of the learning environment informed my recommendations for future instructional designs.

Findings

This case study explores the evolving scientific practice and ecological content knowledge of one team of four focus students. It takes a chronological approach, walking through key microgenetic moments of activity from each of the four cycles of investigation. It concludes by examining the overall development of students' knowledge and practice across the course of the study. Throughout the analysis I detail students' knowledge of the creek ecosystem across the three dimensions previously described (their understanding of the organisms, their understanding of the physical environment, and their understanding of the water chemistry) and how they progressively connected these dimensions in their treatment of the creek as a system. In addition, I trace four aspects of students' practice across their investigations: asking questions, planning and carrying out investigations, analyzing data and developing explanations, and communicating information. The narrative for each cycle begins by detailing the instructional design in order to provide context for the analysis.

Cycle 1: Seeing What Lives At The Creek

> We figured out that there were a lot more crawdads than we expected. We actually didn't expect to find as much crawdads. We probably didn't think we would find any. That's one of the animals that we didn't figure we'd find. It also surprised us that we think something might be eating or they might just get being cut off somehow because we found a lot of larger crawdads that were cut in half.
>
> - Mychel, Cycle 1 Retrospective Interview

Instructional design of Cycle 1. The instructional design for the first cycle of investigation aimed to expand students' awareness of the different components within the creek and challenge their perception of the creek as a singular space. On day one we opened our investigations with a whole class discussion around the broad question "What type of a place is the creek?" Using this question as a springboard, the students generated a list of the different things they predicted that they might see in the creek and various questions about the creek that might want to explore. This discussion was designed to prime students to recruit what they already knew about places such as the creek as they considered what might important to investigate in this system. It also initialized students' scientific practice as they considered what questions they might want to ask, what they might focus on observing during their investigations, and to an extent also what they might want to explain about the ecosystem. During the last half of the class period, the students broke into their creek teams to prepare for their first creek investigation. Each team brainstormed what they wanted to find out about what lives at the creek and planned how they would gather their observations. They were also asked to pick either water depth or water speed as a focus and once again plan what they wanted to find out about this aspect of the creek and how they would gather their observations. The time allotted for planning was purposefully kept short because I had conjectured that the students would likely have a limited vision both of what they could investigate at the creek and of how they might use the tools they had at their disposal to collect data. I also conjectured that the students would initially privilege the animal life in the creek. Because of this, the planning worksheet deliberately focused students' attention on aspects of the physical environment. I chose to highlight water depth and water speed because these were aspects of the physical environment that were accessible to students through gross visual observation and also could be quantitatively measured using simple tools and student-developed methods. I wanted to emphasize measurement early on in the design because more sophisticated forms of ecological investigations are characterized by the progressive mathematization of qualitative observations to quantitative measures. In addition, water depth and water speed were strongly variable both within and between different areas of the creek and were likely to be correlated with the distribution of different organisms that students might observe. I conjectured that this might create opportunities for students to begin to see relationships within the system and to connect their ideas about the organisms they were seeing with they were also noticing about the physical environment.

On the second day we headed out to the creek for our first visit. The design of this visit focused on establishing safety norms while working in the field, building familiarity with the available equipment, developing a sense of what could be found at the creek, and experiencing the creek as a variable space. I laid out the equipment each team would need to enact their data collection plans, as well as additional tools that I thought they might find useful, prior to the students' arrival at the creek. For example, the focus group's equipment included two large tubs, two yardsticks, one small green scoop, one large net, an invertebrate identification key, a digital camera, and two pairs of boots (Mychel also brought a third pair with her). In addition, I assigned each team a general location in the creek to work in to minimize arguments over who was in whose space and maximize the range of microhabitats investigated by the class as a whole. When the bus arrived at the creek, I gave the students a short safety reminder and then directed each team to their equipment and their assigned area of the creek. Using the same worksheet packet in which they had developed their questions and plans, the students first drew a rough sketch of their section of the creek while standing along the bank. This task was designed to give students an overview of the space before they dove into the details of their team's specific observations. Once each team had safely settled in their area, they were given permission to carefully enter the water and gather their observations. The students were given defined space on their worksheets to write what they noticed. However, the structure of these observations was open-ended. Overall, I conjectured the design of this creek visit would shift students' perspective of what could be seen at the creek, increase the saliency of how tools are used and observations are gathered, and stimulate thinking about the variability of different components of the creek (e.g., the number of invertebrate larva or the water speed) and how these components were distributed across space.

On the third day the students met in their creek teams to begin planning their research meeting presentations. I conjectured that the design of these presentations would generate new ideas about the components and relationships within the creek, highlight variability, and allow students to see patterns of distribution across the creek. As these students were fairly inexperienced with presenting in front of their peers, I kept the research meeting format fairly structured. Each team had a planning guide that outlined key questions they needed to address and which member of the team would share that portion of the presentation (Fig. 2). At the end of the day we began the presentation portion of our research meeting. During these presentations, a team would come to the front of the class and share what they had focused on, how they collected their data, what they had discovered, and what they still wanted to find out. When it was their turn to speak, many students needed explicit encouragement and ample wait time to find their voice. As they listened to presenting team, the rest of the class would write down a question, a suggestion, or something that surprised them on their listening notes. After presenting, the team would then field a handful of questions and comments from the audience.

Each presentation lasted approximately 5-8 minutes. We repeated this format with the remaining six groups on the fourth day. After all of the teams had presented, we wrapped up the research meeting (and this cycle of investigation) by talking about what type of data we might want to collect the next time we visited the creek and looking at all of the pictures each team had taken at the creek.

Prepare for your team's presentation

1. The Team Leader will begin by describing…
   - What section of the creek the team focused on.
   - What questions the team was interested in about what lives in the creek or what the water is like.
2. Then the Equipment Manager will describe…
   - How the team made their observations about what lives in the creek.
   - What the team found out about what lives in the creek
3. Then the Data Recorder will describe…
   - How the team made their observations about the water depth or speed.
   - What the team found out about the water depth or speed.
4. Finally the Videographer will describe…
   - The team's answers to these four questions:
     1. What did your team find most surprising at the creek?
     2. What difficulties is the team having or what do you want to change about how you collect data? Why do you think it would be good to make those changes?
     3. What do you think your team would find if you went back to the creek in a few days and measured similar things? Why?
     4. What does the team wants to find out next about the creek and why you are interested in those things?

Figure 2. Research meeting planning guide – Cycle 1

Students' trajectory within Cycle 1. As described above, we began our investigation on day one by generating a list of what students predicted that they might see in the creek and the various questions that might want to explore (Fig. 3). The four students who are the focus of this study (Dennis, Larry, Mychel, and Christine) each contributed to this class list. During the discussion students initially focused on the animals that they thought would live at the creek. These included crawdads, fish, frogs, slugs (suggested by Larry), and turtles (Dennis). As this list of living organisms grew, I began to probe for the non-living aspects of the ecosystem as well. Dennis was one of the first to bring up an abiotic feature of the creek when he declared, “Obviously we’re going to see rocks”. Mychel took up this discussion of the creek’s substrate and extended it to turbidity by describing the creek as likely to be muddy and murky. With further direct probing, the students begin to list different characteristics of the water that might be important to pay attention to. This list eventually included water depth, pH (Dennis), temperature (Christine), and speed.

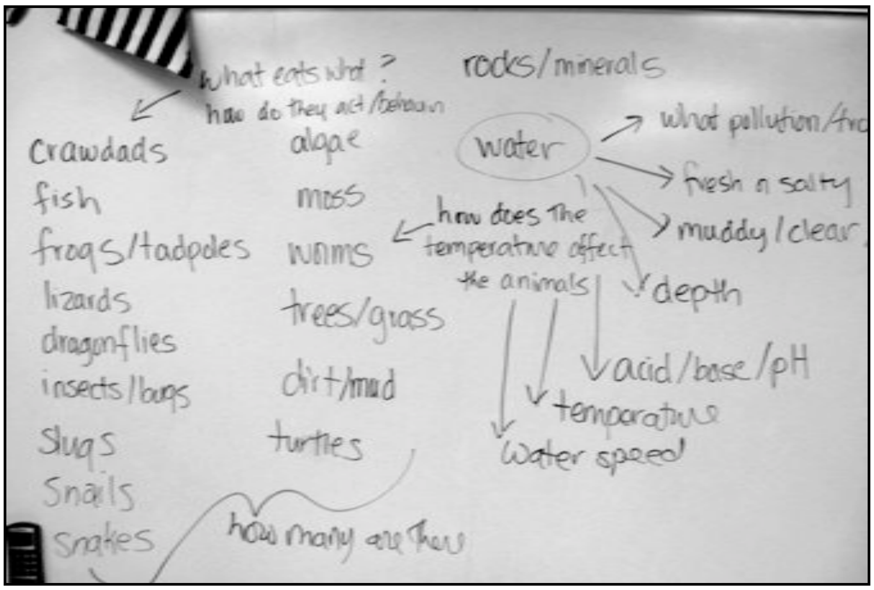


Figure 3. Class list of predictions about what is at the creek and questions to investigate

When the students broke into their creek teams to begin planning their first creek investigation, Mychel designated herself the leader and guided the team’s discussion about what they wanted to find out. Both Mychel and Larry pushed to focus on the animals that they thought would be easy to find at the creek. The team settled on researching frogs, tadpoles, and slugs and decided to examine how many tadpoles were in each stage of their cycle and how many frogs and slugs were in each area. Interestingly, none of these organisms were in fact common residents of this particular creek. In planning how they would gather observations, the team seemed to treat seeing the animals as a straightforward endeavor. For example, they wrote that for the frogs that they would simply “count the amount in each area” and for the slugs that they would see “how many in more populated areas in the creek and how many in less populated areas”.

In thinking about what they want to find out about the water, the team chose to study the water depth instead of the water speed because it seemed a more feasible feature to investigate. Larry suggested that it was possible that the creek might not have any speed but that it had to have depth, and Mychel, Christine, and Dennis quickly concurred. However, once again their ideas about how to gather their observations lacked detail, and they wrote that they planned to “measure the depth of each area” without any reference to how they would measure or where they would measure. I had been circulating throughout the class while the students were talking and joined the team at the end of this conversation. So I asked them what they wanted to find out about the water depth (Excerpt 1). Larry explained that he thought the creek was going to be shallow, and he animated this prediction with a gesture that suggested the creek would be low and uniform (line 2). I countered Larry’s categorization with the question, “Everywhere?” (line 3). Both Larry and Mychel responded that the creek would not be shallow everywhere. Rather, there could be some variation in the depth of the water (lines 4-5). Mychel punctuated this description with hand gestures indicating various heights. When I continued to probe the students about what they wanted to know about the depth (line 6), Larry revealed that his reasoning about water depth was coupled to his thinking about the organisms at the creek (line 7). Mychel agreed and further suggested that the incidence of tadpoles would be inversely related to water depth or, in her words, “Tadpoles would be in more shallow water” (line 8). Thus even on this first day, students’ reasoning about physical aspects of the creek such as the depth was integrated with their ideas about which animals live where. In this we glimpse an early seed of the integration of concept and practice in students' activity, as the students' perspective of this relationship seemed to inform the questions that they asked and the ways in which they planned to conduct their investigations. However, the details of these relationships often did not make it into their written questions or data collection plans.

Excerpt 1 – Plans to investigate water depth

1	Researcher:	What do you want to know about the depth?
2	Larry:	If there's more shallow. My prediction is that it's going to be shallow. *(Gestures with hands low and spreading out.)*
3	Researcher:	Everywhere?
4	Larry:	Not everywhere. It may be deeper in some areas where the water is.
5	Mychel:	It could be deeper. There could be more different types. *(Gestures with hands moving up and down.)*
6	Researcher:	So what do you want to know about the depth?
7	Larry:	What animals live there
8	Mychel:	Tadpoles would be in more shallow water.

In addition, the students seemed to treat the larger processes of data collection as unproblematic during their planning. They did not debate how they intended to make the frogs, tadpoles, or slugs visible so that they could be counted or even discuss what tools they might need. They also did not discuss about how they would select the different areas in which to count the organisms and measure the depth. None of these issues of observation and measure seemed salient to students at this time.

On the day two at the start of the creek visit, the team rushed to gather their equipment and pull on their boots as soon as they were released from the safety briefing. Mychel grabbed the yardstick, Christine the green scoop, and Larry the large net. Dennis, the fourth member of the team, was absent this day. The team was so excited to get down to the creek that I had to remind them to take their observation packets and the rest of their equipment with them. Down by the bank they began drawing their sketch of their section of the creek. Mychel suggested that they mark where the biggest rocks were in their section as well as where they could see a water strider. She also began to record a list of organisms that they saw in their section, and Christine and Larry followed her example. They listed the water strider that they had already drawn as well as a tadpole (likely a minnow) that Mychel had said that she saw. By this time the team had received permission to slowly and carefully enter the water. Christine and Larry picked up their scoop and net and began looking for animals. Their approach was to try to first visually identify an animal and then use the scoop or net to catch it (as opposed to scooping first and then seeing if they had caught anything). Meanwhile Mychel picked up the yardstick, walked to the center of the creek, put the yardstick down once in the water, looked at the water level, and declared the depth to be six inches. She walked back to the bank and recorded this on her observation sheet. Then she headed back into the water and repeated the process near the far bank. This measurement, although slightly shallower then the first, she also declared to be six inches. Though Mychel's process of measurement superficially resembled the practice of professional ecologists who use their understanding of the degree of variation necessary to have a meaningful difference in a variable to guide the precision of their measurement, there was no evidence that Mychel was attending to depth in this way. Rather, her later descriptions of the areas seemed to superimpose the value of six inches to the entire space, even though some parts of the area in which this team was working were twice that depth. It is more likely that Mychel simply viewed the repeated value of six inches as a way to double-check that she had found the "right answer" for creek depth. While Mychel was measuring the depth of the creek, Christine and Larry were struggling to find anything of interest in the creek. However, Christine would soon catch the team's first organism (Excerpt 2).

Excerpt 2 – Catching their first organism

		(Mychel has just used the yardstick to take two depth measurements of the water and is moving to record these on the data sheets on the near bank. Larry has the dip net and is looking for organisms in the middle of the creek with the net out of the water. Christine is doing the same about a meter downstream with the small scoop.)
1	Christine:	I see nothing. *(Walks from center to far edge of creek. Another team nearby is talking about finding crawdads under rocks. Christine looks up and then heads towards a pile of rocks, spots a crawdad, and breathes in fast.)* Guys I found one!
2	Mychel:	Found what?
3	Christine:	*(Crouching and pointing with finger.)* I found one right here. *(Larry walks over to and places the dip net in the general area.)* No, look. *(Points back and forth from where Larry put the net to where the crawdad is.)*
4	Larry:	*(Grabs Christine's scoop.)* Let me see that, Chris
5	Christine:	*(Mychel splashes over still holding the yardstick, loses her balance, and trips past the area Christine and Larry are looking at.)* Look, Mychel.
6	Larry:	Hold this. *(Hands net to Christine. Starts to scoop with the small scoop.)*
7	Christine:	*(Puts net in the water downstream from Larry's scoop. Crawdads swim into the net.)* Did I get it? I got it!
8	Larry:	Yeah, you got it! *(Christine, Larry, and Mychel all look in the net.)*
9	Mychel:	You got it. Oh! Those are…
10	Larry:	There's two!
11	Christine:	Two! *(Mychel and Larry turn away from the net and head to the far bank. Christine stays looking at the net.)*
12	Larry:	*(Shouts to another team who's looking at them.)* There's a baby crawdad!
13	Mychel:	*(Stops.)* Gimme this. *(Goes to grab the net from Christine). Actually. (Turns back to the far bank.)*
14	Christine:	There's a baby. Look at this baby one! There's three. *(Christine, Larry , and Mychel work to get the crawdad out of the net and into the team's bucket for viewing.)*

As she slowly moved through the water, Christine appeared to overhear another team talking about where they had found crayfish, adjust where she was searching based on this new information, and ended up immediately spotting a crawdad (line 1). She called out to her team that she had "found one", and the others rushed over. As Christine had not clarified what she had found, Mychel asked, "Found what?" (line 2). Christine did not answer Mychel's question, but instead pointed to where she was looking (line 3). By this time Larry had arrived and lowered his net into the water while looking at where Christine was pointing. However, he had placed his net in the wrong spot to be able to catch the crawdad, and Christine seemed to try and use gestures to correct this placement. At this time, Larry seemed to assume control of catching this crawdad. He grabbed Christine's scoop, thrust his net at her, and tried to scoop up the crawdad (lines 4-6). At the same time, Christine rested the net in the water while watching and seemingly serendipitously became the one to actually catch the crawdad as it swam away from Larry and into her net (line 7). By this time Mychel, who had been having trouble walking on the slippery rocks, had finally joined the others. As they all stared into the net, they realized that Christine had caught not just one but multiple crawdads (lines 9-11) and turned almost immediately to transfer the contents of the net to one of their tubs for closer observation. During this time students from other nearby teams had been closely watching all of the commotion. Larry acknowledged their stares and paused to shout in their direction, "There's a baby crawdad!"

The transfer of organisms from a net or scoop into a tub for closer observation was a purposefully designed aspect of students' work at the creek that I had suggested and overtly encouraged. This served a number of functions in students' practice. First, it problematized what it meant to "see" an organism in the creek because students often discovered that they had scooped up more than what they originally thought they had caught. Second, it transformed the act of catching an organism into a knowledge-generating activity by slowing students' pace of observation and allowing more details about the organism to emerge as students observed it over time in the tub and debated what they were noticing. And third, it fostered comparisons both within and between teams. A team could compare new organisms that they added to the tub to those that they had previously captured. And students could also walk over to another nearby team, look at their tub, and compare what that team had found to the organisms in their own tub.

As seen in this excerpt, students attempted the relatively simple task of observing an organism in field conditions, they first had to gain access to the organism. Christine and Larry tackled this problem by gingerly walking in the creek until they saw something that they were interested in. Then they needed to catch the organism. This often required the students to use new tools in new ways. Often, as happened in this excerpt, the actual catching of the organism was at least partially the result of unintentional actions. Finally, students were often initially unaware of what they had caught even after they had caught it. In this case, closer examination of the net revealed at first two and then later three crawdads, instead of the single crawdad that the students originally thought they had caught. This exposed a potential critique of the team's method of observation, as the act of scooping revealed crawdads that the team had not been able to first visually identify by looking in the water. The team's actions also highlighted the collective nature of observation. Seeing an organism was a trigger to bring the team together. It was also a moment, as when Larry shouted, to communicate to other nearby teams. As such, students were learning from their teammates and from other classmates both what was at the creek and how to act in the creek to make organisms of interest visible. However, students' written records of their time at the creek did not capture either the breadth or the nuance of what they were experiencing in the water and saying to each other. Rather this team's entire data record from this first creek consisted of a list, but not a count, of organisms that the team either saw or caught ("water spider, tadpole, caught crawdads") as well as the two depth measurements ("6 in, 6 in") taken by Mychel.

After catching these crawdads and observing them in the bucket, the team continued their search for more organisms. In so doing, they began to concentrate their efforts on one section of the far bank near where they had found the first crawdads. Larry became increasingly skilled at capturing crawdads, both alive and dead, in this area with the small scoop, and he continued to deposit the crawdads he found in the team tub for collective observation. Two of these crayfish that he found were much larger than the others. They also were dead and cut almost in half. The team attributed this to a purposeful action by another organism, rather than decay, but could not think of what could be "eating the crawdads". During this time Christine and Mychel shared the use of the large net. However, both struggled at times to walk in the creek while wielding this new tool, and neither successfully captured any more organisms. At one point near the end of their observations, Mychel briefly drew attention to the fact that the team was neither seeing in the creek nor actively looking for the three organisms (frogs, tadpoles, and slugs) described by their questions and data collection plans. She asked the others, "Should we forget about frogs? Because there's more of these *(points to the tub)*." When Larry and Christine didn't object, Mychel simply crossed off the word "frogs" from her planning page and wrote in "water striders".

