Teaching the Systems Aspects of Epistemologically Authentic Experimentation in Ecosystems through Immersive Virtual Worlds

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ABSTRACT

Helping students to learn epistemologically authentic forms of experimentation is an important goal for ecosystems science education. Ecosystem scientists have developed forms of experimentation that offer insight into the behavior of systems dynamics and that honor the systems nature of the concepts. These forms of experimentation and the broader assumptions that surround them represent shifts in thinking about the nature of systems and of experimentation. However, teaching them in the classroom in ways that do not reduce their systematic aspects is difficult, particularly in that these systems dynamics play out over expansive spatial and extended temporal scales that students typically struggle with. Experimentation plays a critical role in helping scientists move from analyzing patterns and drawing inferences from those patterns to analyzing causality. Immersive virtual learning environments may play a role in enhancing the presence of these concepts in the classroom. EcoXPT is an inquiry-oriented middle school curriculum designed to leverage the forms of epistemologically authentic experimentation that ecosystems scientists engage in towards teaching students about the complex causal dynamics of ecological systems and how scientists come to understand them. This paper presents the theoretical importance of the forms of experimentation that EcoXPT offers and considers both the affordances and limitations of doing so in an immersive, computer-simulated world.

BACKGROUND

Experimentation in science class is often taught in connection with physics and chemistry and less often in the context of biology. Experimentation is important to enhancing student understanding in science (Duit & Treagust, 1998; McElhaney & Linn, 2011; Rea-Ramirez, 2008), so it is important to consider how it contributes to ecosystems science learning. While experimentation is included in the Next Generation Science Standards (NGSS) middle grades life science standards for ecosystem science (Achieve, 2013), teachers tend to be more familiar with techniques related to observation than experimentation in ecosystem science. Part of the challenge is in the systems aspects; teaching experimentation in the context of complex systems in ways that honor that complexity, particularly in the classroom, is quite difficult. One of the few experiments in extant ecosystems science curriculum is one that many middle school teachers know well—the "Bottle Biology" (Wisconsin Fast Plants Program, 2003) experiment simulating a microcosm of an ecosystem and testing conditions that lead to the health of a small fish.

Modes of Investigation in the Ecosystems Sciences

The ecological sciences offer a particularly rich domain to analyze in terms of complex causal and systems effects (Tilman 1989). However, the ecosystem sciences also offer particular challenges in bringing investigation to bear on students' learning. Often causality in the natural world does not offer the opportunity for intervention. Hurricanes and earthquakes happen, events play out on a scale that one cannot and would not want to manipulate, and global experiments on an "n of one planet Earth" do not enable a control.

Experimentation in ecosystems is challenging, and yet ecosystem scientists have developed forms of experimentation that offer insight into the behavior of systems dynamics and that honor the systems nature of the concepts (e.g. Weathers, Strayer & Likens, 2012). The above challenges have led to the development, within the field of ecology, of a deep relationship between experimentation, modeling or theory, and observational approaches (like comparison and documenting changes over time) (Pace & Groffman 1998). Strong ecological inference most often relies on accumulation of evidence gathered using multiple approaches (Pickett et al. 1994), and this integrative epistemology distinguishes modern ecological science from other scientific domains that rely on stringent control within laboratory settings or on the notion of isolating the effects of single variables.

Given the scope and speed of global environmental change, ecosystem scientists are increasingly engaging in experiments that strive to replicate and assess the effects of large scale changes in environmental parameters (Brown et al. 2001, Osmond et al. 2004, Knapp et al. 2012). Such large-scale in situ experimental designs highlight the need to consider the contextual complexity inherent in implementing an ecosystem experiment and in interpreting the results of the intervention. Interpretation of results from ecological field experiments can be difficult due to transient dynamics, indirect or feedback effects, environmental variability, and multiple stable states or site history (Tilman 1989). These challenges may be met by conducting experiments over multiple scales (Hairston 1989, Carpenter 1996, Knapp 2012), taking advantage of "natural" experiments (Turner et al. 2003), and monitoring a system for a long period of time following experimental manipulation (Brown et al. 1986, Silvertown et al. 2006, Knapp 2012).