Dennis was not able to be a part of this first creek visit, and this lack of first-hand experience with the phenomena might have put him at a disadvantage during the following class periods. He would later seem more prone to suggest anthropogenic explanations for what the team had observed at the creek, and his efforts to contribute to collective sense-making would often be silenced by others. However, Dennis's strong background in farming and hunting and his limited interpersonal skills potentially also contributed to these patterns. In his retrospective interview for this cycle, Dennis explained that his primary goal for the next investigation was "to figure out a bunch of stuff that everyone else did since I wasn't there." This drive to experience what they had missed out on was echoed by many students – even those who had been at the creek. Students who explored the water depth often wanted to look at the water speed, and those who had developed expertise with only a few animals often wanted to go back and look for the ones that they had not yet seen.

On the third day the students met in their creek teams to begin planning their research meeting presentations. Larry was absent during this planning phase, and once again Mychel took charge of the team. She would read each question aloud, share her answer, discuss this with Christine, and then narrate her writing as she filled in the research meeting planning guide. (These questions were shown earlier in Fig. 2). Both Christine and Dennis frequently copied a version of Mychel's answer during her narration. Excerpt 3 illustrates this pattern of activity and details how the team arrived at what they were going to share about the organisms in the creek.

Excerpt 3 – Planning for research meeting presentation

1	Mychel:	What did our team find out about what lives at the creek? Ah, we found out. What our team found out about what lives at the creek. We found out that something is possibly eating the crawdads.
2	Christine:	Yeah. *(Begins to write on her paper.)*
3	Mychel:	*(Begins to write on her paper.)* That something is possibly eating the larger crawdads. We found out that something is possibly eating the…
4	Dennis:	*(Looks at Mychel)* Maybe Gran's Kitchen. Maybe the people from Gran's Kitchen is coming out and getting them.
5	Mychel:	*(Looks at Dennis)* I doubt it. For some reason I don't think fried crawdads are on the menu.
6	Christine:	*(Looks at Dennis)* We found a dead one that was eaten.
7	Mychel:	*(Looks at Dennis)* It was like in half.
8	Dennis:	*(Knowing sigh. Looks off across the room).* Oh.
9	Mychel:	*(Looks at Christine)* I don't know why Larry put that in the bucket.
10	Christine:	*(Looks at Mychel. Has finished writing)* Probably to look at it.
11	Mychel:	*(Goes back to writing)* Something is eating the larger crawdads. *(Interruption to talk about logistics of the research meeting.)*
12	Mychel:	Okay. *(Begins to write again.)* We found out that something is possibly eating the larger crawdads.
13	Dennis:	*(Looks at Mychel.)* I think possibly a cat.
14	Mychel:	*(Ignores Dennis and looks at Christine.)* Please say I wrote possibly right.
15	Christine:	*(Looks at Mychel's paper.)* I think you did.
16	Mychel:	*(Continues to write.)* Possibly eating the larger crawdads
17	Christine:	*(Looks at Mychel's paper)* Because I didn't see no little ones eaten.

Mychel began by suggesting that they share how “something is possibly eating the crawdads”, and Christine agreed (lines 1-2). Mychel then repeated this phrase, adding in the modifier “larger”, while writing it on her researching meeting planning guide (line 3). Dennis interrupted this process and suggested that the crawdads were being eaten by the people at the local diner (line 4). This suggestion was quickly rejected by Mychel (line 5). Christine, potentially recognizing that Dennis’s comment did not align with what they had observed, then specifically described what they had seen for Dennis (line 6), and Mychel extended Christine’s description (line 7). Dennis responded, “Oh”, in an intonation that suggested that this was not what he had first imagined (line 8). As Mychel continued to write, Christine shared that she “didn’t see no little ones eaten” (line 17). This highlighted the importance of the modifier “larger”. In doing so, Christine was synthesizing what the team had seen across the population of crawdads in their area and drawing distinctions based on their qualitative observation of crawdad length.

Near the end of the third day the class began the presentation portion of our research meeting. These presentations would extend into the fourth day. Christine, Dennis, Larry, and Mychel all actively listened during the other presentations and wrote down at least one question or surprising finding for each team. All four also raised their hands to participate in the discussions, although only Larry and Mychel were called upon by their peers. Many of the students’ questions asked for clarification of the data that the other teams presented. They wanted to know the details of the type, number, and size of organisms observed. For example, Mychel asked the first team, “How many fish do you think you guys saw?” The students also probed their peers about their process of observation. Mychel asked one team, “What did you use to catch the fish?” and another, “How did you identify the larva?” Similarly, Larry wrote about wanting to know how a team measured the water. In her listening notes, Christine even differentiated between seeing and catching organisms in the creek as she wrote that it surprised her that one team "caught one fish" and also questioned "how much fish did you see". This form of differentiation is useful for generating ecological measures that are not grounded in having to catch organism. In addition, some of Larry's questions pushed for clarification about space and location, a theme less prevalent with the other students. For example, he asked one team, "Do you know where all the dragonfly, like, the larva was at, like their habitat?" and another, "Did you look under any rocks to find any animals?" The students also wrote about their surprise when another team found something different than they had experienced. They were surprised that teams reported seeing tadpoles, catching fish, and finding different types of invertebrate larva. Dennis was also surprised that other teams were able to find the speed of the water and that one team was working in an area where the water was 9 ½ inches deep. These listening notes suggest that students were closely attuned to novelty and difference in their peers' observations.

The focus students took their turn to present midway through the research meeting. The team moved fluidly from one presenter to the next before fielding questions from the class (Excerpt 4). Mychel opened the team's presentation by describing the general area that they worked in and their initial question about tadpoles (line 1). However, she did not include anything about her ideas to change the question to focus on what they actually saw. Larry then described how the team collected data on what lives at the creek (line 2). In addition to sharing the team's list of organisms and their idea about something eating the large crawdads, Larry drew attention to the locations (under rocks) in which they searched and the habitats (mossy areas) in which they found the crawdads. Next, Christine shared their two measurements of water depth (line 3), and finally Dennis read the team's answers about what surprised them, what was difficult, what they think they would see again, and what they want to find out next (line 4).

Excerpt 4 – Research meeting presentation

1	Mychel:	The part of the creek we focused on was near the biggest tree where all the equipment was it was kinda basically in front of that and kinda rocks and stuff. And the question we were interested in were we wanted to find tadpoles and how many and what level of the cycle the tadpoles was in if we could catch any and we also wanted to work on the depth.
2	Larry:	We made our observations about what lived in the creek by moving some rocks and looking under them. We looked around different habitats. The things they would live. And in some places like in mossy places we would find so many crawdads in there. *(Reading his paper.)* We found water striders, crawdads, tadpoles, fish, and grasshoppers. And we found out that something is possibly eating the larger crawdads.
3	Christine:	*(Reading her paper.)* How we made our observations. We measured with our ruler that we had. And we measured two areas and both areas were basically six inches.
4	Dennis:	*(Reading his paper.)* What did your team find most surprising at the creek. That the larger crawdads were the ones that were being eaten. What difficulty was we could try to find some of each animal instead of focusing on one. So we could study more than one animal. And we think we would find mainly the same things because everybody was finding the same things. And we also think that the team wants to find out what's eating the crawdads because we found a bunch of dead crawdads.
5	Researcher:	Okay, everyone should have something written down for team four. And I want to encourage anyone who hasn't raised their hand to offer a suggestion or a question. *(Multiple students raise their hand, and Dennis points to one student.)*
6	Student 1:	How do you plan on finding out what was eating the larger crawdads?
7	Dennis:	Looking around and stuff. It's possible that…
8	Mychel:	*(Mychel holds up her hand in the stop position and interrupts Dennis with something inaudible. Then she points to Larry)*
9	Researcher:	Anyone on the team can answer any question.
10	Mychel:	Yes, but Larry knows more about it.
11	Larry:	I found three dead crawdads chopped in half like by something under a rock or something um and I think there was a fish eating on the crawdad when I moved the rock. I just saw a crawdad dead right there. And I saw fish pass by right there underneath the rock. So I think the bigger fish are eating it. And once the big fish kill them the little fish get to eat off them. I think the fish are eating them.
12	Dennis:	*(Arms crossed in front)* And there might be a possibility that they're eating crawdads at Gran's Kitchen.
13	Mychel:	I haven't seen crawdads on the menu so I doubt it. *(A second student asks a question about where they found the grasshopper.*

		Then Dennis calls on a third student, Jackson.)
14	Student 3 (Jackson):	Do you all guys think that coons could have eaten the crawdads?
15	Team members:	*(The team members look back and forth at each other quizzically. Dennis shrugs his shoulders)* Coon? What? Raccoons? Um.
16	Student 3 (Jackson):	'Cause raccoons love crawdads. Yeah, they love crawdads. *(Inaudible comment about seeing 'coons at his grandmothers creek.)*
17	Larry:	There may be other creatures that come by the creek to take drink.
18	Mychel:	*(Interrupts)* And see crawdads
19	Larry:	And see crawdads and eat them.
20	Researcher:	Yeah, and it could be one thing that could kill it, and then other things in the creek that could also be eating it.
21	Larry:	And finish it off.

When the presentation was opened for questions, suggestions, and comments (line 5), the students listening to the team were most interested in their novel observation about the dead crawdads. The first student asked the team about their future data collection plans and the process by which they might determine what is eating the crawdads (line 6). Dennis began to answer this question (line 7), but Mychel interrupted him and positioned Larry, who had been at the creek but not a part of planning the research meeting, as the one with expertise in this matter and thus the one who should answer the question (lines 8-10). Larry shared how he had moved the rocks in the creek to observe the dead crawdads and how he thought that fish were eating the crawdads because he found them nearby (line 11). He also suggested that maybe the big fish were killing the crawdads and then the little fish were able to eat them. After this, Dennis interjected with his anthropogenic explanation of people at the nearby diner eating the crawdads (line 12), which Mychel once again dismissed (line 13). The third student who asked the team a question, Jackson, continued this discussion of crawdads and offered an alternative suggestion that "coons could have eaten the crawdads" (line 14). Jackson's idea had resonance with the team, as Larry and Mychel wove it into an explanation of how other creatures could potentially come to the creek to eat and drink (lines 17-19). As seen here, the teams used the question and answer sections of these presentations to flesh out the processes by which they conduct their investigations, the details of what they observed, and their explanations of these observations. This was generative collective work, and new ideas flowed both from the presenting team to the audience and from the audience to the presenting team. In this exchange, the community typically gave more weight to novel observations and privileged the first-hand experience of the students who had conducted these observations.

After all of the teams had presented, we talked about what we type of data we might want to collect the next time we visited the creek. During this discussion the students were fixated on the organisms that they had seen and how those organisms live their lives and meet their needs. For example, after one student shared that he wanted to learn more about the crawdads, other students chimed in that they wanted to know how they move, where they are found, and what they are most similar to. Larry suggested that we also study how the crawdad camouflages itself. However, the students struggled to transform these interests into descriptions of what type of data or evidence we could gather about the crawdads. We wrapped up the research meeting (and this cycle of investigation) by looking at all of the pictures that each team had taken at the creek. Many of these were snapshots of different team members. Most of the others, however, were pictures of different organisms each team had caught. This quick comparison of the teams' pictures highlighted the differences and similarities across the different areas of the creek. While looking through these pictures, I again asked the students what types of data we could collect at the creek. Here, the students focused on the types, numbers, and size of the organisms at the creek.

At the end of this cycle the focus students participated in a retrospective interview about what they had experienced and what they wanted to investigate during their next visit to the creek. Each student highlighted their observations of the crawdads and explained how they wanted to extend their study of this organism. Dennis had been intrigued by what the others had shared about the big crawdads, and he drew on ideas both from his own experiences hunting and from what others had suggested during the research meeting to reason about how the team could determine what was eating those crawdads. In this, he finally shed his focus on an anthropogenic explanation of the phenomenon: “Well, looking at the carcasses and stuff and seeing if I can see any teeth marks. Or I can see if the animal lost a tooth by biting…Looking for signs on the ground. Cause it might be a land one. And looking for scat and stuff…Might be something out of the creek. Like Jackson said, a coon.” Christine wanted to find out more about the crawdads’ habitat, and Mychel wanted to explore both the spatial distribution of the crawdads and what was eating them. Larry was most interested in focusing on what the team had not yet done and brought up potentially investigating crawdad length (which they had informally noticed but not formally measured) and water speed (which they had rejected in favor of water depth). In his words, “We didn't get to find out the speed. So I might want to find out how much that is. And how big the animals are…It can affect what kind of creatures are there by the speed of the water. And if you measure the crawdads you can see if they are big, like that one that was chopped in half or something. If I would have measured that we could have seen how big it was and compared it to the littler ones.” These responses seem to indicate that students’ interests could potentially be pulled in two directions. They might want to develop further expertise in the phenomena that they have already begun to investigate. But they also might want to explore phenomena that they think is important or interesting but that they didn’t have time to study (or didn’t think to study) during the last investigation. This suggests a potential tension between developing depth and breadth in their understanding of the creek ecosystem. During the interview the students also described how they had learned new things about the creek by listening to the other team presentations. As Christine described, "It surprised me the most mainly all the groups caught a bunch of crawdads and which I didn't think there was going to be a bunch…It helped me learned that the creek has a bunch in each area. So maybe the crawdads are in each area of the creek." Like Christine, all of the students crafted a description of how animals were distributed across space in the creek based on patterns that they noticed across the different team presentations.

At the end of this first cycle, the students also completed a pre-test in which they were asked to describe what the creek is like and how the parts work together to make a functioning ecosystem. These descriptions were analyzed for their number of general components, specific components, and different types of relationships, as well as the number of relationships in the longest chain and if present the longest cycle (Table 2).

Table 2.
Characteristics of students' pre-test explanations of the creek

	Dennis	Christine	Larry	Mychel	Mean
Number of different types of components:					
General components (e.g., animals or water)	2	1	1	0	1
Specific components (e.g., crawdad or nitrates)	0	1	3	4	2
Total number of components	2	2	4	4	3
Number of different types of relationships:					
Organism impact on other organism	0	0	0	0	0
Organism impact on the physical environment	1	0	0	0	0.25
Organism impact on water chemistry	0	0	0	0	0
Physical environment impact on organism	2	1	1	2	1.5
Water chemistry impact on organism	0	0	0	0	0
Total number of relationships	3	1	1	2	1.75
Number of different relationships:					
In the longest chain	2	1	1	1	1.5
In the longest cycle	2	0	0	0	0.5

The students included an average of 1.75 relationships and 3 components in their descriptions of the creek. Many of the components students included were general references to water. In addition, Dennis, Christine, and Larry still wrote about "animals" in general instead of making any claims about specific organisms, even though by now all of the students were familiar with the specific types of animals that could be found at the creek. Only Mychel included specific animals, such as the crawdads, in her description. However, Christine and Larry described specific forms of the creek's substrate, including rocky areas and grassy areas.

All of the relationships included by the students connected organisms in some way to the physical environment. For example, Larry wrote that the "rocky areas, grassy areas, and tree areas all have different animals living in each part." Only Dennis included any multi-step chain or cycle in his description of how the creek functions, and even he only described in vague terms that "the creek (water) help animals by giving them a home and some a source to drink" and "the animals help the creek by getting rid of stuff that isn't sopose to be in there."

Summary of students' development of knowledge and practice in Cycle 1. The first cycle of investigation was characterized by shifts in how students perceived the biotic components of the creek ecosystem (Table 3). From the beginning, the students' investigations were propelled by their interest with the organisms that lived in the creek. However, most students could initially only guess as to what they would find along the banks and beneath the surface of the water. As they gathered observations at the creek and listened to others report on their findings back in the classroom, the students were fascinated by the presence (and absence) of different animals and began to speculate about how the needs of these animals were being met.

Table 3.
Summary of students' knowledge and practice during Cycle 1

	Understanding of the Organisms	Understanding of the Physical Environment	Understanding of Water Chemistry
Knowledge	• Shift from hypothesized animals to actual animals (crawdads) and their needs • Attention to similarities and differences in the types and number of organisms across space	• Delineation of different types of substrate (mossy, rocks) and, for some, their connection to the location of specific organisms (crawdads)	• None emphasized

	Asking Questions	Planning and Carrying Out Investigations	Analyzing Data and Constructing Explanations	Communicating Information
Practice	• Initial focus on incidence of hypothesized animals in undefined areas • Shift to focus on crawdads, including the relationship of incidence to water speed and substrate • Evolution of focus connected to experiences in the creek	• Process of how to collect data not included in plans • Activity at the creek driven by what was readily observable (see-catch method) rather than developed questions and plans • Observation was a collective act • Written data limited to a list of organisms seen/caught and two depth measurements	• Stories used to develop explanations of anecdotal qualitative data • Attention to patterns within personal, team, and class experiences	• Other teams used as resource at the creek • Research meeting used to learn what others observed and how to collect data • Novelty emphasized • Verbal communication contained more detail than written

The students also began to develop more sophisticated ideas about the physical environment at the creek and delineated different types of substrate (e.g., mossy, rocks) that could be found in different areas. Some of the students, in particular Larry, also began to connect the characteristics of the substrate to the location of specific organisms such as the crawdads. However, although the team had gathered data on the water depth, they did not integrate this into their understanding of the creek. Three factors might have contributed to the teams' disregard of water depth. First, only Mychel was involved in measuring and recording the depth. Second, the way in which Mychel measured the depth obscured rather than highlighted variation. And third, water depth, though at times reported in other team presentations, was rarely interrogated during the question and answer portions of the research meeting.

The students also began to wonder about the relative incidence of these organisms both in the creek as a whole and in different partitions of the creek. However, although all of the students attended to patterns of similarity and difference across the research meeting presentations, they had different interpretations of what they had heard. Christine attended to the number of groups that had caught crayfish and thus perceived similarities across each area. Dennis likewise saw similarities in the type of animals in each area, but noted differences in incidence across each area. As he explained, "There was almost the same animals, but there's more in different sections and less in different sections." Larry and Mychel saw the creek as having distinct habitats and suggested that different types animals could be found in different places in the creek. As Larry said, "I think every one of the groups throughout the creek caught something so I think throughout the creek there was animals in each part. So there many be different kinds of animals in different parts just because that's their habitat." Thus after only a brief exposure to ecological research, the students had already highlighted two important ecological ideas: species richness (the number of different types of organisms in an area) and species incidence (the frequency with which an organism appears in an area). However, they disagreed about the patterns of richness and incidence across the creek. This suggested that future investigations focused on these patterns would not only tap into students' current forms of reasoning but could also potentially be motivated by contest within the classroom community about what students might find.

The living organisms at the creek also permeated how students engaged in scientific practice. During the initial discussion and planning for the first creek visit, the questions that the students asked primarily focused on the incidence of specific organisms in undefined areas of the creek. These initial questions often centered on animals such as frogs and slugs that were absent or rare at creek. In addition, although the students asked questions about which area had the most and the least of an organism, they had no initial way to delineate one area from the next. Over the course of the investigation, personal, team, and class experiences at the creek informed the evolution of the students' questions so that by the end of this first cycle all of the members of the focus group wanted to extend what they had begun to observe about the crawdads. Dennis and Mychel wanted to solve the team's mystery of what was eating the large crayfish. In addition, Mychel, Christine, and Larry wanted to find out more about how the crayfish were distributed within the creek and predicted that this might be related to the general habitat (Christine), substrate (Mychel), or water speed (Larry). These questions both delved more deeply into the elements of the creek of current interest to this team and reached out tie in novel phenomena that they had not yet explored.

In planning and carrying out their investigation, the team did not detail in their plans how they intended to collect their data. Consequently, it was not surprising that once at the creek, the students' activity seemed to driven by what was readily observable rather than the questions that they had developed the day before. This was linked to the way in which the students structured their observations. They worked to first visually identify an organism in the water and then catch that organism in their net. Throughout the creek visit some students seemed to develop increased facility with the various equipment as well as a sense for where an organism, such as a crawdad, would likely be found. The teams' written data records were limited to a list of organisms and their two depth measurements and did not capture either the breadth or the nuance of what the students would later share during the research meeting.

Because of the limitations of their written observations, students did not have a wealth of data to examine at the end of their visit to the creek. Instead, they frequently used stories to develop explanations of anecdotal qualitative data, as when Larry explained why he thought fish were eating the large crawdads. As described earlier, students also began to attend to patterns within personal, team, and class experiences. These patterns at times became the basis for the questions students wanted to investigate during their next creek visit.

Sharing information within and across teams emerged as both a spontaneous and a structured practice in this cycle. At the creek, the capture of new organisms triggered moments of collective observation in which students flocked around nets or tubs to see what had been caught. Students would also spontaneously eavesdrop on other teams or shout out their findings to others nearby. The research meeting format created a structure by which students could learn by experiencing the creek vicariously through others (as in the case of Dennis) and making comparisons across a range of experiences. Students quizzed each other about how they had conducted their observations, the details of what they had seen, and their explanations of these observations. Novel observations seemed to be particularly valued and emphasized in these presentations. In addition, students were consistently able to convey their knowledge and practice in more detail through verbal communication (both in class and during interviews) than they could through written communication (both on class worksheets and the pre-test).

Cycle 2: Seeing the Water

> I learned how to do to check phosphate which was pretty cool. Um, I did not know that phosphate was connected to fertilizer and all the stuff that my group taught me about nitrates and dissolved oxygen and pH scale and all that. I really learned a lot from that.
>
> - Larry, Cycle 2 Retrospective Interview

Instructional design of Cycle 2. During this cycle of investigation, the students explored two classroom-based sequences of activity that were designed to reveal formerly invisible components and relationships of aquatic ecosystems. Though these sequences of activity explored different systems than our local creek, each was positioned as being able to offer insight into our investigation of the creek. In the first sequence, the students investigated the water chemistry in aquatic microcosm jars. This activity was designed to expand students' understanding of the abiotic resources in aquatic ecosystems, how to measure for these resources, and the influence these resources have on the living organisms in the system. The design was also structured to support students in uncovering ecological relationships by comparing data from different sources, such as across a set of microcosms, and looking for patterns in the data. In the second sequence of activity, the students examined potential sources of variation in measures of ecological phenomena by measuring the shell thickness of a variety of snails from the same population. This activity was designed to shift students' perspective of differences in their data and help them differentiate differences due to measurement or natural forms of variability from those that suggest shifts in the ecosystem.

On day five, which was the first day of this cycle, we began our microcosm investigation by splitting the class in a jigsaw format so that each member of a creek team learned how to conduct a different water chemistry test. One member from each team was assigned to the pH/hardness group, nitrates group, dissolved oxygen group, and phosphate group. I chose to use a jigsaw design because it would later position every student as an expert within their team. In addition, I chose to focus on these five variables because they were likely to be influential in our local creek. However, unlike water speed, students were not going to be able to develop a way to measure these variables on their own. Most were even unaware that these variables existed in aquatic systems since they could not be directly sensed. Consequently, students needed to be taught how to conduct these tests. However, I did not want the measures to be black-boxed for students. Rather, I wanted them to have a general feeling for how the measure worked. So I designed a process in which each group would compare the measurement of their variable before and after they performed a specific action on water. By having students use the measure to capture the impact of their actions, I conjectured that students would develop an understanding of the invisible processes these measures were detecting.

Each water chemistry group began by reading about what they were measuring and how to conduct their test. All of the tests relied on either a paper strip or a vial of solution that used color as an indicator. The group then tested a sample of tap water to provide a base-line reading of their variable. Next, they performed an action on the water to change the level of that variable. The dissolved oxygen group aerated the water by stirring, the hardness/pH group added limestone, the nitrate group stirred in a vial of "animal excretion", and the phosphate group added fertilizer. Each group then re-tested the water and explained how their action had impacted the value of what they were learning to measure. Once they had learned how to conduct their water chemistry test, the group read a half-page description of the role of that variable in aquatic ecosystems and used this reading to answer questions about what could cause changes to this variable and the role it might play in our local creek.

On the sixth day, the students went back to their creek teams and applied what they had learned about water chemistry to the four different types of aquatic microcosms described earlier. I conjectured that the design of this activity would support students in developing explanations of key relationships between the visible components of their jar and the water chemistry measures. These microcosms held a dual status in this design. They were self-contained mini-ecosystems in their own right. However, they also stood as a model of processes in other aquatic systems, such as our local creek. Each team selected one of the four types of microcosm to investigate. Once given their specific microcosm jar, the students were instructed to first make general observations about what they noticed about the contents. After this, each team measured the temperature, pH, hardness, nitrates, phosphates, and dissolved oxygen levels in their microcosm. During these measurements, the team followed the lead of whichever member had become the local expert in that variable the previous day. The design was for students to coordinate what they observed about the visible components of their jar with the measured values of abiotic resources. At the end of class, the team filled out a worksheet that led them to consider how they thought the different parts of the microcosm worked together, if it was a good model of the creek, and whether the ecosystem in their microcosm was sustainable. I had conjectured that students might use what they had learned about the water chemistry measures the previous day to identify any particularly low or high value of these measures in their microcosm and use this to project out what might happen to the system.

On the seventh day we wrapped up our investigation of the microcosm jars with a whole class discussion oriented around the question, "What's in the water?" The goal of this discussion was to uncover relationships between the components of each jar and their water chemistry measurements. Prior to class I had arranged all of the water chemistry measurements for each team's microcosm jar into a single table and posted this on the board (Fig. 4). After orienting students to the structure of the table, the students broke into their teams to discuss two things: something interesting about their team's jar that they wanted to share with the class and what pattern that they saw in the data from all of the team's jars. After they had a few minutes to discuss these questions, each team shared what they had noticed about their jar. We then looked together variable by variable across the chart for any trends or anomalies across all of the jars. To wrap up our discussion, I passed out a card to each team with one component of the microcosms listed on it: dead leaves, oxygen, minnows, plant/algae, nitrates, phosphate, fertilizer, and snails. We began with the plant/algae card and built a class concept map that highlighted relationships between different components of the microcosms (Fig.5). I conjectured that the activities of this day would further uncover ways in which the organisms in the microcosms influenced the water chemistry measurements and vice versa.

Figure 4. Class table of the water chemistry measurements for each team’s microcosm jar

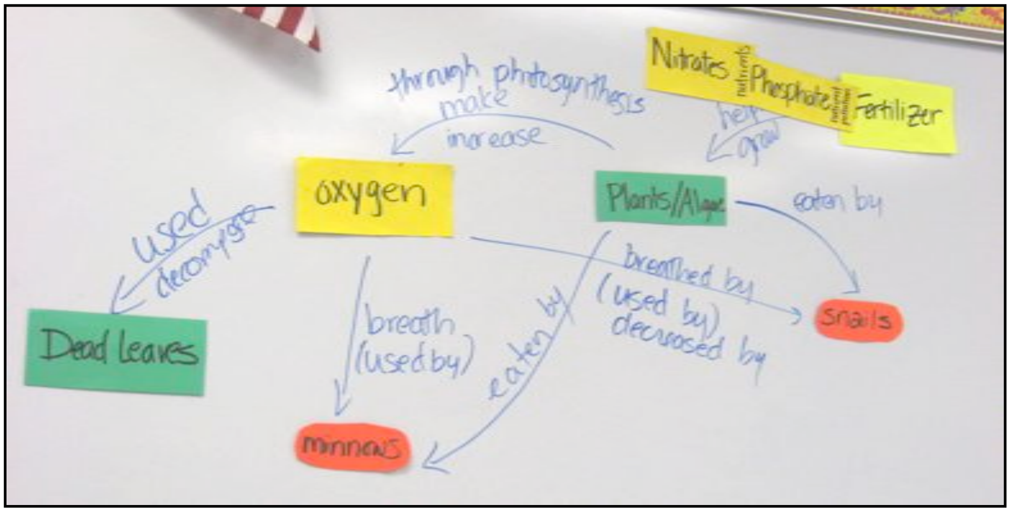


Figure 5. Class concept map of how the microcosm jars function as an ecosystem

The design of the second half of the week focused on supporting students in developing a sense of the scope to which variation in a measure could be due to differences in measurement process or natural forms of variability (such as within species differences in crawdad size) and not due to direct ecological causes. Though ecologists typically treat sources of uncertainty such as measurement error or natural variation as resulting from random process acting on an underlying probability distribution (Regan, Colyvan, & Burgman, 2002), the students in this class treated these sources more simply as being causal processes with either unpredictable or undeterminable impacts on a measure. I chose to ground this discussion in students' measurements of the shell size of a sample of snails taken from the same population because aquatic snails are readily available and a large population can be housed in a small aquarium. In addition, their shell size exhibits a strong degree of natural variation and the process of measuring its thickness would likely produce an array of variation due to measurement error. On the eighth day, each team selected nineteen snails from our aquarium of approximately four-dozen ramshorn snails and measured the width of each snail using a caliper. Each team also measured a special twentieth snail, which I had set apart to be measured by all seven teams.

After they had measured twenty snails, each team created a display of their data and calculated what they thought was the typical shell thickness for a snail from our colony.

On the ninth day, I transferred each team's display to a comparable format that could be posted for the whole class to see. These seven displays would ground our discussion of variability due to measurement error and natural variation. I wanted students to first gain familiarity with the other teams' data by exploring the typical snail shell thickness for each team and how spread out each team's measurements were. We then discussed why, when each team measured twenty snails from the same population, the teams all had different results. I chose to highlight variation due to measurement error first as this could be isolated in the design from all other sources of variation by focusing on the one snail that all teams had measured. I revealed each team's measurement of this snail and asked why these values were different. I conjectured that students would be able to explain multiple ways the process of measurement could have contributed to differences in this snail's shell thickness. After we had explored measurement error as a source of variation, I wanted to pull out the other source of variation in students' measurements: natural variation. I asked students if all of the differences in our measurements of snail shell thickness were due to differences in measurement. I conjectured that the students' qualitative observations of different snails throughout this activity would have given them a sense of natural variation in snail size. Lastly, I highlighted how our measurements of snail shell thickness were a negative case of causal variation. Since the snails all came from the same ecosystem, the differences between the teams could not be explained by differences in shelter, food, or any other direct ecological cause. I conjectured that after completing this sequence of activity students would be able to recruit all three sources of variation (measurement error, natural variation, and direct ecological causes) when predicting and making sense of differences in measurements.

Students' trajectory within Cycle 2. On day five the creek teams split up in a jigsaw format to learn how to conduct different water chemistry tests. In the focus group, Christine learned about pH and hardness, Dennis learned about dissolved oxygen, Larry learned about phosphate levels, and Mychel learned about nitrates. This jigsaw structure positioned each student as the team expert in one abiotic aspect of the creek. In introducing the tests, I led a short discussion with the whole class where I asked students what we might find if we closely examined a sample of the water from creek. Larry said that we would find water, and I agreed with him. I then asked if the only thing in the sample would be H_2O, and the whole class disagreed. However, the students struggled to detail what we might find. They suggested dirt/rocks, small plants, germs/microbes, and trash. I connected these ideas to the categories of microorganisms and dissolved solids and then used soda as an illustration to spark students' thinking about dissolved gases as well. Finally I introduced the names of the various water chemistry tests and set each group free to explore their assigned test. Most of the students' discourse during this class period focused on accurately completing the steps of the testing procedure, and all of the groups successfully connected their changes in measure to their actions on the water. However, only the nitrate group was able to fully complete the back section of the worksheet in which they read a half-page description of the role of that variable in aquatic ecosystems and used this reading to answer questions about what would cause changes to this variable and the role it would play in our local creek.

On the sixth day, the students were back in their creek teams to apply what they had learned about water chemistry to the aquatic microcosm jars. At the urging of Larry and

Christine, the focus group chose to study a "D" jar because it was the only type of microcosm that had fertilizer. Once given their jar, the team quickly noted that there were two snails, many plants and algae, and some settled fertilizer in the microcosm. They then spent a number of minutes debating whether or not the snails were alive. At one point Larry shared that he was going to write, "The fertilizer helped the plants to grow". However, Mychel critiqued this, saying, "But that's not a general observation. That's not something you can just tell." Consequently, no one included Larry's statement as an observation on their worksheet. However, the team later chose to include it as part of what their explanation of what would happen to the jar if they left it for another two weeks and wrote, "We predict the plants could grow until fertilizer runs out."

After completing these general observations, the team measured the temperature, pH, hardness, nitrates, phosphates, and dissolved oxygen levels in their microcosm. For each variable the student who had learned the test the previous day took the lead and handled all the materials. Each time the other members of the team actively positioned this student as the expert for that variable. For example, when Mychel handed the oxygen kit to Dennis and said, "Here you go oxygen man," this represented one of the few times across the entire study in which she ratified his contribution to the team. The expert typically narrated their actions as they conducted the test while the other team members watched and at times commented on the similarities or difference to their own tests. At the end, when it was time to interpret the color of the result, multiple members of the team often gathered around the expert and offered their own ideas of what the level was. It is likely that these other students asserted themselves more during this step because it did not require any specialized knowledge of the procedure but rather utilized a skill that they themselves had built within the context of their own test. Learning how to conduct these tests of water chemistry was very impactful for students as all of them brought up the experience during their retrospective interview for this cycle. Christine commented that that most important thing this week was that she "found out how to do hardness and pH…Because I'd never done that before." And Larry mentioned, "All the stuff that my group taught me about nitrates and dissolved oxygen and pH scale and all that. I really learned a lot from that."

However, although the team had gained expertise in conducting these tests, they struggled to interpret the test results and integrate them into an explanation of how the ecosystems in their microcosm jars functioned. After finishing the tests, the team turned to complete the questions posed on their worksheet. When trying to decide whether the ecosystem in their microcosm was sustainable, they could not connect their water chemistry measurements to their reasoning about the components of the jar. They seemed to have no reference point for the measures, although details of these could be found in the reading from day before. The team finally decided that the microcosm would be sustainable because, as Larry said, there was "still a lot of plants and algae". They also agreed that the microcosm was a good model of the creek because it had plant life, living creatures, and rocks, but that it did not do a job of modeling the fertilizer in the creek. When I asked students in their retrospective interviews to critique how the microcosm modeled the creek, each of them once again favorably compared the living components in the jar to those in the creek and were critical of the fertilizer because it was unnatural. As Christine said, "Yeah *(the jar is a good model for the creek).* 'Cause maybe the creek had the plants and algae. But we had fertilizer and it didn't look like creek fertilizer. 'Cause it looked like the one that you buy in stores for fish." To explain how the ecosystem in their microcosm jar functioned, the students each drew a web on their worksheet. All of these webs included the jar at the center with spokes leading to the four components of their microcosm:

rocks, snails, plant/algae, and fertilizer. Larry, Christine, and Mychel also drew connections between these components and wrote that the plant and algae are food for snail, the rocks give snails a floor, and the fertilizer helped the plants grow. However, none of the webs included any other specific terminology from our water chemistry tests.

On the seventh day we wrapped up our investigation of the microcosm jars by discussing "What's in the water?" After orienting students to the table that I had made of all of the water chemistry measurements for each microcosms, the teams to discussed what they wanted to share about their team's jar and what patterns they could see in the data from all of the team's jars. During this time the focus group began by debating (again) whether or not their snails were dead. After a few minutes, we gathered as a class to share what we had noticed about the different jars, beginning with the "A" jars. Only one team had selected an "A" jar, and they shared that they had noticed that their fish were moving around in circles as if they were trying to get more oxygen. We looked at the dissolved oxygen value that they had recorded for their jar, and it was indeed low. I asked the class why this jar likely had such a low oxygen reading. Students suggested that this was because there were no plants in the microcosm that could make oxygen as well as fish and snails that were using oxygen. I then asked what they thought was going on with the dead leaves. One student recalled reading that "whenever the dead leaves decompose, they're using oxygen." I then explained how bacteria were responsible for a lot of decomposition and how they often use up lots of oxygen in the process. After this, the three teams with the "C" jars shared that one of the microcosms was really bright and clear, one had a dead fish with stuff growing on its, and one had snails crawling over each other and seeming to mate.

Next the teams with the "D" jars shared their observations. Larry shared for the focus group that their microcom had a lot of fertilizer at the bottom, one dead snail (which did not move), and one living snail (which had poked his head out of its shell). The other two "D" groups shared that another microcosm also had a dead snail and the other was "glowing green" with lots of plants. I tied this observation of the color of the water to students' experiences seeing a lake that looked all green and asked them why they thought this particular jar had turned green. One student mentioned phosphate, and we noted that the "D" jars did tend to have a higher level of phosphate. When no one had other ideas, I asked the students to talk more about this in their teams. Larry, who was the phosphate expert in the focus group, shared with the team that phosphate is a fertilizer, and Dennis said he thought the green was algae. Larry then connected the two ideas and stated that "the fertilizer makes the algae grow more. The fertilizer and the phosphate kinda made the algae spread." When I restarted the whole class discussion, Larry and Dennis shared their reasoning with the whole class. Larry explained, "Since the fertilizer and the phosphates is helping the plants grow maybe the plants are spreading around and making the tank or the jar green," and Dennis added, " Basically we're saying it's the algae." I connected these ideas to a story of an algal bloom and explained how excess fertilizer can help algae grow so fast that the algae eventually die and start to be decomposed by bacteria in the water which in turn use up all the oxygen. I asked students what other elements in the ecosystem this cycle might this influence. Dennis suggested that animals like a turtle would eat the algae. Another student suggested that turtle would then die when the algae dies because it wouldn't have anything to eat. Finally, a third student shared that all types of animals would die because less oxygen might kill even those animals that don't use the algae for food.

We then looked variable by variable across the chart for any trends across all of the jars. Of the trends we noted, the high levels of hardness, phosphates, and nitrates in the "D" jars intrigued students the most. Dennis suggested that this was maybe due to the fertilizer, which was only in the “D” jars. We compared the “C” and “D” jars and noted that the only differences in the setup were that there were no fish in the “D” jars and no fertilizer in the “C” jars. Mychel shared, “I think it’s because of the fertilizer because that changed the chemicals. Fish might affect nitrates because of the poop, the waste, excretion.” Here she explained how she thought that the fertilizer, and not the fish, was the primary driver of the higher water chemistry levels because it affected more of the measures and not just the nitrates.

To close our discussion, I passed out a card to each team with one facet of the microcosm jars listed on it (dead leaves, oxygen, minnows, plant/algae, nitrates, phosphate, fertilizer, and snails), and we built a class concept map connecting the cards together. Mychel spoke for the focus group and added “fertilizer helps the algae grow” to the map. Though we were able to place all of the pieces on the board, we ran out of class time to exhaust all of the potential connections within the system, particularly regarding the nitrogen cycle.

In their retrospective interviews for this cycle, I asked the focus students to explain how the different parts of the microcosm jars interacted with each other. All of the focus students described how the fertilizer helped the plants grow, how the plants give off oxygen for the animals, and how the animals could be eating the plants. For example, Christine explained, “The plants and algae, they give the fish like oxygen…. The fish feed on the algae…it has fertilizer and would help (the plants) grow.” Dennis also explained how sunlight and fertilizer specifically from animal dung could support plant growth, while Christine specified how dead leaves don’t give off oxygen. Only Larry described the role of bacteria in decomposing dead material, although he did not tie this into the oxygen cycle. And only Mychel connected increased nitrates to fertilizer and animal waste. (This had also been the test that Mychel had trained as an expert in on the first day of this cycle.) However, none of the students mentioned hardness, pH, or phosphates.

The second half of the week focused on supporting students in thinking about the multiple sources that contribute to variation in a measure. This discussion was rooted in the students' measurements of the shell thickness of snails taken from the same population. On day eight, each team used a caliper to measure the shell thickness of nineteen snails they personally selected from our aquarium. Each team also measured a special twentieth snail, which I had selected and which was the same for all seven teams. Figure 6 shows the display the focus team constructed of their twenty measurements. The team used the shape of the display to determine that their typical shell thickness was between six and seven millimeters.