Shifts in Epistemic Assumptions

These forms of experimentation and the broader epistemological assumptions that surround them represent a shift in thinking that invites consideration of the nature of systems and the nature of experimentation. This shift requires:

- Considering perturbations over time rather than solely focusing on events
- Recognizing a broad spatial scale that extends well beyond a test tube
- Focusing on interactions in contrast to attempting to isolate single variables

Considering perturbations over time is important to understanding the history, patterns, and behavior of an ecosystem. It requires attention in a prolonged sense in addition to single events and includes interactions between fast and slow variables. The legacy of what happened includes past disturbances, delays, and extended time scales (e.g. Carpenter & Turner, 2001). It requires a shift towards realizing that processes and steady states are essential aspects of the behavior of the system.

This realization is in direct contrast to how human cognitive architecture works for how we attend. Human perception requires constant filtering of information in order to manage the vast amount of stimuli that comes out way. We necessarily limit the information coming in and in order to gain attentional capture, information needs to rise above the threshold of what we consider normative (Mack & Rock, 1998). This leads us to stop attending to the status quo and to focus instead on events that rise above it. Chi (1997) found that learners need to make an ontological shift towards focusing on processes and steady states rather than events. This event-based reasoning is problematic when considering ecosystems dynamics (Grotzer, Kamarainen, Tutwiler, Metcalf & Dede, 2013). We tend to lose sight of the on-going processes and steady states and to ask "What happened?" instead of "What is going on?"

Situating causal dynamics within a broader spatial scale is often critical to constructing the causal story of what is going on. Where one draws the parameters of an ecosystem often dictates the influences that often considers. Yet, the drivers of ecosystems outcomes can often be distant from the outcomes that grab our attention. These distant drivers can easily fly under the radar and escape attention. Ecosystems dynamics often involve vast spatial scales. For instance, the Delaware River Watershed spreads across five states. These vast spatial scales introduce relevant variables that interact with the ecosystems dynamics more local to our attention.

Similarly to how we focus on events, we tend to prune the spatial scales that we attend to. Our attention is often to what is most obvious to us, what we can notice around us. Grotzer and Solis (2015) considered the concept of "action at an attentional distance," the understanding that causes and effects can be separated in both physical and attentional space. They found that, when asked to reason about the causal dynamics within an environmental scenario, second, fourth and sixth graders tended to reason locally and ignored the possibility of distant drivers. However, they also found that when children had the supporting mechanism knowledge, they were able to reason about action at an attentional distance.

Attending to interactions and patterns of interaction is an important element of ecosystems science reasoning. Even in instances in which scientists conduct lab studies, they attend to how the variables interact and to setting up microcosms that include the essential variables. This is understood in medicine; how a drug behaves in the laboratory can be quite different from how it behaves in everyday life given the many potential interacting factors. However, attending to interactions is an aspect of scientific reasoning that can be lost in the common focus on isolating and controlling for single variables in the science classroom. An important tension exists between trying to understand how the underlying mechanisms behave and understanding how the underlying mechanisms behave when they are in interaction.

The Critical Role of Intervention in Moving From Seeking Patterns to Analyzing Causality

Students can learn much about complex causality, inquiry, and ecosystems science from a purely observational immersive simulation as we have found with our work on

EcoMUVE (Grotzer et al., 2013; Metcalf et al., 2013), yet constructing coherent understanding about the patterns of causation within the system requires deeper exploration of causal mechanisms. Research in causal learning has focused on the role of co-variation between causes and effects (e.g. Bullock 1985; Bullock, Gelman, & Baillargeon 1982; Shultz 1982; Shultz & Mendelson 1975; Siegler 1976; Siegler & Liebert 1974), accounts of mechanism in generating causal inferences (e.g. Bullock, Gelman, & Baillargeon 1982; Schultz 1982; Carey & Spelke 1994), and the influence of spatial and temporal proximity on those judgments (Michotte 1963; Bullock et al 1982; Shultz 1982; Kushnir & Gopnik 2007). More recently, those who study the nature of science and causal inference have argued that intervention is critical to drawing causal conclusions (e.g. Gopnik et al., 2004; Pearl, 2000).