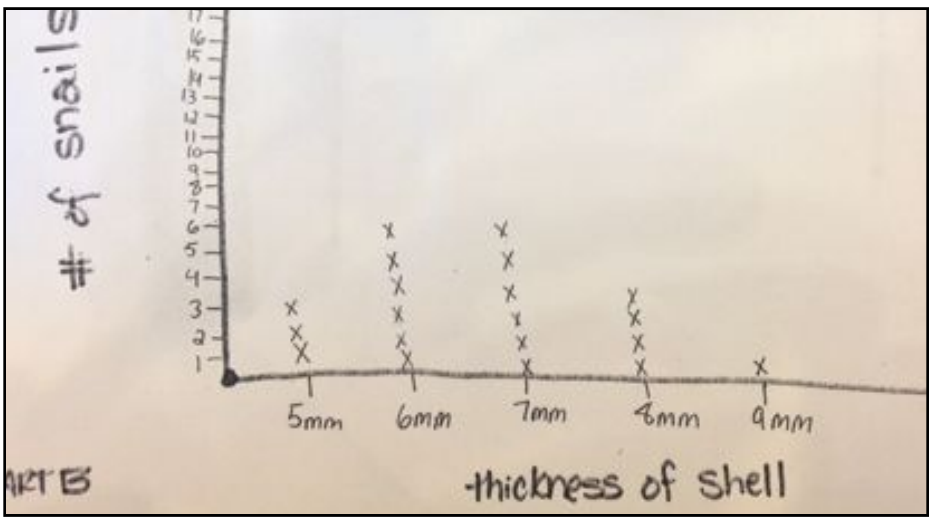


Figure 6. Team display of snail shell thickness data

On day nine, I transferred each team's display to a comparable format and posted these at front of the room. The variability between the displays surprised most students. As Christine recalled in her retrospective interview, "When we did the bar graphs. I saw that many peoples' bar graphs were really high and low. And well, it shocked me because ours was totally different." We discussed how we might determine the typical snail shell thickness for each team and, at a student's suggestion, calculated the median of each sample. We also compared how spread out each team's measurements were and, at another student's suggestion, calculated the range of each sample. Though the students had studied measures of center and spread previously in math class, many struggled to explain how we might determine the typical value and the spread of values for each team.

We wrapped up this cycle by talking about why, when each team measured twenty snails from the same population, the teams all had different results (Excerpt 5). I began this discussion by recalling how there had been one snail that every team had measured and revealing each team's measurement of that snail (line 1). I then asked why these measurements of the same snail were different (line 3). The students quickly attributed this difference to something being wrong with our measurements (line 4). Larry suggested that we might have used the measurement tool in different ways and pointed out the caliper had two different arrows that pointed to slightly different numbers (lines 6 and 8). Another student suggested that some teams might have measured the snail along a different axis than the other teams (line 10). Since this established that the ways in which we measure have the potential to produce variation in our data, I asked the students to brainstorm what we could do at the creek to help us make sure that we were measuring in similar ways. The teams came up with three suggestions that all prioritized communication and consistency: measuring with other groups, writing what we did down and asking what other groups did, and re-measuring the same way the other group did if you at first measured different.

Excerpt 5 – Exploring variation in snail shell thickness

1 Researcher: So the last thing I want to talk about is why these values are different. And I just want to point out one thing for you. You remember how we all measured the same snail?...This group got an 8 for the snail *(Points to the value on that team's display)*. This group got a 10 for the snail *(Points to the value on that team's display)*. This group got a 5 *(Points to the value on that team's*

display). This group got a 6 *(Points to the value on that team's display)*. This group got an 11 *(Points to the value on that team's display)*. This group got a 7 *(Points to the value on that team's display)*. And this group got a 7 *(Points to the value on that team's display)*. You all measured the same snail. *(Gestures across the whole class.)* Did you get the same value though?

2 Students: No. *(Shaking heads no).*

3 Researcher: So what happened? *(Larry raises his hand).*

4 Student 1: Maybe somebody wasn't measuring correct. *(Other students muttering about who might have done something wrong).*

5 Researcher: Okay, so when we measure, would you agree that sometimes there's some slight errors in our measurements?

6 Larry: Well there were two little lines right there, and a lot of them when you would measure, one of them was before 10 and one was after 10.

7 Researcher: Okay, so maybe some of us did slightly different things in the way we were measuring.

8 Larry: Maybe one of them measured one time with the arrow after 10 and got 11 and maybe the other times they measured before 10.

9 Researcher: Okay, can you give me some other ideas that you have about why you guys measured all the same snail and you might have gotten different measurements? It didn't grow that much in fifteen minutes did it?

10 Student 2: No, some might have measured this way *(Gestures widthwise on his paper.)* like some might have measured how long it was. (*Gestures lengthwise on his paper.)*

11 Researcher: Ah, so some might have measured a different way on the snail. So we might have used the tool differently and we might have measured different parts of the snail.

12 Larry: Like if you measured that way *(gestures lengthwise)*, you might have gotten 11.

13 Researcher: Okay, so I want you to think about this. When we measure the creek when we are using our tools and thinking about how we are taking our measurements, how can we be sure that we are measuring in similar ways?...What's something that we can do? Talk in your groups. *(Team discussions lead to three suggestions: measuring with other groups, writing what we did down and asking what other groups did, and re-measuring the same way the other group did).*

14 Researcher: Okay, I want you to remember this issue of measurement because that's something we're going to work on the next time I come to the creek…Besides that, what are some other reasons why you got different values?...I see some things up here at 15 and 16 and other things down here at 2. Is all of that measurement error? Where else is that variation coming from?

15 Student 2: It's not like all the snails are the same size.

16 Researcher: You mean not all the snails are the same thickness?

17 Student 2: *(Laughs)* No. *(Makes a mock surprised face).*

18 Researcher: So there are some small ones and some big ones? *(Student murmer yes)*. Did all of you measure the exact same snails? *(Students shout no)* Some of what you measured were the same but were all twenty the same? *(Students shake*

head no). So each of your groups took a different sample...And are all the samples exactly the same? *(Some students shake head no).* Even if we got the measurements perfect, which we could never do, would all samples be the same? *(Students shout no)* So they would all be slightly different…So were all these snails living in the same place?

19 Students: No! Yes! No! *(Conflicting responses shouted out).*

20 Mychel: They were in a colony! *(Points to the colony in the back)*

21 Researcher: They were in the same place. Had they been getting the same oxygen levels? *(Students shout yes).* Had they been getting the same phosphate levels? *(Students shout yes).* Are the differences that we see, a 16, a 6, and a 9 *(points to values on the display).* All of these, are these due to differences going on in the ecology? No. It's just that sometimes there's just natural variation.

Now that variation due to differences in measurement seemed to be firmly on the table, I shifted the conversation to talk about whether all the variation we were seeing in the snail shell thickness was due to measurement error (line 14). One of the students laughed at this suggestion and commented that not all snails are the same size (line 15). I explained that since none of the teams measured the same twenty snails and since the snails naturally were different sizes, the teams were likely going to get different measurements even if we all measured perfectly (line 18). Finally, I asked students whether the snails had been living in the same place and receiving similar inputs of oxygen and other abiotic factors (lines 18 and 21). After a brief disagreement about whether the snails had been living in the same place that Mychel helped settle by pointing to the snail colony that was still in the back of the classroom (lines 19- 20), the students agreed that all of the snails had received similar inputs (line 21). As the ending bell for the class was about to ring, I wrapped up our discussion by explaining how this meant that the differences we were seeing between the snails could not be due to differences in the ecosystem but rather had to be due to other sources of variation.

During the retrospective interview that followed this discussion, I probed what each focus student had learned about variation by presenting them with four different scenarios. In each scenario I asked the students to explain whether they thought the measurements produced would be similar or different. I asked first about what would happen if all four members of their team measured the length of the same crayfish. I then asked what would happen if the team worked together and measured the length of twenty crayfish from one area of the creek. The third scenario asked students to compare what would happen if they measured the length of another twenty crayfish from the same area. And finally the fourth scenario asked students to compare the measurements from the first area with the length of twenty crayfish from a different area of the creek. The students expected the length measurements to vary in each scenario. However, they consistently attributed the variation in different scenarios to different sources.

In the first scenario, the students expected the repeated measurements of the same crayfish to vary due to differences or errors in the way each of them measured crayfish length. In the second scenario, they expected the twenty crayfish from one area in the creek to vary because a there would be crayfish of all ages (and thus all sizes) in the area. They used the same age-based reasoning in scenario three to describe why one sample of twenty crayfish from one area would have different lengths than another sample of twenty crayfish from the same area. Dennis talked about this variability when he explained for scenario two, “Some could be big, some could be little…Because that’s how they grow up” and for scenario three “They might still be different altogether. Cause you might have caught a lot of little ones or big ones in the other and same thing with the other.” Here, Dennis described naturally occurring between-crayfish variability as being causal (“that’s how they grow up”). However, as this cause had unpredictable impacts on the length of any one particular crayfish taken from the creek (“some could be big, some could be small”), there is a semblance of chance underlying the lengths that he expected to find in any one sample of twenty crayfish. Finally, in scenario four the students attributed differences in crayfish length between two different areas of the creek to causal differences between those locations. For example, one area might have a better habitat for crayfish with more food sources and thus support better crayfish growth.

Although the students reasoned about multiple potential sources of variation in measurements of crayfish length, they seemed to treat these sources as acting in isolation from each other as they described only one source of variation in each scenario. Though this was appropriate for the first scenario, the rest of the scenarios presented cases in which multiple sources of variation would interact to produce differences in length. For example, both measurement error and natural variation would contribute to the variation in length in the sample of twenty crayfish from the same area. It may be that students responded in this interview with what they thought was the most salient source of variation, and a different form of questioning might trigger students to consider multiple sources of variation. Alternatively, this might be indicative of an underlying difficulty the students were having with understanding the sources of natural variation, as Lehrer and Schauble (2004) found in their work with students.

During the retrospective interviews I also asked each student to describe what they wanted to investigate next about the creek. The students were interested in many of the same types of questions as they were after the first cycle, although the large dead crawdads that had been so intriguing during first cycle had fallen out of favor. Instead, all of the students described wanting to explore the incidence of one or more types of animals in different sections of the creek. For example, Larry explained, “We stayed in one spot last time. I really want to. Like one group was at the end and they were catching a lot of crawdads, and they caught a minnow in the weeds a little. I’d like to try different places and see what the population of crawdads and other animals are in that area.” However, while Dennis and Larry still focused on the distribution of crawdads, Christine and Mychel were now intrigued by whether they could find snails in the creek. As Christine described, “I would probably want to figure out if there’s any snails. And if we do find snails to see if their thickness is the same as we did here.” From a design perspective I had specifically chosen to use snails in the microcosm jars and the exploration of shell thickness because of their ability to influence microcosm dynamics and to illustrate patterns of variation even though they were not a significant factor in the ecosystem of our local creek. However, the snails seemed to strongly attract students’ interest and influence their goals for the next creek visit. On the other hand, none of these students expressed a current interest in exploring any of the new abiotic measures at the creek, although they had identified learning about these measures as something that had been important to them this past week. Finally, Mychel was also interested in exploring the water speed at the creek since they had not yet explored this variable, which echoed Larry’s wish from the first interview.

Summary of students’ development of knowledge and practice in Cycle 2. The second cycle of investigation was characterized by shifts in how students viewed the water within aquatic ecosystems. While working with the microcosm jars, the students discovered new variables, new ways of measurements, and new ecological relationships. This expanded their view of the elements that play a role in aquatic ecosystems, particularly within the abiotic dimension, as well as the range of potential interactions among these elements. When exploring the snail shell thickness, the extent to which the measure varied when there were no ecological differences surprised the students and provided a context for them to begin to rethink how to interpret differences in their findings. Because of this, I anticipated that in future investigations these students would not treat every measured difference as attributable to a specific known cause.

In this cycle, students' drew upon different forms of ecological knowledge than during the first creek investigation (Table 4). Students' ecological explanations frequently referenced elements of the food chain and the general oxygen cycle, concepts that were already familiar to many students and were further reinforced by their observations. As far as the new components introduced this week, only the role of "fertilizer" seemed to have gained salience across the students' explanations of aquatic ecosystems, although this was likely also already familiar to some students. Neither the relationship between decomposition and the oxygen cycle, which had featured prominently in our class discussions, nor the specific role of phosphate, which Larry and Dennis had elucidated during our discussion of algal blooms, were included in any of the students' explanations.

Table 4.
Summary of students' knowledge and practice during Cycle 2

	Understanding of the Organisms	Understanding of the Physical Environment	Understanding of Water Chemistry
Knowledge	• Typical snail behavior • Plants/algae produce oxygen and food for snails and fish • (Some) Bacteria decomposes dead material • Organisms exhibit natural variation	• (Some) Rocks provide a home/footing for snails	• Fertilizer supports growth of plants and algae • (Some) Nitrates and animal waste are fertilizer

	Asking Questions	Planning and Carrying Out Investigations	Analyzing Data and Constructing Explanations	Communicating Information
Practice	• Continued focus on the incidence of animals in different areas of the creek • Added focus on snails • No integration of water chemistry	• The existence and how to measure pH, hardness, phosphates, nitrates, and dissolved oxygen • Expectation that measurements will vary	• Relationships can be uncovered by comparing data from different jars/locations • Observed differences can be due to measurement error and natural variation and not just direct ecological causes	• New measures and ideas about ecological relationships can be learned from what others experienced

A number of factors might have contributed to the particular idea of "fertilizer" taking root in this group, rather than an explanation of say decomposition. First, two of the more vocal members of the group, Mychel and Larry, both specialized in measures related to fertilizer: nitrates and phosphates. Second, the team selected a microcosm jar whose novel element was the addition of fertilizer. And third, fertilizer was often referenced in our whole class discussion and thus reinforced in the students' experiences. Thus this facet was repeatedly emphasized in the experiences of this team over the first three days of this cycle. However, unlike I had conjectured, none of the other relationships involving water chemistry that were emphasized at the class level, became established in the students' explanations. Furthermore, although the students spent much of the week observing and debating the behavior of the snails in their microcosm, they did not fully integrate what they noticed about animal behavior. Holistically, the students' ecological knowledge at the end of this cycle synthesized ideas from a variety of sources and experiences: their prior knowledge (e.g., Christine's plants providing food), prior experiences (e.g., Dennis's animal dung), work with their team's microcosm (e.g., fertilizer), comparison of other teams' jars (e.g., Larry's decomposition), and expertise in new measures (e.g., Mychel's nitrates).

Though the students consistently reflected in their interviews how excited they were to learn how to measure the variables introduced to them this cycle, the students did not integrate any of these variables into the questions they were asking about the creek. Rather, they maintained their interest in exploring which area of the creek had larger populations of different animals. While many in the team still wanted to focus on crayfish, Christine and Mychel were also swayed by the novelty of this week's focus on snails. Students also seemed to develop an expectation that their measurements will vary when conducting investigations and a recognition that these differences might due to measurement error and natural variation and not be indicative of a direct ecological cause. In addition, the role of communication in scientific endeavor was further emphasized as students continued to learn new measures and ideas about ecological relationships from the experiences of others and not from direct experience. Some also developed skill in uncovering ecological relationships by comparing data from different sources, such as a set of microcosms, and looking for patterns in the data, as when Mychel connected the pattern of nitrate and phosphate levels across the microcosms to differences in the components of the different jar designs.

Cycle 3: Seeing connections across space

> There's deep parts, and then there's shallow parts. And the shallow parts there were more grass, and in the deep parts there were more animals to us because we found crawdads and fish and a worm. And then in the deep part also there wasn't as much grass as in the shallow parts.
>
> - Christine, Cycle 3 Retrospective Interview

Instructional design of Cycle 3. As we took our second visit to creek during this third cycle, the design closely mirrored that of our first cycle of investigation. However, I adjusted the design slightly in ways that I conjectured would support students in highlighting relationships within the creek and in drawing comparisons across different areas. The cycle also created opportunities for students to investigate, if they so chose, any of the new water chemistry measures at the creek and to continue to refine their methods of observation and data collection.

We opened this cycle of investigation on the tenth day with a brief class discussion about what we could do to improve how we collect data at the creek. The students then split into their creek teams and began planning for our second visit to the creek. Whereas the planning worksheet for the first cycle prompted students to attend to what lives at the creek and what the water was like, the prompts for this cycle were intentionally more open. Students were first asked, “What does your team want to find out about how the parts of the creek work together?” and then “How do plan to gather observations at the creek to help answer this question?” As had been seen in the retrospective interviews at the end of the previous cycle, many students were on their own beginning to pose questions about the relationships between different elements at the creek. My design and framing of this cycle explicitly validated this shift in students’ practice and positioned it at the center of our creek investigation. This transition in the practice of questioning from cycle 1 to cycle 3 allowed teams to attend to more elements within the creek, but it also explicitly emphasized the search for relationships or patterns between these elements.

On the eleventh day we headed out to the creek for our second visit. The design of this day paralleled our first visit to the creek. Once again I laid out the equipment each team would need to enact their data collection plans. For this visit, each team could decide for themselves where to conduct their investigations, and many teams chose to work in different areas than before. When the bus arrived at the creek, I gave the students a brief safety reminder and then directed each team to their equipment. The students were given defined space to write what they noticed in the same worksheet packet in which they had developed their questions and plans, but as before the structure of these observations was open-ended. Overall, I conjectured that this second creek visit would highlight more relationships between features at the creek and foster comparisons across different areas.

On day twelve, the teams broke off to begin planning their research meeting presentations. Once again each team had a planning guide that outlined key questions they needed to address (Fig. 7). This guide allowed more flexibility in the presentation than in the first cycle. At the end of the day we began the presentation portion of our research meeting. These presentations followed the same structure as the first research meeting, a team would come to the front of the class and share while the rest of the class would write down a question, a suggestion, or something that surprised them on their listening notes. During the presentations the teams would often post a summary of their findings on a class map of the creek over the location they had investigated. As the map became populated with the result of multiple teams, this served to highlight spatial comparisons across the creek. After presenting, the team would then field a handful of questions and comments from the audience. We continued our research meeting presentations on the thirteenth day. During this cycle, the students tended to be more fluid in their presentations, speak longer, and participate more freely around each other's work. As a result, I frequently had to cut off the discussion at the end of the presentations in order to have time for all teams to present. During the transition between teams, I explicitly highlighted comparisons across the findings and the observational practices of different teams.

Prepare for your team's presentation

In your presentation, you will need to share…

1. What the team investigated
2. What section of the creek the team focused on.
3. How the team made their observations.
4. What the team found out.
5. The answers to at least two of the questions below.

- What did your team find most surprising at the creek?
- What does your team want to improve or change about how you collect data? Why do you think it would be good to make those changes?
- What is one claim your team feels confident in making about how the different parts of the creek work together? What is your evidence for that claim?
- How does what you learned studying the creek relate to what you learned studying the jars or snails?
- What does the team wants to find out next about the creek and why you are interested in those things?

Use the post-its to write down what you think is most important to report

Figure 7. Research meeting planning guide - Cycle 3

Students' trajectory within Cycle 3. We opened this cycle of investigation, and our tenth day of working together, discussing as a class what we could do to improve how we were collecting data at the creek. The students generated a list that included: better teamwork and organization, include new measures, focus only a few things at a time, measure instead of catch, work together to find ways to measure, and measure several times. These items illustrate how students' view of what might be important for understanding the creek ecosystem (new measures of water chemistry) were expanding as well as how they view their observational practice as an evolving activity. Students were beginning to differentiate activities that generating data on the organisms at the creek from those that that simply caught organisms. They also were beginning to value repeated measures of variables and systematic measurement protocols, ideas which they had carried over from their work with the measurement of snail shell thickness during the previous cycle.

The class then broke into our creek teams to prepare for our second trip to the creek. For this visit, the focus students decided to explore how the depth of water changed across their area of the creek. They partitioned the creek horizontally from bank to bank and planned to measure the depth of the water four times each in three different sections. Many of the class suggestions, including a focus on measuring rather than catching as well as measuring several times, were evident in the teams' data collection plan. This plan emerged out of negotiations between Mychel and Larry, who was the team leader for this creek investigation. Mychel first suggested that the team should focus on water speed, but became stumped trying to find a way to turn her idea into a question. Larry argued that they should focus, like they had during the first visit, on water depth but improve on what they had done by more systematically measuring across the creek. As I circulated among the teams, Larry shared his idea with me. I encouraged the plan, and Mychel and Dennis tentatively agreed. Christine was absent during this planning period. As the team moved on to determine how they would collect their data, Mychel suggested measuring the depth in three locations: both sides of the bank and the center of the creek. At this stage, the classroom teacher stopped by and asked the team about the number of times they were planning to measure the depth. Mychel explained about the three locations that they were going to target, and Larry added that they were going to have each member of the team measure in each spot for a total of twelve measurements of depth, four in each of the three areas.

On day eleven we headed back out to the creek. After the day's safety briefing, the focus team immediately rushed over to their equipment pile. Dennis and Larry slipped on the boots, grabbed a yardstick and the camera, and headed to the water while Mychel and Christine gathered the rest of the worksheets and tubs. Larry walked straight into the water and immediately began measuring the depth in the approximate center. He placed the yardstick in the water once, looked at the level, and declared the depth in the center to be 10 ½ inches. By this time, Mychel (who had her own boots) and Dennis had both entered the water. In the process of trying to write down the depth measurement, Mychel proceeded to slip and douse herself completely in the cold water. Dennis helped her up and out of the creek, and she spent the next twenty minutes drying out in a sunny spot on the bank. Meanwhile Larry had continued to measure the water depth. He yelled at Christine, who was still on the bank, to record that the far bank was 6 ½ inches deep. He then walked back to the near bank, placed the yardstick down once, and shouted at Christine to record his finding of 3 ½ inches. After taking one measure in each location, Larry declared the depth measures done. It was not clear whether he thought that just his three measurements of depth were complete and the other members, as originally planned, should still repeat what he had done or if he thought that these three measurements were enough for the whole team.

At this time Christine, who had no boots, went to check on Mychel. As she had been absent yesterday during the planning session, it took a while for Christine to catch up with the team's goals and plans for this day's data collection. Meanwhile, Dennis and Larry grabbed a scoop and net respectively and turned their focus to the crawdads and other organisms in the creek. Larry headed to the same area of the far bank where he had found so many crawdads during the last visit, and Dennis followed. The adopted the same observational process as in the first visit in which they first tried to visually locate an organism before they scooped into the water. However, minutes passed, and they were unable to spy a single crawdad. Frustrated, Larry told Dennis, "I think the weather's affecting this. Can't see anything." The two continued to shuffle around in the same general area, and Larry finally spied a large, almost-dead fish. He scooped this up in his net, took it over to the team's tub on the bank. All of the team gathered around the fish and debated if it was dead or dying. Larry even called me over, as an expert, to see what they had found. Then he and Dennis headed back in the creek as Christine followed along the bank. This time they found three crawdads in the same general area that they had been looking before. Larry added these to the team tub and then moved downstream to look for more organisms. In this new area, he found another fish and two more crawdads and added these to the collective count. Dennis and Christine headed off to join Larry. When they arrived, Larry called their attention to an odd organism in the creek. With the help of Dennis and Christine, Larry was able to catch this organism and get it into the team's tub. All three then took this organism, which upon closer obervation turned out to be a type of worm, in the tub back to Mychel to observe.

Mychel's fall created a unique dynamic during this visit in which Dennis and Christine floated from Larry, who stayed primarily in the creek, to Mychel, who stayed primarily in a sunny spot on the bank. However, although they were not in the creek, the students on the bank were not completely passive. As they watched Larry and the others working in the creek, they took note of other organisms such as water striders that they could observe from the bank. In addition, the team's observational protocol of taking organisms that they found out of the creek and placing them into the team's tub served an important function during this visit in uniting the team members who stayed on the bank with those in the creek. By watching the actions of her teammates, Mychel could visually trace each organism the team found back to the location it was discovered, and then join with the rest of the team in more closely observing the organism in the tub.

Near the end of our time at the creek, I joined the team as they were gathered around their tub. As we looked at the organisms they had collected, Larry shared how he always seemed to catch more crawdads in the grassy areas. I asked him about how he could use data from the creek to prove this. Larry wasn't quite sure how he could do this and answered, "They just seem to be more by the bank." By the end of their time at the creek, the team's observations included the previously described depth measurements and an organism count of 5 crawdads, 2 fish, 1 worm, and 2 water striders. Larry had also noted on his sheet that the "crawdads might be going upstream and clinging to algae with claws". To him, this story helped explain his initial difficulty in finding crawdads during this second visit.

On day twelve, the teams broke off to begin planning their research meeting presentations. Once again Mychel took the lead in assigning what each student would present, although Larry insisted on being the one who shared the findings that he had gathered. Christine, Dennis, and Larry each worked silently on writing out the parts they would share, while Mychel narrated her writing out loud and created opportunities for the others to chime in from time to time. Larry did this the most and interjected elements of what he had observed into Mychel's summaries of what the team found surprising (the dead fish) and a claim they could make (that it gets more shallow as you go up the creek). This claim was built on Larry's experience of the water moving higher up his boots as he moved downstream in search of more crayfish. In their retrospective interviews, the students described preparing for this research meeting in a much different way than they did previously. In particular, they went into the meeting looking for opportunities to connect what other teams had to say to their own research. As Mychel explained it, "I'm hoping to find out if anyone found what we were wanting to see. If anyone found out the oxygen levels to see if it affects the animals and stuff." Christine also wanted to find out how other teams might have collected dissolved oxygen measurements. In addition, Larry wanted to see if he could compare the findings of other teams to their observations of water depth and animal counts.

In their presentation, the team shared both their observations about depth and their observations about the organisms (Excerpt 6). However, they did not integrate the two. This was not surprising, as the team had explored the depth in one set of areas and the animals in another area rather than exploring both in the same spaces. After Christine and Dennis had described their overall approach (lines 1-2), the team posted their depth measurements on the class map of the creek. Larry then shared their observations (line 3). He explained where they had taken the three depth measurements and the values they had found, but then he did something that he had not done before. He called into questioned whether their measurement of 3.5 inches really captured the depth at the near bank or was it was an anomaly due to small hill in the section he measured. This suggested that although he only took one depth measurement in each area, he was aware that a single value might not always typify a phenomenon. It also indicated that the students were transforming the research meeting from a site to share ideas to also being a site for critique, including self-critique, of practice. Larry also shared his story of the crawdads swimming upstream. Mychel then described how the team had been surprised about to find large hurt fish in the creek, how the microcosm jars had highlighted how the environment affects the organisms living in an area, and how they still wanted to investigate how the water speed and oxygen levels might affect aspects of the ecosystem (line 4).

Excerpt 6 – Research meeting presentation

1	Christine:	*(Reading her paper)* Our team investigated the animals and the water depth. We measured the depth in three areas and caught animals in two areas.
2	Dennis:	*(Reading his paper)* The area we focused on was kinda near the bridge. It was kinda in the middle of the creek. The way we made our observations was with tape measures and yardsticks and nets.
3	Larry:	*(Reading his paper)* We found out that towards the bank on the farthest end when you would just get in and go straight was 6.5 inches. And in the middle the very middle of the creek it was 10.5 inches. And when you would first walk into the creek when you just get in it was 3.5 inches. And that could have been different because when you would get in there was a little hill in our part. So it could have been 6.5 inches there. And we found out that the crawdads were swimming upstream and grabbing out algae and moss there. And they would try to hide. I know it seems a little weird but I saw one do that.
4	Mychel:	*(Reading her paper)* We're going to be answering three questions. What was surprising was that fish in creek were bigger than the one team found last time. They seemed to be getting hurt by something maybe poisoned by pollution. What we learned about our jars. We learned about how the environment affects the things that are living in it. So like the rocks and stuff give them a place to hide and stuff. And what we want to find out next. We want to find water speed because it might affect the ecosystem. We also want to find the oxygen level because it might affect some of the ecosystem, plants.
5	Student 1:	So, how did you know how the animals behaved as you claim when you only examined crawdads?
6	Mychel:	We didn't only examine crawdads,
7	All:	We found worms, water striders, fish and crawdads.
8	Student 2:	How many fish did you find?
9	Dennis:	Two and they were both dead.
10	Mychel:	*(Looks at Dennis)* One was dead and one was dying.

11 Student 3: Do you know why the fish were dying?
12 Dennis: Yes.
13 Mychel: Maybe, maybe, maybe.
14 Dennis: Pollution, pollution I think.
15 Mychel: Might be the pollution coming down from the carwash.

Throughout the research meeting, all of the focus students actively listened during the presentations and wrote down questions that they had or things that surprised them for each of the other teams. Mychel even offered a rare suggestion to one team: “My suggestion would be to measure more things in the creek and then see how it affects the creatures. To see if like the size of the plants might be why you didn’t like see any in your plants.” Dennis, Larry, and Mychel all raised their hands at one point or another to discuss the other teams’ presentations, and each was called upon to share. Some of their questions probed similar topics as in the first research meeting: the type, number, and size of organisms observed. However, they also began to ask for more detail about the location studied, number of observations, and process of observation. For example, Dennis asked one team, “Did you measure the depth in more than one spot.”

Throughout the meeting the students also began critiquing the explanations of the other teams and the way in which the teams developed those explanations. For example, the first question that the focus team fielded from the audience questioned the source of one of their claims (line 5). Later, when Dennis confidently asserted they had an explanation for one of their observations (line 12), Mychel was careful to highlight the tentative nature of this idea and characterize it as something that only might be happening (lines 13-15). Thus in this cycle, the students were using the research meeting as a vehicle first to interrogate what other teams saw, the processes by which the teams collected data, and the claims the teams main and then to connect these ideas to their own actions and findings.

In the retrospective interview at end of this cycle, I once again asked the students to describe what they wanted to investigate in our next (and final) visit to the creek. Here, the team began to diverge in their interests. Dennis, consistent to the end, still wanted to focus on animals and their habitats and shared, “I really want to study more about the animals. Like how they’re generating and where they’re getting their food sources, like where their certain grounds are, like their mating grounds and stuff.” Meanwhile, Christine once again had been swayed by the most recent events and wanted to figure out why there had been so many dead fish and suggested testing the water in that area and seeing if other animals had experienced similar die-offs. In contrast, both Mychel and Larry wanted to explore the oxygen levels in the creek and how the oxygen was related to other variables such as water speed, water depth, and the animals. As Mychel explained, “We want to find out the oxygen level cause we want to see if near the plants if the oxygen level is greater. And if in the deep areas if it’s greater or lower then in the shallow. And we want to see how it might affect the animals that live in that ecosystem.”

As with previous cycles, the interests of all of the students touched in some way on the animal populations at the creek. However, only Dennis still described this in general terms of wanting to focus on where the animals live or what their habitat was. Both Larry and Mychel were able to identify key factors about the environment (e.g., oxygen level, water speed, and water depth) that they wanted to specifically investigate relative to the animal populations. Even Christine showed a slight glimmer of this focus when she described that she wanted to see “how the water is like by where we caught the dead fish” (although she did not clarify what about the water she was most interested in). Thus the students were not just focused on the animals, but rather the relationships that they thought existed between the animals and the physical environment and water chemistry at the creek.

However, given the limited amount of time that we could spend at the creek during the last visit, a single team would not be able to collect enough data to answer most of these questions. Rather, teams (and even classes) would need to pool their data in order to be able to explore patterns of covariation between different aspects of the creek ecosystem. However, in order to successfully pool their data, the students would have to partition the creek into consistent sections in which different teams could be responsible for different variables. The boundaries of these partitions would impact the extent to which students would be able to capture patterns of ecological relationships in their data. So the students could not just create arbitrary divisions. However, I also did not want to force what I knew to be ecologically meaningful partitions onto the students. Consequently, as part of the retrospective interviews for this cycle, I asked students how they would choose to divide the creek up into different areas. (By this time the students were in agreement that the creek was not one uniform space but seemed to have distinct areas.) All of the students divided the upstream sections of the creek from the downstream sections according to the water depth, patterns of substrate/vegetation, or both of these variables. Christine explained the way she would partition the creek, saying, "Probably the deepest part. And then split it up into the middle part and then the shallow part where's there more grass. There's deep, and not so deep, and then there's shallow." Patterns in these two variables were not only correlated to each other but also to changes in water speed, which other teams had heavily attended to. This suggested that the students could, at this stage in their investigation, use ecologically meaningful indicator variables to reason about partitions in the creek and held similar views about the general regions where those variables visibly changed. This effectively positioned the class to collectively partition the creek at the start of cycle 4.

Summary of students' development of knowledge and practice in Cycle 3. This third cycle was characterized by shifts in how students described relationships within the creek ecosystem and connected the relationships to specific areas in the creek. Though the students still focused on the animal life in the creek, they began explicitly linking their ideas about the populations of various organisms to their perception of trends in other biotic and abiotic components. In addition, they used similar trends to construct ways in which the class could partition the creek. The students also began to view communication as an important aspect of scientific study and began to explicitly treat research meetings as a venue for advancing their knowledge and practice by learning from and making comparisons to the work of other teams.

Most of the students' ideas about the creek ecosystem that emerged from this cycle integrated the physical environment with animal life (Table 5). The students tied the crayfish to the algae and other forms of vegetation in the shallower areas by the bank and wondered about the extent to which water depth and water speed might impact the organisms at the creek. Some of the students, particularly Mychel, also began reasoning if the relationship between organisms and water depth might be connected to dissolved oxygen levels. These ideas about space and the relationships between biotic and abiotic components of the creek dominated both the students' explanations of the ecosystem and the types of questions that they were asking about the system.

Table 5.
Summary of students' knowledge and practice during Cycle 3

Knowledge	Understanding of the Organisms • Crayfish use algae to hide and are found most by the bank	Understanding of the Physical Environment • Water depth and speed might impact organisms • Water depth parallels changes in plants/substrate	Understanding of Water Chemistry • Dissolved oxygen might impact organisms and be related to water depth • Pollution might be killing fish	
Practice	Asking Questions • How a feature, such as depth, changes across space (relationship to the bank) • Focus on relationships between organisms and characteristics of the physical environment and water chemistry	Planning and Carrying Out Investigations • Data collection plans include attention to location and number of measurements • Observation of organisms driven by what was visible • Disconnect between where different variables are investigated • Data collection plans can be cooperatively improved • Written observations include counts of organisms and location of depths	Analyzing Data and Constructing Explanations • Reliability of individual data points questioned • Stories used to develop explanations of anecdotal qualitative data • Microcosm suggested how organisms might be affected by their environment	Communicating Information • Tubs create collective moments of observation when students cannot all be in the creek • What others experienced used to make sense of own questions and findings • Research meetings used to critique methods of data collection and explanations

As the students designed their investigation, they began to include more detail about the intended location and number of measurements in their data collection plans. However, despite this attention to space, the team still had a disconnect between where they investigated water depth and where they investigated the animal life. Consequently, they could not integrate their data from these two variables to develop an explanation of the relationship between water depth and the number of organisms. As in the first visit to the creek, the team's observational practice was driven by what was visible. Once again, they would wait until they first visually identified an organism in the water and then work to catch that organism in their net. In addition, their written records of their data once again took the form of a list of organisms and depths. However, this time this list included counts of each type of organism and the specific location of each depth measurement.

When analyzing their data, the students continued to use stories to develop explanations of anecdotal qualitative data, as when they described how they thought pollution might be hurting the fish. However, there were also hints of potential shifts in their approach to making sense of data and constructing explanations. As indicated by Larry and Mychel during the research meeting, some of the students began to view single measurements or observations more tentatively. This suggested that they were beginning to question the reliability of individual data points and were potentially situated to begin to privilege data patterns rather than point. In addition, Mychel shared how the team used what they had seen in the microcosm jar to think about how the organisms at the creek might be affected by their environment. Although the exact relationships students focused on at the creek differed from what they had focus on in the jar, it seemed that the microcosm might have influenced the types of relationships that students now thought were important to explain.

Students' means and purposes of communicating information also continued to develop during this cycle. The research meeting was no longer just a place to hear what others had done or what other areas of the creek were like. Rather, during the research meeting the students looked for how they could use what the other teams shared to make sense of their own questions and findings. In addition, the students began to critique the methods of data collection and validity of claims developed by other teams. This was not something I had specifically asked the students to do, but rather emerged in the moment. The students were beginning to view other teams' data collection methods and forms of analysis as practices that they needed to attend to and cooperatively improve if they were going to be able to apply what those teams had learned to own investigations.

Cycle 4: Uncovering Relationships at the Creek

> Crayfish hide in grass. Grass gives invertebrates and fish oxygen. Invertebrates create nitrates. Nitrates fertilize grass.
>
> - Mychel, Post-Test

Instructional design of Cycle 4. On day fourteen we opened our last cycle of investigation with a whole class discussion that set the stage for how the teams would plan their last visit to the creek. We began by deciding how to partition the creek. As described earlier, this was necessary in order to gather data that could be shared and used to answer all of our research questions. I gave each team a template of the creek asked them to use dry erase markers to divide the creek into three to four distinct areas. After each team had developed their own plan about how to partition the creek, I highlighted similarities in how the different teams had divided the creek and led the students to consensus about any disagreements. By the end we had partitioned the creek into four distinct sections.

I next listed the variables that this class had earlier expressed an interest in studying on the board (crayfish, invertebrates, water depth, water speed, dissolved oxygen) and explained that these were the variables that this class would focus on at the creek this week. I asked each team to come up with two questions about these variables that we might want to try and answer, and we collectively discussed the teams' ideas. This discussion was designed to foreground the types of relationships that we would later look for in our data from the creek. Finally, we wrapped up the day's discussion by critiquing a selection of hypothetical data collection plans (Table 6) and used this critique to create a class list of what to include in a good data collection plan. I had designed these hypothetical plans to purposefully highlight decisions about the details of each step, the tools used, the location and number of trials, repeated measurements, and alternative methods of data collection. I conjectured that students would reference many of the ideas highlighted by this discussion when designing their own data collection plans for the creek the next day.

Table 6.
Hypothetical data collection plans

	Data Focus: Water speed	
	George's Plan	Charlotte's Plan
Scenario #1	Use a ping-pong ball to measure the speed of the water in ft/s. In one section of the creek, find the speed three times by the right bank, three times in the center, and three times by the left bank. Then find the average speed of all nine samples by calculating the median.	Using a tape measure, mark off a distance of 5 feet. Have one person stand at the upstream end of the tape measure with a ping-pong ball. Have a second person stand at the other downstream end with a timer. On the count of three, the first person will drop the ball in the water and the second will start the timer. Stop the timer when the ball reaches the end of the 5 feet. Calculate the speed of the water using the formula speed=distance/time by taking the distance in feet (5 feet) and dividing it by the time in seconds.
	Data Focus: The number of crayfish in an area	
	Megan's Plan	Portia's Plan
Scenario #2	Using one of the long nets, take a scoop by sweeping the net along the bottom of the creek. Dump the scoop in a bucket and count the number of crayfish. Repeat this process twenty times in a section of the creek. Record the number of crayfish found in each scoop, even if it is zero. Calculate the average number of crayfish per scoop or sample. Repeat the same procedure in a different section of the creek and compare the average number of crayfish per scoop in the different sections.	Put a hula hoop down over an area of the creek. Flip over any rocks and count the number of crayfish in that area. Do this by both banks and in the center of the creek. Count up the total number of crayfish found altogether.

We spent day fifteen planning for our third (and last) visit to the creek. We first reviewed the qualities of good data collection plans that the students had developed the day before. Then I assigned each team a specific variable to attend to during this round of data collection and two locations in the creek in which to collect data. This was a significant shift in the design as teams were no longer carrying out investigations to answer their own questions. However, the students' questions had evolved to the point that it was impossible for a single team working on their own to gather the data they needed to answer these questions during the half-hour we had at the creek. In addition, they now privileged taking repeated measures of a variable rather than relying on a few data points. Since the time we could be in the field was inflexible, something had to change in the design to support this more sophisticated practice. I chose to maintain the level of complexity in the questions that students were asking and instead distribute the task of answering those questions amongst multiple teams. Students were still working to investigate questions that they had personally developed as a class. However, instead of one team gathering the data needed to determine if, for example, slower water speeds seemed to create a better habitat for water striders, the work of four teams (two investigating water speed and two investigating the incidence of water striders) would be used to answer this question.

Due to their expertise in working with crayfish, I gave the focus group the task of studying the number of crayfish in sections 3 and 4. Each team then merged with another team that was studying the same variable but in different sections of the creek in order to collectively plan how they would gather their data. In this case, the focus team merged with a second team that was going to be collecting data on the number of crayfish in sections 1 and 2. As in previous cycles, the students' instructions for their plans were very open-ended. The planning worksheet simply asked, "How do you plan to gather observations about your variable at the creek to help answer the class questions?" However, now two different teams were planning together. These teams knew that they were going to be working separately at the creek, but that their findings would need to be able to be fairly compared. I conjectured that this would encourage students to make some of the formerly implicit elements of their data collection procedures more explicit as they talked with the other team. I also conjectured that this design would support students in systematizing their decisions about the number of measurements to take and the locations of those measurements.

On the sixteenth day of the study, we embarked on our final visit to the creek. The structure of this day paralleled our first two visits to the creek. However, for this visit each team had already been assigned a defined section of the creek to work in. When the bus arrived at the creek, the students listened to the safety briefing, gathered the equipment that I had previously laid out for their team, and headed off to their section to start gathering data. Because I was going to translate the students' observations into computer-generated data displays, their worksheet packet had a more defined structure that encouraged them to record the results of each trial or sample. The class in this study successfully made it to the creek as scheduled. However, a multi-day storm postponed the visits of many of the other sixth grade class. Since we were pooling our data across the entire sixth grade, this delayed when we could begin data analysis.

On day seventeen, while waiting for all of the classes to be able to get to the creek, I pulled together a short class session in which we analyzed our snail shell thickness data from cycle 2. The design of this day focused on developing heuristics that we could use to determine if two sets of data came from areas with similar ecological processes or areas that were different. We began by looking at the class summary of each team's data display for snail shell thickness (Fig. 8). I had overlaid each display with a box-plot and the value of the mean, since we would later be using these tools to help us make sense of representations of our creek data.

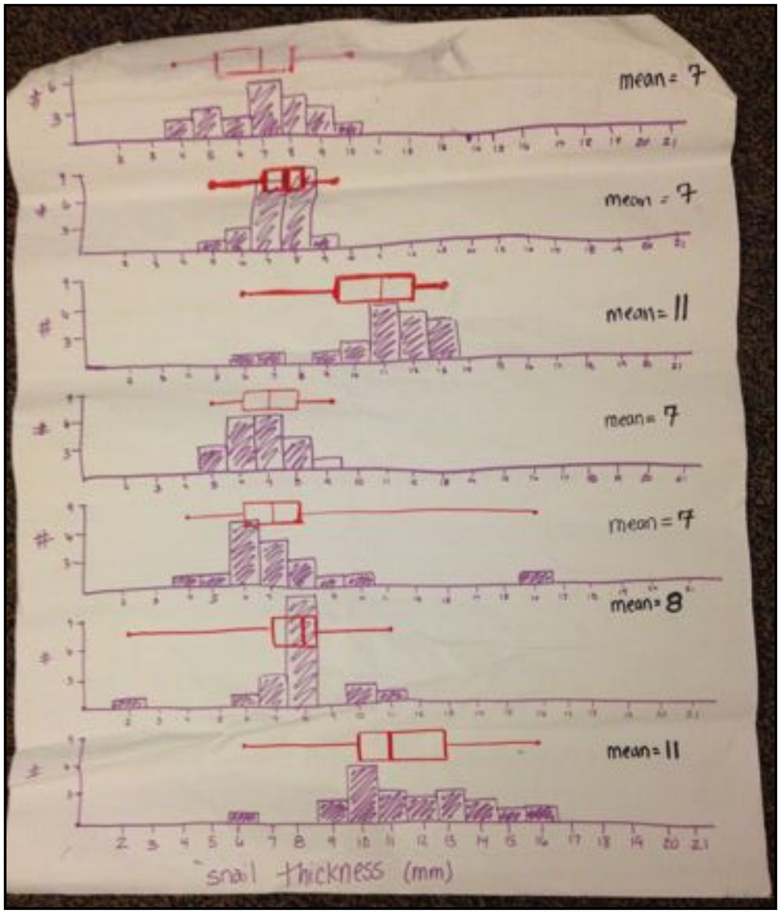


Figure 8. Class summary sheet of snail shell data

After posting the class summary sheet on the board, I covered all but the mean values and asked the class, "Which group had the best habitat, the best ecosystem for the snails?" I had thought that students would recall that all of this data came from snail in the same habitat. However, this backfired. Most of the students selected the two groups that had the largest mean value for shell thickness as having the best habitat. I then asked, "How many different habitats, how many different ecosystems of snails did I bring in?" At this stage many students began confusing our work with the snail colony with our work with the different microcosm jars. Because of this confusion, I abandoned the question and instead drew a diagram on the board that walked students through what we had done back in the second cycle and how all seven of the displays represented snails from the same ecosystem.

After this brief review, I asked the students, “So why are these different? Why didn’t all of your groups get the exact same measurements?” The design of this probe was to draw out students’ ideas about measurement error and natural variation in the snail samples. As ecosystem differences were not a potential source of variation in our snail shell data, we used the displays to develop heuristics based on the center and spread of the data that we could use to look at different data sets and determine if they likely came, as these snails did, from similar ecosystems. I then provided students with a worksheet that had three different example data sets, and the students worked in teams to use the heuristics that they had developed to determine if these examples likely came from the same ecosystem as our snails.

After the rain had stopped and the rest of the classes had collected their data at the creek, we shifted to talk about our collective creek data. I opened day eighteen by giving each student a packet that had computer-generated displays of all of the creek data collected by every team. I had created these displays based on each team’s written data records from the creek visit. The students first familiarized themselves with the packet by finding which displays represented the data that their team had personally collected. After this we turned to the page that summarized the light data from all four sections of the creek (Fig. 9).

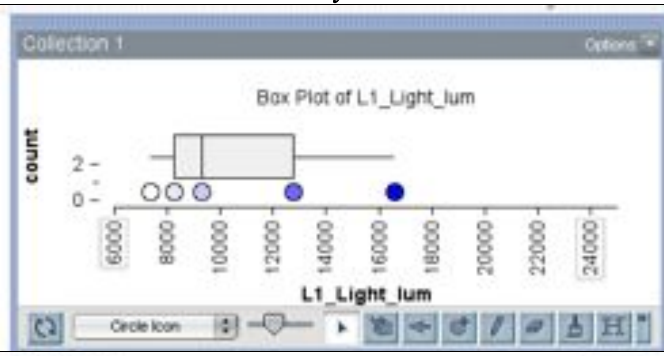
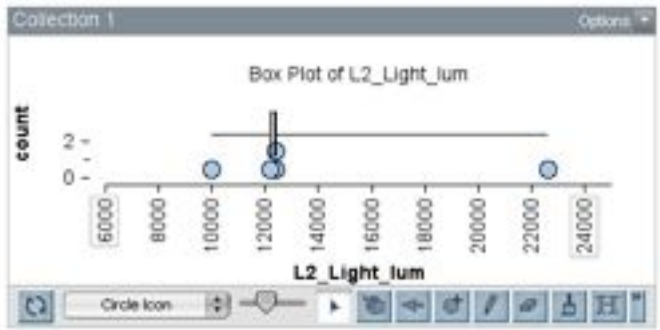
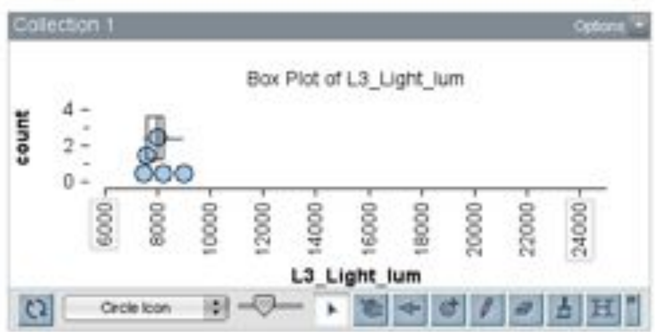
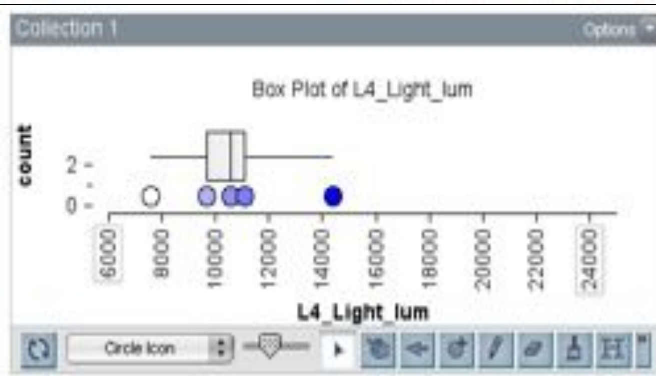
Light	
	Day 1
Location 1	
Location 2	
Location 3	
Location 4	

Figure 9. Light data summary sheet

Students used these displays and the heuristics that they had developed with the snail shell data to determine if there was likely an ecological difference in the light in different sections of the creek or if the differences in the displays could be explained by chance measurement error and natural variation. For the light data, the students used the data displays to determine that sections 1 and 4 were not distinct enough to be treated separately (their means were similar and box plots overlapped). However, sections 2 and 3 did seem to be distinct from the other two sections.

In addition to these displays, I had also created a table that included the mean value of each variable for each section of the creek (Fig. 10). We color-coded this table based on our analysis of the displays. Green signified the highest value for that variable, red the lowest value, and yellow the middle value. Any sections that we determined to be similar were filled in with the same color. Based on our analysis of the light displays, we colored section 2 of the light row green (because it had the highest mean value), sections 1 and 4 both yellow (because their mean values were in the middle and the sections had been determined to be ecologically similar), and section 2 red (because it was distinct and had the lowest mean value). I purposively designed this display so that students could use the colors to test conjectures about the relationship between different variables in the creek. I chose to begin this analysis with the light data because it exhibited relatively clear patterns in relation to our heuristics. We continued to work for the rest of the class period to analyze all fifteen of the variables that the entire sixth grade had gathered data for.

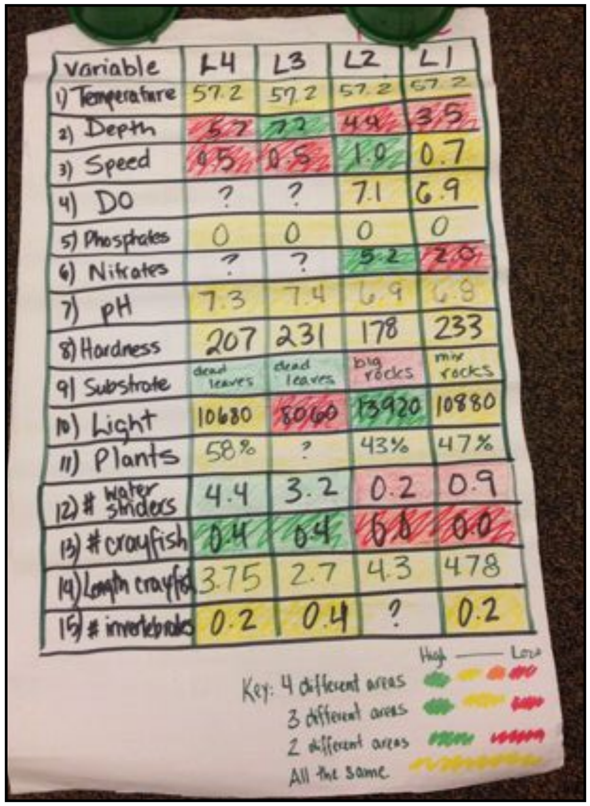


Figure 10. Creek data summary sheet and analysis

On day nineteen, our last day together, we wrapped up our analysis of the variables and produced a completely color-coded table. Once the table was finished, we used this to test claims about relationships in the creek. I first asked students to look at the water strider data and come up with a claim that we could make about the water striders. For example, students could predict that the number of water striders would be higher in areas with more plants. I then modeled how to walk through interpreting this data. In this example, our data would not support the claim that the more water striders would be found in areas with more plants because we did not detect a meaningful difference in the plants in each section. As can be seen in figure 10, we had colored every section for the percent of plant cover yellow. This coloring pattern indicated that we had determined that the displays for each section were similar enough (e.g., similar means and overlapping box-plots) to suggest that the plant cover was essentially the same in all four sections even though each section had a different mean value. Consequently, even though there were areas with more water striders and areas with less water striders, we could not explain this by the distribution of plants. Once we had found a pattern of covariation (or lack thereof), we would discuss whether or not this pattern made sense with our experiences at the creek. At the end of day we wrapped up our entire study by generating one last class concept map of the ecological relationships at the creek.

Students' trajectory within Cycle 4. We began day fourteen by discussing in teams how to partition the creek. Many of the teams, including the focus students, used what they remembered about differences in the substrate and vegetation to make decisions about where to divide the creek. Other teams focused on sectioning the creek at places where they had noticed changes in water speed or depth. When we joined back together as a class, I highlighted two areas on our class map of the creek that the teams had seemed to partition in a consistent way: the shallow grassy area up by the car wash (which later became section 1) and the deeper area down by Gran's bridge (which later became section 4). I then asked the students whether they thought that the middle area should be kept together or split into two sections. Most of the students thought that it should be divided because of key differences within that middle area. One student brought up that "once you get to the tree it gets darker", and another said that it should be split "because one side (gestures to the right) is faster than the other side (gestures to the left)". The focus team also shared what they had noticed about the change in substrate in that area. Given all of these factors, we decided to split the middle into two different areas (sections two and three). We numbered all of these sections based on the direction of water flow.

Following this discussion, I listed on the board the variables that this class had expressed an interest in studying and would thus focus on at the creek this week (crayfish, invertebrates, water depth, water speed, dissolved oxygen). I asked the teams to think about these variables and brainstorm some questions that we might want to try and answer about them (Excerpt 7). One team suggested that we study "whether the invertebrates live near the bank" (line 2). I modeled how we could revise this question to explicitly compare the invertebrates in two sections: those near the bank and those in the center of the creek (line 3), and we explored competing predications about where there might be more invertebrates based upon what the invertebrates might require to meet their needs (lines 4-7).

Excerpt 7 – What we might want to answer about the creek

1	Researcher:	Let's get some questions up here on the table. What is one question that we could use data to answer about these variables?
2	Student 1:	Whether the invertebrates live near the bank…
3	Researcher:	Okay, so we could say, "Are there more invertebrates near the bank or near the center of the creek?" So if that is the question, what do you think would be the predicted answer to that? Do you think there would be more near the bank or near the center? Thumbs up or thumbs down. Thumbs up near the bank. Thumbs down near the center. *(The class is about evenly split).* Okay so we don't have consensus here. Someone give me an explanation of what you are thinking.
4	Student 2:	I think the center because there's more rocks and places to hide and stuff.
5	Researcher:	Okay, so one prediction might be the center and our explanation might be more places to hide. Okay, can someone give me an explanation of why they think the bank? There's more near the bank.
6	Student 3:	Maybe there's more sand and grass or food. Maybe what they eat is the grass.
7	Researcher:	There's something interesting about this. Both of those explanations have to do with how the invertebrates meet their needs.

We wrapped up the day's discussion by critiquing a selection of hypothetical data collection plans and using this critique to create a class list of what to include in a good data collection plan. The students emphasized explaining the steps in detail (including the tools), collecting data multiple times (samples), collecting data in multiple locations, and choosing a method that works for your target variable.

On day fifteen I assigned each team a specific variable that they would collect data on during their last visit to the creek and two locations in the creek in which to collect data. The focus group was assigned to study the number of crayfish in sections 3 and 4. The teams then merged with a second team that was going to be investigating the same variable but in different sections to collectively develop their data collection plans. Once the focus group and their partner team were together, Mychel opened the discussion by referring back to one of the data collection scenarios we had discussed the previous day, and she and Larry debated whether it would be good to collect twenty samples of crayfish in each of the sections. One of the students from their partner team wondered why they would need so much data and suggested taking ten scoops inside. The two teams agreed on this and settled on collecting ten samples from each area.

After some confusion over which sections each team was responsible for, the teams continued to discuss their plans. Mychel suggested, “Maybe we can do the same plan in each section”, and this led to a discussion of how they were going to scoop for crayfish. Students from the partner team suggested that they use hula-hoops, a tool they were familiar with using to count organisms, but the focus group rejected this idea. Then Mychel suggested using “blind scoops”, where you didn’t chase after the crayfish but rather just scooped in an area and saw what you ended up with. This methodology had been introduced within the hypothetical scenarios the previous day. Larry said, “That won’t work because you won’t catch the crayfish” and suggested looking under rocks instead. Mychel and a student from the partner team questioned this approach because it might lead them to chase the same crayfish from rock to rock and recount it over and over. Larry then revoiced another idea from the previous day that maybe they could put a net over a rock, flip the rock, scoop, and then see if they caught a crayfish. The team members agreed with this suggestion and developed a plan to collect, as Mychel called it, ten “flipping-rock-scoops” in each section. For Mychel, Larry, Dennis, and Christine, this was the first planning session in which they actually thought through how they were going to use their tools to gather data on the crayfish.

As the team members wrote these details on their data collection plans, I stopped by and asked about their plans. After listening to the number of samples that they were planning to collect and how they planned to use the net to catch what they revealed by flipping rocks, I asked the teams how they would decide where to flip the rocks and scoop. Dennis said they should be "in the open" while Larry thought they should be in "the grassy area", and Mychel countered that perhaps they should sample all over each area. I suggested that maybe they could draw a map of the locations and use that to help them decide. Each student began drawing a small map on their data collection plan (Fig. 11). The students included key landmarks such as the car wash bridge, Gran's bridge, and the big tree. They then partitioned the map into the four sections that the class developed the day before. Mychel then asked the others, "Do we want to draw circles where we want to scoop?" They agreed, and all started to draw circles everywhere in their section. This created a jumbled mess of differences in where they had place the circles, so the team decided to simplify things by collecting three scoops along each bank in the grassy parts and four scoops in the rocky middle. This way they would cover both substrates in each section.

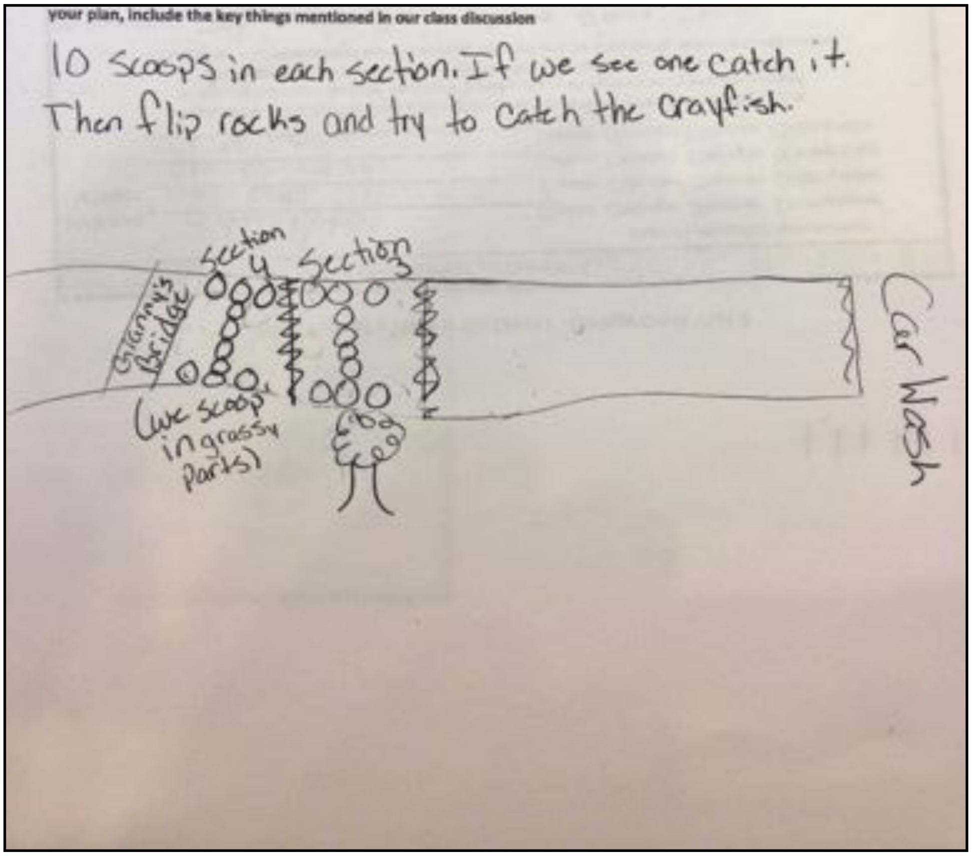


Figure 11. Data collection plans – Creek visit 3

On day sixteen we headed out to the creek for our final visit. After our safety briefing, the team once again rushed to gather their equipment. However, this time the group had accidentally received a mismatched pair of boots that were too small for the boys to wear. Consequently, Dennis and Larry spent the first minutes at the creek running back and forth along the bank trying to find a pair that would fit. While Dennis and Larry searched for boots, Mychel and Christine began to collect the team's data on the number of crayfish in sections 3 and 4. The two worked out a system where one would do the scooping while the other would point out the area to scoop and record the data (Excerpt 8). Dennis and Larry would later join up with Mychel and Christine as they wrapped up their team's data collection.

Excerpt 8 – Collecting data during the third creek visit

		(Mychel has been scooping with the net and Christine has been recording data on the observation worksheet)
1	Mychel:	You want to take samples now? *(passes net to Christine and takes clipboard from her.)*
2	Christine:	How many are we doing left?
3	Mychel:	(*consults clipboard with observation notes)* We are on sample six.
4	Christine:	Where do you want me to do one?
5	Mychel:	*(looks at clipboard and then points to center of creek)* One more right here
6	Christine:	Where? *(moves toward Mychel)*
7	Mychel:	Right here. *(points down)*
8	Christine:	*(puts net in the water)* Right here?
9	Mychel:	Yeah.
10	Christine:	*(scoops across the water and looks in net)* There's nothing here. Wait! What's that? Is that the beetle?
11	Mychel:	*(looks in the net)* Yeah, I can't get it out.
12	Christine:	Oh. There's nothing.
13	Mychel:	Ok. *(writes none on the observation sheet under sample 6)*. Ok, one more right here. *(points to area near the far bank)*
14	Christine:	*(moves to take a scoop where Mychel pointed)*

In this visit to the creek, the team used a very different method to investigate the crayfish in their section. Instead of waiting to first see a crayfish and then catch it, Mychel and Christine blindly scooped in pre-selected locations. Thus these scoops took on a different status than before. They became the means to uncover what organisms might be in the creek rather than a means to capture what has already been uncovered. As Christine began to sample, she asked Mychel where she should scoop (line 4). Mychel consulted her clipboard, which had the details of their plan and the results of prior samples, and pointed to a spot near the center of the creek (line 5). Christine checked that she had the right location (line 8) and then scooped into the water (line 10). She looked into the net and announced that there wasn't anything new in the net (line 12). Mychel then wrote "none" for this sample on their observation sheet and pointed out the next location for Christine to scoop (line 13). By following this process, Mychel and Christine constructed the first data record for their team that included the results of individual trials and recorded scoops that had no organisms (Fig.12). Though this record also detailed the other organisms the students found, it clearly represented how many crayfish were (or were not) present in each scoop.

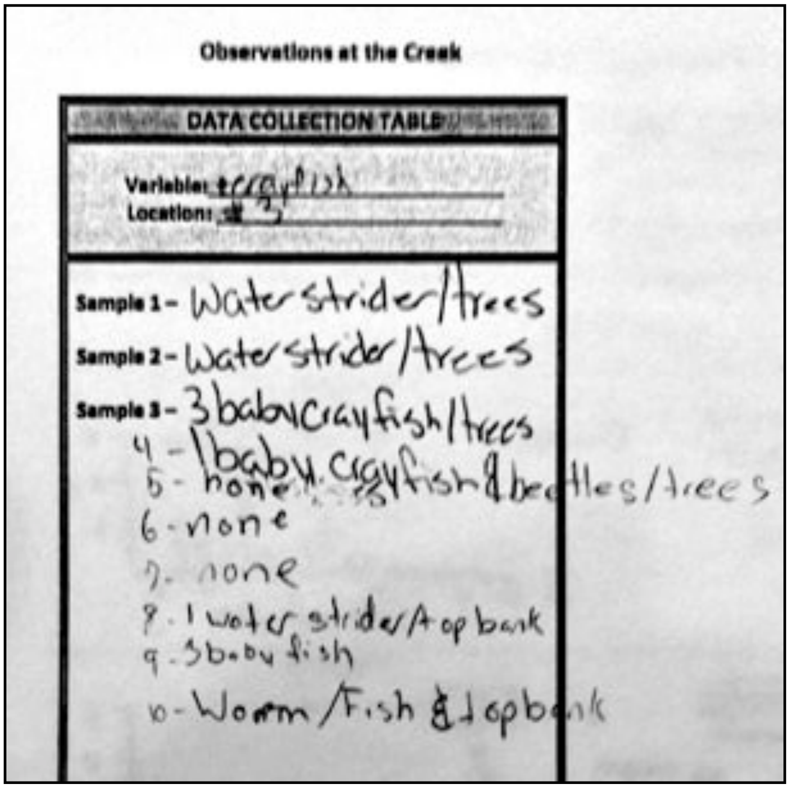


Figure 12. Observation worksheet – Creek visit 3

On the seventeenth day while waiting for all of the classes to be able to get to the creek to collect data, we spent a short class period analyzing the snail shell thickness data from cycle 2. We began by looking at each team's data display for snail shell thickness and broke into teams to discuss why all of the groups did not have the exact same values. All of the teams readily came up with the idea that measurement error might have contributed to the differences. Mychel initiated this idea in the focus group (Excerpt 9, line 1), and Christine and Dennis readily agreed (lines 2-3). Larry also suggested a different source of variation: the groups could have taken different samples of snails to measure (line 4). Larry was one of the few students who spontaneously recalled this influence of natural variation on the snail shell data.

Excerpt 9 – Reasons for variation in snail shell thickness

1	Mychel:	What do you think it was different? Maybe they measured wrong?
2	Christine:	Yeah, that's what I was thinking.
3	Dennis:	That's what I say. Or they could have like measured differently.
4	Larry:	Nobody got all the same samples. Maybe they took different samples.
5	Dennis:	Really they measured differently.

After discussing both measurement error and natural variation in the snail samples, we eliminated ecosystem differences as a potential source of variation, as the snails had all came from the same colony. We then used the display to develop heuristics for how to look at different samples of a measure and determine if they likely came from areas with similar ecological processes. The class developed two heuristics that they would use to determine if the samples, though different, were similar enough to say that they came from the same ecosystem. Students would look to see if the means were similar and the extent to which the box-and-whisker plots overlapped. We applied these heuristics to a worksheet that had three different example sets of data (Fig.13), and the students worked in their groups to determine if these sets of data likely came from the same ecosystem as our snails (Excerpt 10).

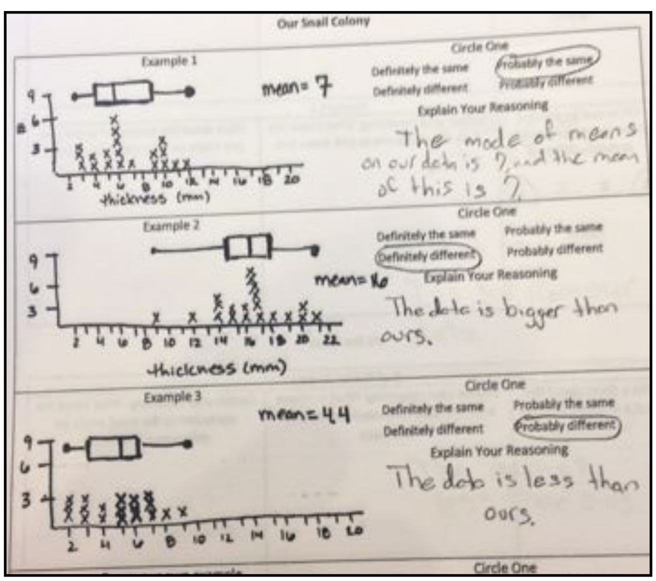


Figure 13. Snail data analysis worksheet

Excerpt 10 – Determining if two samples are from the same ecosystem

1	Researcher:	Do you think that example one belongs with this set of data that we collected on the snails or do you think that it's different? *(Students working in teams)*
2	Mychel:	I think it does. Probably. Not definitely.
3	Larry:	Not the second one though.
4	Mychel:	The second one I think is too much.
5	Larry:	Yeah.
6	Mychel:	And the third one a little too low.
7	Dennis:	The third one fits in with the group.
8	Christine:	The first one fits in because we got 7 too. *(looking at Dennis)*
9	Dennis:	Yeah, I meant to say the first one.
10	Christine:	Yeah, and the second one was too high.

In the focus group, the students quickly scanned through the three examples to determine if the samples came from the same ecosystem as the snails that we had measured. Mychel said that the first one was probably the same (line 2), but both she and Larry thought that the second example did not belong (lines 3-4). In their words it was "too much". Likewise, the third example was "a little too low" (line 6). However, neither Larry nor Mychel explicitly described what specifically was too much or too low. Though they were basing their decisions on some form of comparison, the vagueness in their language at times made it difficult to follow exactly what they were privileging in this comparison. However, Christine seemed to definitely be basing her decision on a comparison of the means because of her reference to the number 7, which was the mean for the first example (line 8). Christine and Mychel also attended to the mean values of the data sets when explaining on their worksheet why the first example probably came from the same ecosystem as our snail colony. They wrote, "The mode of the means of our data is 7 (referring to the class data displays of snail shell thickness) and the mean of this is 7 (referring to the example data set)."

On day eighteen, we explored the data displays for each variable investigated at creek. Students used the heuristics that they had developed with the snail data to determine if there was likely an ecological difference in a variable across different sections of the creek or if the differences in the displays could be explained by chance measurement error and natural variation. As described in the instructional design, I modeled this process for students by analyzing the patterns in the light data. Students next looked at the data displays for crayfish length (Excerpt 11).

Excerpt 11 – Interpreting the length of crayfish data

1	Researcher:	So what are we looking at when we are trying to decide whether the same thing is going on for the length of crayfish or if different things are going on? What are our visual clues when we look at the data?
2	Student 1:	The box plots.
3	Researcher:	What about the box plots.
4	Student 2:	To see if they line up.
5	Researcher:	Why does it matter if the box plots line up? What does that tell you about the data?
6	Larry:	It tells you that pretty much that they're from the same ecosystem.
7	Researcher:	Why? Why is it telling you that?
8	Larry:	If they're lined up together they're going to be. If their median. If they line up or overlap that means they're pretty close together and that means you're in the same ecosystem.
9	Researcher:	So looking at those boxplots…if I have a crayfish of 4.0 cm in length, how many different of our location could that have likely come from? *(pause)* Could that have come from location 1?
10	Students:	Yes.
11	Researcher:	What about location 2?
12	Students:	Yes. No. Yes.
13	Researcher:	Well we didn't get an exact number of 4.0, but did we some around it, close to it?
14	Students:	Yes.
15	Researcher:	What about location 3?
16	Students:	Yes.
17	Researcher:	What about location 4?
18	Students:	Yes.
19	Researcher:	So those boxplots are telling us when they overlap that a lot of the samples that we're getting in those different places are what?
20	Mychel:	(whispers) The same.
21	Students:	The same.
22	Researcher:	We're getting the same type of values. So what's our conclusion? Should I have all four of these be separate? Or are there two different types of systems going on here for crayfish? Are they all the same? What was your decision?
23	Larry:	Mostly the same.
		(Other students agree that the sections are mostly the same, so we color the boxes for crayfish length in all four sections yellow).

When asked what visual clues we should look for, students suggested we look at the box plots (line 2) and see if they line up (line 4). Larry explained that boxplots that line up or overlap signify that “you’re in the same ecosystem” (lines 6-8). As I continued to probe about what this means about the individual values, Mychel hinted that the overlap signified that we were getting a lot of the same values in each section (line 20). Because of this overlap, Larry suggested that mostly the same thing seemed to be happening in all of the sections (line 23). We colored all of the sections for crayfish length in our summary data table for the creek yellow to represent they all had similar crayfish lengths.

We repeated this process as a class for all of the variables. Many of these discussions required a strong amount of instructor scaffolding throughout the decision making process, as in the last excerpt. Occasionally we would come across a set of displays that was difficult to make a decision about. This was most likely to occur when a variable was populated with only four or five measures or when the variable exhibited a large amount of variation. In these cases, we discussed how collecting more data might make it easier to see the patterns in the data and thus would make our decision more clear.

On day nineteen, after we had analyzed all of the variables and completely color-coded our table, we began to use this table to make claims about relationships in the creek. I asked students to first look at the water strider data and come up with a claim that we could make about the water striders (Excerpt 12). I drew attention to sections of water strider data that had been colored red (line 1) and the sections that had been colored green (line 3). The students, including Larry, correctly interpreted that this told us we had found few water striders in the first two locations (line 2) and more in the last two (line 4).

Excerpt 12 – Making claims about the water striders

1	Researcher:	I want to make a claim about the water striders. Here, this red. *(points to red sections on table)*. What does that tell me about the water striders?
2	Student 1:	Not very much
3	Researcher:	What does this tell me about the water striders here? *(points to green sections)*
4	Larry:	More
5	Researcher:	So lets look at our data, why do you think there might have been more water striders in location 3 and 4 than location 1 and 2? Is there any other of our variables that might be affecting it?
6	Student 2:	Maybe they like the shade more than the light?
7	Researcher:	Let's see if that works, are the areas where there's more water striders the shadier ones? So let's look up here. *(points to the light row on the table)*. The area where the most light is what do we know about the water striders?
8	Mychel:	Not a lot
9	Researcher:	Not a lot of them. And the area where there's the least light what do we find *(pointing from the red light section down to the water strider box).*
10	Student 3:	More.
11	Researcher:	So I think that's supported by our data. So our claim is that sometimes we can find more water striders in shady areas. And we know that because location 2 which had lots of light had few water striders and location 3 that had little light had lots of water striders *(writing on board).*

One student suggested the claim that water striders might like the shade more than the light (line 6). We looked at the light data and saw that in the sections where we had measured the most light there were few water striders and the sections where we had measured the least light there were more water striders (lines 7-10). Thus the data patterns supported the relationship in the students' claim. We further discussed why this pattern made sense. Students suggested that the shade might have helped the water striders avoid becoming too hot or it may have helped the water strider avoid being seen and thus eaten by other organism. The students repeated this process and made claims about the relationships between water speed, substrate, water depth, and the number of crayfish. Finally, we concluded our investigations by generating one last class concept map of the ecological relationships at the creek.

At the end of our study, the students completed a post-test in which they were asked to describe what the creek is like and how the parts work together to make a functioning ecosystem.

These descriptions were analyzed for their number of general components, specific components, and different types of relationships, as well as the number of relationships in the longest chain and if present the longest cycle (Table 7). These results were then compared to student's pre-test descriptions. On average, the students included more components and relationships, including longer chains and cycles, in their post-test descriptions of the creek. Many of these included types of relationships that were completely absent on the pre-test: ways in which organisms might influence the water chemistry and ways in which the water chemistry might influence the organisms.

Table 7.
Characteristics of students' post-test explanations of the creek

	Dennis	Christine	Larry	Mychel	Mean	Change in mean from pre
Number of components:						
General components	4	0	1	0	1.25	+0.25
Specific components	1	7	4	6	4.25	+2.25
Total components	5	7	5	6	5.75	+2.75
Number of relationships:						
Organism impact on other organism	0	1	0	2	0.75	+0.75
Organism impact on the environment	0	0	1	0	0.25	0
Organism impact on water chemistry	0	2	1	1	1	+1
Physical environment impact on organism	2	2	1	0	1.25	-0.25
Water chemistry impact on organism	0	1	2	1	1	+1
Total relationships	2	6	5	4	4.25	+2.5
Number of relationships:						
In longest chain	1	4	3	4	3	+1.5
In longest cycle	0	3	0	3	1.5	+1

Dennis showed no substantial pre/post-test change in his description of the creek. He continued to generically describe how the creek provides food and habitats for animals. However, Christine's, Larry's, and Mychel's post-test descriptions of the creek were substantively different from what they had written on the pre-test. Each now included four or more specific biotic and abiotic components of the creek and between four and six relationships, including multi-step chains or cycles. These chains and cycles integrated elements that had been highlighted in the microcosm jars with elements that had been highlighted in the creek investigations. For example, one of Christine's relationship cycles described how nitrates make plants grow, the grass feeds the crayfish, and then the crayfish leave fertilizer (nitrates) which help the plants grow (Fig. 14). Though there were some differences between the students, Christine, Larry, and Mychel all included relationships between crayfish and grass/plants, elements of the oxygen cycle, and elements of the nitrogen cycle in their description. Larry also included a novel relationship that described how plants slow down the water speed. This observation most likely stemmed from his experience investigating crayfish along the vegetated bank of the creek.

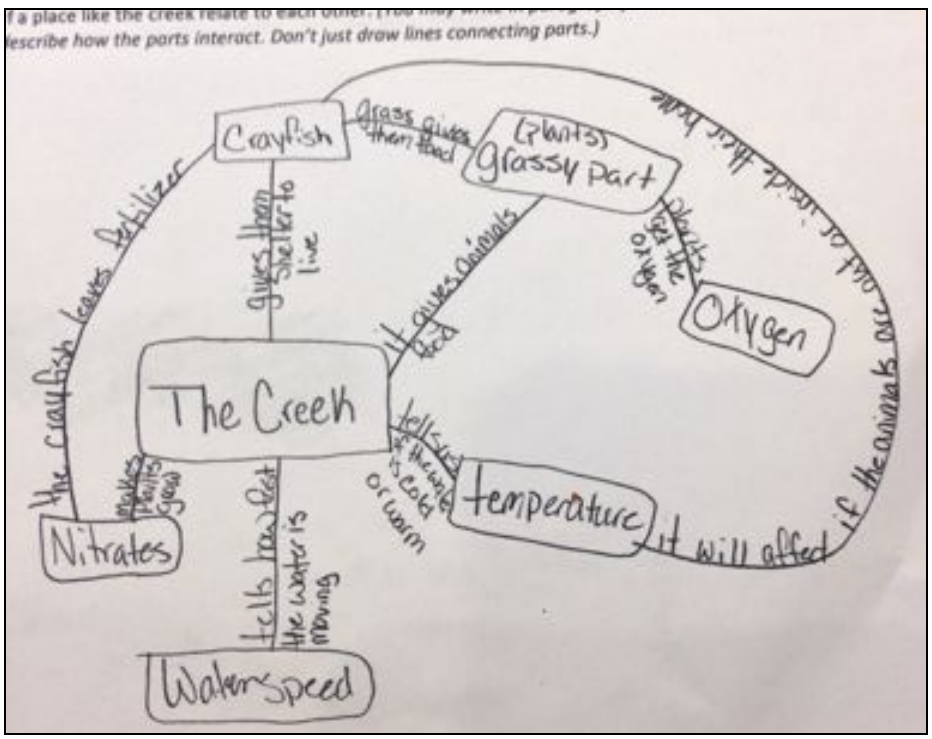


Figure 14. Christine's post-test explanation of the creek

Summary of students' development of knowledge and practice in Cycle 4. This cycle of investigation was characterized by continued development in the way students were reasoning about relationships in the creek, partitioning the creek into sections, and systematizing their data collection. Then latter part of the cycle was also distinguished by the students' struggle to make sense of whether their data did or did not signal an ecological difference in different sections of the creek. This form of reasoning, in which every difference in data does not signal a difference in the underlying process, was foreign to these students and at times seemed to be at the very edge of what students were comfortable exploring.

Throughout this cycle, students broadly integrated their ideas about the organisms, the physical environment, and the water chemistry when describing relationships within the creek (Table 8). These relationships also dominated the types of questions that students asked. Some of these relationships emerged from what students had noticed over time in the creek: the team's partitioning of the creek based on differences in substrate, their references to crayfish behavior and relationship to substrate when developing data collection plans, and Larry's description on his post-test of how the water speed is slowed down by plants. Other relationships, including students' references to the oxygen and nitrogen cycle, seem to have carried over from the students' microcosm investigations. Students even merged the two as they described on the post-tests how crayfish use dissolved oxygen produced by the plants and in turn produce fertilizer or nitrates that help plants grow. In this, they positioned the crayfish from the creek as functionally equivalent to the snails from the microcosm jars. However, none of the students in this focus group seemed to take up any of the new relationships highlighted during the class analysis of the data from the last creek visit.

Table 8.
Summary of students' knowledge and practice during Cycle 4

	Understanding of the Organisms	Understanding of the Physical Environment	Understanding of Water Chemistry
Knowledge	• Crayfish hide under rocks and in grass and eat plants • Crayfish/fish/invertebrates use (dissolved) oxygen • Plants/grass produce (dissolved) oxygen • Crayfish/invertebrates leaves fertilizer/nitrates	• Water speed is slowed down by plants • Differences in substrate signal key differences in the creek	• Nitrates help plants grow • Fertilizer has nitrates / nitrates are fertilizer

	Asking Questions	Planning and Carrying Out Investigations	Analyzing Data and Constructing Explanations	Communicating Information
Practice	• Focus on relationships between organisms and characteristics of the physical environment and water chemistry	• Plans include attention to location, number of measurements, repetition, and means of using tools • Plans for the same variable need to be consistent • Observation driven by plans • "Blind-scoops" used to make organisms visible • Written observations include results of specific trials/samples and records of zero/absence	• Differences can be due to measurement error and natural variation and not just direct ecological causes • Overlapping values and similar means suggest a similar underlying process • Patterns of covariation can suggest relationships • Stories used to develop explanations of quantitative patterns	• Other teams' data can be used when they follow similar data collection procedures

During this cycle the students also engaged in new forms of practice, particularly when planning and carrying out investigations. They continued to attend to the location, number, and repetition of measurements in their data collection plans, but they also began to include specific descriptions of how they intended to use the available tools to capture the crayfish at the creek. Students also privileged consistency across different teams' plans for observing the same variable because other teams' data could only be used if they followed similar data collection procedures. Thus it became important to clearly communicate data collection plans to each other. Furthermore, the way in which Mychel and Christine gathered their data on crayfish at the creek was driven for the first time by the details of their data collection plans. This included a new approach to catching the crayfish: scooping blindly in a chosen location and then seeing what organisms they found. In part because of this new approach, the students' written observations from include results of specific trials or samples and records of scoops of zero.

As they worked with data, the students continued to recognize that differences could be due to measurement error and natural variation and not just direct ecological causes. Most also began to look for specific forms of data patterns. Both Mychel and Larry consistently treated overlapping values and similar means as evidence of similar underlying processes and began to use patterns of covariation between variables to suggest relationships at the creek. In addition, at times the students also repurposed the same form of stories previously used to explain qualitative anecdotes to develop explanations of quantitative data patterns.

Development of Student's Ecological Knowledge and Practice Across the Study

When these focus students began this study, they held only a limited view of how the creek worked and the means by which they could study the ecosystem. However, over the course of four cycles of investigation the students changed the ways in which they thought about ecological relationships at the creek as well as the ways in which they investigated ecological questions (Table 9).

Table 9.
Development of student's ecological knowledge and practice

		Cycle 1 (Creek Visit)	Cycle 2 (Microcosms)	Cycle 3 (Creek Visit)	Cycle 4 (Creek Visit)
Knowledge	Understanding of Organisms. Physical Environment, and Water Chemistry	• Attention to the types and number of organisms, primarily crawdads, across undefined areas of the creek. • Delineation of different types of substrate (mossy, rocks) and their connection to the location of crawdads	• Observational focus on snail behavior • Plants/algae produce oxygen and food for snails and fish • Fertilizer supports growth of plants and algae • Expectation that organisms will exhibit natural variation in size	• Crayfish hide in vegetation (algae/bank) • Water depth, water speed, and DO might impact organisms and be related • Changes in water depth parallel changes in plants/substrate • Pollution might be killing fish	• Crayfish hide under rocks and in grass and eat plants • Crayfish, invertebrates, and fish use (dissolved) oxygen produced by plants and grass • Crayfish and invertebrates produce fertilizer/ nitrates • Water speed is slowed down by plants • Differences in substrate signal key differences in the creek
Practice	Asking Questions	• Initial focus on hypothesized animals in undefined areas • Shifts after visit at the creek to crawdads and patterns of incidence in relation to water speed and substrate	• Continued focus on the incidence of animals in different areas of the creek, including snails. • No integration of water chemistry	• How a feature, such as depth, changes across space (relationship to the bank) • Focus on relationships between organisms and characteristics of the physical environment and water chemistry	• Continued focus on relationships between organisms and characteristics of the physical environment and water chemistry
	Planning & Carrying Out Investigations	• Data collection not included in plans, and activity in the creek driven by what was visible rather than research questions • Written observations primarily a list of organisms.	• The existence and how to measure pH, hardness, phosphates, nitrates, and dissolved oxygen. • Expectation that measurements will vary	• Plans include attention to location and number of measurements • Observation of organisms driven by what was visible • Plans cooperatively improved • Written observations include counts	• Plans include attention to location, number of measurements, repetition, and means of using tools • Plans for the same variable need to be consistent • Observation driven by plans and "blind-scoops" used to make organisms visible • Written observations include specific trials and records of zero
	Analyzing Data & Constructing Explanations	• Stories used to develop explanations of anecdotal qualitative data • Attention to patterns within personal, team, and class experiences	• Differences can be due to measurement error and natural variation and not just direct ecological causes • Comparison of data from different jars/locations used to uncover relationships	• Reliability of individual data points questioned • Stories used to develop explanations of anecdotal qualitative data	• Differences can be due to measurement error and natural variation and not just direct ecological causes • Overlapping values and similar means suggest a similar underlying process • Patterns of covariation between sections can suggest relationships • Stories used to develop explanations of quantitative patterns
	Communicating Information	• Observation of other teams at the creek and in research meeting used to learn the type and number of organisms observed and ways to collect data.	• Experiences of others used to learn new measures and ideas about ecological relationships	• Tubs create collective moments of observation • Experiences of others used to make sense of own questions and findings • Research meetings used to critique methods and explanations	• Data produced by others can be used when they follow similar data collection procedures

At the start of the first cycle the students had only vague, and often wrong, predictions about what they might see at the creek. Consequently, during this cycle they paid particular attention to the types of animals that actually made the creek their home. The students were especially captivated by the vast number of crawdads, including large dead ones, that they found during their first creek visit. In preparing for this visit, the students had developed extremely vague data collection plans that treated counting organisms as an unproblematic endeavor. Once at the creek, the team did not attend to these plans and instead focused on organisms that were plentiful in their area rather than the organisms that they had asked questions about. In addition, the students' written data records did not include any counts but were limited to a list of organisms and two depth measurements. While at the creek the students began to delineate different types of substrate, such as mossy areas and rocky areas, in different areas of the creek, and some would later suggest that the substrate might be related to the distribution of organisms across the creek. In analyzing their data, the students primarily used stories to develop explanations of anecdotal qualitative data. However, some also began to take notice of patterns within personal, team, and class experiences. Many of these patterns emerged as a result of observing others at the creek and listening to team presentations during the class research meeting. Most of what the students communicated to each other in these settings centered on the type and number of organisms observed as well as the methods used to catch these organisms.

During the second cycle the students continued to focus on animals, but they also began to connect the animals to other visible and non-visible components of aquatic ecosystems. The students also used microcosms to learn about the existence of new factors in aquatic ecosystems (hardness, pH, nitrates, dissolved oxygen, and phosphates) and how to conduct water chemistry tests for these components. However, although the students continually referenced the importance of learning these new measures, they integrated only select portions of the class discussions of water chemistry into their explanations of aquatic ecosystems. In these explanations, the students primarily detailed how plants, algae, fish, and snails were interconnected through the food chain, oxygen cycle, and impact of fertilizer. The students' work with the microcosms also reinforced how they could use the experiences of others to learn about new measures, construct new ideas about ecological relationships, and draw generative comparisons across data from multiple sources. The activities in this cycle also supported students in coming to expect that measurements would vary and that these differences could be due to measurement error and natural variation and not just direct ecological causes.

During the third cycle the students focused on exploring specific ecological relationships at the creek that connected animal populations with the physical environment. The students attributed the saliency of attending to organism-environment relationships to their investigation of the aquatic microcosms the previous cycle. However, the students' ideas about the food chain, oxygen cycle, and fertilizer that had permeated their descriptions during that cycle did not re-emerge in their explanations of the creek. As the students designed their second creek investigation, they began to include more detail about the intended location and number of measurements in their data collection plans. However, as in the first visit to the creek the team's observational practice was driven by what was visible, and they would wait until they first visually identified an organism in the water before they tried to catch it in their net. The team also included more detail in their written data record of this visit and noted counts for each type of organism they found and the specific location of each depth measurement. When analyzing their data, the students continued to use stories to develop explanations of anecdotal qualitative data. However, some also began to view single measurements or observations more tentatively.

This suggested that they were beginning to question the reliability of individual data points and were potentially situated to begin to privilege data patterns. Students' means and purposes of communicating information also continued to develop as students began to treat the research meeting as a way to use what others had done make sense of their own questions and findings. In addition, the students began to critique the methods of data collection and validity of claims developed by other teams.

In the fourth cycle, students finally began to integrate their ideas about organisms, the physical environment, and the water chemistry when asking questions and describing relationships within the creek. Some of these relationships emerged from what students had noticed over time in the creek, and others seemed to be carried over from their microcosm investigations. Students even merged the two as they positioned the crayfish from the creek as functionally equivalent to the snails from the microcosm jars in their ecosystem explanations. However, students did not integrate any of the new relationships highlighted during the class analysis of the data from the last creek visit into their explanations of the creek. During this cycle the students also shifted the ways in which they planned and carried out investigations, and they began to include detailed descriptions of the location, number, repeated measures, and means by which they would collect their data. Students also privileged consistency across different teams' data collection plans, as data on the same variable could only be pooled if they followed similar data collection procedures. Furthermore, the way in the team gathered data at the creek was driven for the first time by the details of their data collection plans. This included a new approach to catching crayfish in which they scooped first and then saw what they found as well as more detailed written data record that, for the first time, included the results of specific trials and scoops of zero. These shifts in data collection were in response to the need to share data across teams that emerged from the more sophisticated questions students were asking about relationships at the creek. As they worked to analyze their data, the students continued to recognize that differences could be due to measurement error and natural variation and not just direct ecological causes. And most began to look for specific data patterns. However, only two consistently treated overlapping values and similar means as evidence of similar underlying processes in different data sets and began to use patterns of covariation between variables to suggest new relationships at the creek.

Discussion

Over the course of their investigations in the creek and in the classroom, this case study of four students changed their perception and understanding of ecological relationships as well as the ways in which they investigated ecological questions. Occasionally the group would move in sync, motivated by similar experiences and questions. At other times, individual interests and events, including designed moments to develop expertise, would increase the salience of an ecological feature or activity for a particular student.

The development of students' knowledge and practice seen in this study reflects that of the learning progression for ecology proposed by Lehrer and Schauble (2012). Students began with an initial focus on the organisms at the creek. As they developed expertise with an organism, in this case crawdads, they began to associate this organism with different observable features of the physical environment (e.g., substrate) and eventually partitioned the creek into different sections based on these features. At the same time, the students expanded their investigations beyond their focal organisms to also consider the relationships between these organisms, the visible features of the environment, and the invisible abiotic resources. In their later investigations, the students also began to coordinate ideas about variability in the way they designed their investigations and made sense of their measurements. This case study supports the structure of this learning progression and details, via close analysis of students' activity, ways to design for the emergence of these concepts and practice in tandem. It suggests that the forms of conceptual development proposed by the learning progression can be initiated and advanced by engaging students in increasingly refined and nuanced forms of scientific practice, such as asking questions about relationships, attending to measure, variability, and space when planning and conducting investigations, constructing explanations by looking for patterns in data, and treating communication as a means for collective transformation rather than static reports.

Supporting Student Learning through Structured Comparison

Throughout the students' investigations, moments of comparison seemed to create new opportunities for learning. These moments arose at the creek and in the classroom and occurred within and between teams as well as at the individual level. At the creek, students would compare different organisms within the same area, findings across different areas, how others were gathering data and using tools, and what other teams were finding nearby. These comparisons elicited new insights into the ecological relationships at the creek as well as productive forms of practice. Though the design of the student teams and their placement at the creek supported such comparisons, many also arose spontaneously between students and teams. In the classroom, the format of the research meeting created further opportunities for teams to bring their work into contact with others. Students noticed this, and by the research meeting in the third cycle they were approaching the research meetings looking to learn from what others had done. This finding echoes the work of Lehrer, Schauble, and Lucas (2008) who described how a similar research meeting format created sites of collective comparison for students. The importance of structured comparison was also emphasized in cycle 2 of this study by the breakdown of student learning in its absence. When working with only the water chemistry measurements from their own microcosm jar, the team struggled to make sense of their findings. In contrast, the next day when we compared findings across microcosms, the students were able to construct explanations for patterns in the data. This specific form of the practice of data analysis seems particularly salient for conducting ecological field investigations, both for the students in this study and for professional ecologists (Eberhardt & Thomas, 1991).

In designing this study, I specifically chose to emphasize spatial comparisons across the creek. The team presentations in the first cycle, planning prompts in the third cycle, and division of labor in the fourth cycle all fore-grounded the search for patterns across space. This culminated in the way in which students analyzed the data from the last creek visit. As students' practice evolved, the emphasize on spatial comparison enabled students to generate a meaningful data set that could be explored using methods of informal statistical inference. However, this importance of space was not imposed upon students. From their first visit to the creek, students were noticing differences between locations and using these differences to generate new questions and explanations about ecological relationships. Although the fieldwork of professional ecologists takes many forms, many professional studies echo these student investigations as they also seek to uncover patterns of covariation within differentiated space (Eberhardt & Thomas, 1991; Korfiatis & Tunnicliffe, 2012; Lefkaditou et al., 2014).

Balancing Student Development of Expertise and Exploration of Novelty

The students in this case study were strongly fixated on the animal life both at the creek and in their aquatic microcosm throughout their investigations. Animals dominated the questions that they asked, their data collection at the creek, their responses during research meetings, and their explanations of ecological relationships. At first, the students would describe this focus in general terms, saying that they wanted to find more about the animal's habitat or where most of them could be found. However, by the end of the investigations the students were also integrating specific abiotic features of the creek into their questions about and explanation of the animals.

Though the way in which students searched for animals during the first and second creek visits often paralleled the everyday actions of someone catching crawdads for fun, these experiences seemed to help students build a sense of place at the creek. This sense of place enabled them to suggest meaningful ways to partition the creek as well understand the design move to partition the creek as a class. It also helped the students identify features that might be important for understanding how crawdads were distributed across space at the creek, including the potential influence of unforeseen abiotic elements on this focus organism. Both of these are key components of ecological practice. In addition, the students' persistent interest in crawdads did not exclude a focus on other features of the creek. Rather, the students' questions about the distribution of crawdads and how crawdads meet their needs created a rationale to understand other elements of the ecosystem as well.

For this group, crawdads played a major role in their first creek investigation and continued to do so throughout the entire series of investigations. Multiple factors might have contributed to this persistence of interest. First, it may be that students integrate whatever they initially fixate on, whether it be crawdads or water speed, across future field investigations. Second, animals in general might present a stronger lure of student interest than the non-living aspects of an ecosystem. And third, the students' focus on crawdads might have persisted because of this organism's ubiquity across space and seeming prominence in this specific ecological system. With this single case, it is difficult to tease apart which of these factors (or combination thereof) best explain the team's persistent focus on crawdads. However, a better understanding of this phenomenon would prove useful for future designs.

As the students developed greater expertise with the crawdads, many also expressed an interest in investigating other factors at the creek. New observations and experiences often created a tension between wanting to continue to develop expertise and wanting to explore novel research directions. Novelty was also privileged in what students chose to share and ask questions about during research meetings, as difference seemed to draw students' attention more than similarity.

Both the development of expertise and the exploration of novelty have the potential to support students' ecological learning. Some level of expertise is vital because it often takes time to learn how to collect data about a specific variable in field settings. For example, during the second creek visit members of this team were still struggling to walk in the creek let alone use the tools to effectively collect data on the crawdad population. If students flit from interest to interest with each visit they might not be able to organize themselves and their tools in a way that could make their new variable of interest visible in the creek. However, novel pursuits can open up new ecological connections for students and could thus support their understanding of the broader system.

Limitations

Although this study was grounded in the collective experience of an entire class of students, it closely followed only one group of four students. This focus allowed the study to track the students in detail across the entire learning sequence and generate many conjectures about their development of knowledge and practice. Although it is likely that many other students within this class or participating in similar learning sequences would exhibit similar patterns of learning, the findings cannot be generalized beyond this case at this time. Furthermore, as with any ecological field study, much of what the students experienced was influenced by the particulars of this local environment at this specific time. Even students who study the same creek in future years, let alone students exploring different ecological systems, will be unlikely to experience the exact same phenomena. Something other than large dead crayfish will likely pique the initial interest of future students. However within this design, students were successfully able to move beyond local instances of phenomena and generalize across systems. For example, some of the students recruited their understanding of abiotic influences within the microcosm jar in subsequent investigations of the creek. They also applied what they had learned from working with the snail colony about differentiating differences due to measurement or natural forms of variability from those that suggest shifts in ecosystem functioning in their creek investigations.

Design Implications

This study revealed many ways in which the design of these investigations supported students' development of knowledge and practice. However, the findings also suggest directions in which to improve and expand on the design in future iterations. First, although the students began to develop a more sophisticated stance towards data analysis that did not treat every difference as an ecologically meaningful difference, a deeper statistical understanding of chance would likely bootstrap their early forays into inferential reasoning. Though students did view variation due to measurement error and forms of naturally occurring variation as inherently unpredictable, they still talked about them as being causal influences on their measurements. At the start of this school year, the teachers had originally planned for their classes to complete a parallel exploration of data modeling and chance in their mathematics class. However, testing pressures forced them to abandon these plans. In future studies it would be interesting to see to what extent more structured statistical explorations of chance could support students in making sense of comparative data.

Second, although the students' exploration of snail shell thickness proved useful for grounding an initial discussion of different sources of variation in natural systems, there are many ways in which to refine the design of this learning activity. If teams measured the snails without replacement, this would allow sample-to-sample variability to be more accurately addressed. In addition, the discussion could be restructured to explore the amount of variation expected from each source. Students could explore whether the difference in measurement between two snails was likely influenced more by natural variation then measurement error and develop predictions for the likely range produced by each form of variation. Finally, since the snails so intrigued the students that they wanted to restructure their creek investigations around them (even though the snails were from a different ecosystem), the reasons why the students are looking at snails and how they can apply this investigation to an ecosystem without snails need to be more explicitly threaded throughout class discussions.

Third, as the research meetings proved so generative for students during the creek investigations in cycles 1 and 3, it may prove useful to include a similar meeting about the last creek visit during cycle 4. Although we had considered including a research meeting as part of fourth cycle of this study, the storm delay seriously impeded our available class time, and we had to compress our plans for data analysis. This eliminated the possibility of having teams present their individual findings before formally looking for patterns across the teams' data.

Finally, because time is always a limiting factor in school-based scientific investigation, it might be beneficial to further restrict the scope of variables that students explore both in the creek and in their microcosm jars. This might create time for students to go deeper into a few key ecological processes, such as the carbon/oxygen and nitrogen cycle, rather than skimming a broader range of more tangential elements. Specific decisions of what to privilege would likely be dependent on the field site selected for students to study. Another way to meaningfully bound the scope of what students were managing in the field would be to design the learning sequence so that the cycles of investigation are closer together. In this study, we went to the creek in November, March, and May. Consequently, some of the organisms that students observed during one month were absent when they wanted to focus them in later studies. Many students qualitatively made note of these differences, but because they could not go back in time to collect more detailed data they were unable to quantitatively explore these seasonal patterns. Spacing the creek visits, particularly for cycle 3 and 4, closer together would decrease the seasonal variations that students would experience in the ecosystem. Although it is important that students learn about temporal changes in ecosystems, when students' practice is drastically changing from creek visit to creek visit as in this design, temporal comparisons across multiple visits generate data sets complicated by changes in students' observational practice. In contrast, the spatial comparisons highlighted in the design of this study generate data sets situated in more stable moments of practice.

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