A prevailing model of how humans engage in causal reasoning is a Causal Bayes Net (CBN) Model (e.g,. Glymour 2001; Gopnik & Schulz 2007), which involves summing across multiple causal instances to infer causality despite probabilistic inputs. But simple induction is not enough and can easily lead to confusing correlation with causation, particularly in cases when a plausible causal mechanism can be discerned. Therefore, a critical component in CBN models is the ability to intervene and to act empirically on variables to be able to assess their causal potency (Gopnik & Schultz 2004; Gopnik et al 2004; Lagnado & Sloman 2003; Steyvers, Tenebaum, Wagenmakers, & Blum 2003). CBN models argue that, while one can glean information about potential causal strength from co-variation, it is the ability to screen off variables and assess the outcomes that allows developing an understanding of causal structure to realize a fully causal account.

This cognitive process of distinguishing between correlation and causation is formalized in various aspects of scientific investigation, including modeling, statistical analysis and experimental design. Strong inference relies on the synthesis of multiple forms of evidence from complementary scientific approaches; and experimentation is one of the most powerful inferential tools a scientist can use in teasing apart causal relationships in a complex system. In order to elucidate causal relationships, scientists design experiments that are randomized, replicated, controlled, and conducted at an appropriate temporal and spatial scale for the hypothesis being tested (Tilman 1989, Carpenter 1996, Knapp et al. 2012).

Science instruction aims to provide learning experiences that align with authentic scientific practices and promote the development of scientific literacy that acknowledges the complexity inherent in current science research. However, even by using biological organisms or field trips, it is impossible to represent the power or process of comprehensive ecological experiments within the classroom, due to issues such as short time frames for experimentation, the cost of these resources, and limited access to experimental systems. Experimentation within a domain may be oversimplified by regarding it as extremely domain-general or domain specific (Schauble 1996). In contrast, immersive simulated virtual environments provide a unique opportunity for students to interact with ecosystem components in an experimental manner and to conduct authentic scientific experimentation in a realistic, but virtual setting. Offering students opportunities to investigate knowledge rich contexts enables them to discover the nuances and complexity within that domain as well as patterns that generalize beyond that domain (Berland & Reiser 2010). Context rich problems are important in helping students to develop approaches to inquiry that map closely to what scientists actually do, the theory rich contexts that they focus on (Koslowski, 1996), and how an investigation develops and changes over time (Sandoval & Reiser, 2003; Berland & Reiser, 2010).

Helping students to learn epistemologically authentic forms of experimentation should be an important goal for ecosystems science education and for helping the next generation to understand the dynamics of Earth's environmental systems. However, teaching these forms of experimentation in the classroom in ways that do not reduce their systematic aspects is difficult, particularly in that these systems dynamics play out over expansive spatial scales and extended temporal scales. Students typically struggle with systems relationships (e.g. Assaraf & Orion, 2005; Grotzer & Basca, 2003; Green 1997; Hmelo-Silver et al. 2007) and these concepts of scale are particularly difficult (Dodick & Orion, 2003).

Teaching Epistemologically Authentic Experimentation through Immersive Learning

Immersive virtual learning environments may play a role in enhancing the presence of these concepts in the classroom. Research shows that it can support learning of science concepts by situating the students' investigations in realistic, immersive contexts (e.g. Collela, 2000; Ketelhut et al, 2010; Metcalf et al., 2013). By offering simulated expansive spatial and extended temporal scales and by including important aspects of the dynamic complexity of ecosystems, students can begin to learn how experimentation in ecosystems attends to these factors and honors rather than reduces complexity. They can use multiple sources of evidence, including observations and data collected in the virtual world, to build hypotheses about the particular ecosystem scenario.

EcoXPT is an inquiry-based middle school curriculum on ecosystem science that is based in an immersive virtual environment. It was designed to leverage the forms of epistemologically authentic experimentation that ecosystems scientists engage in towards teaching students about the complex causal dynamics of ecological systems and how scientists come to understand them. It represents a significant revision of an earlier immersive world called EcoMUVE in which students and investigates a problem about why all of the large fish in a virtual pond have died (See Fig. 1). As in EcoMUVE, students collect environmental and population data over time, but in EcoXPT, they also conduct a variety of experiments in the virtual ecosystem as aligned with versions of those that ecosystems scientists employ. Students work in teams to construct hypotheses, supporting their arguments with data and experimental results. Two experimental tools within EcoXPT include mesocosms and tracers.

Mesocosms consist of outdoor experimental systems for examining natural environments under controlled conditions. Often conducted in a series of pools, they are situated in the outdoor environmental contexts, but through having multiple pools, they allow scientists to adjust the variables in each and to draw comparisons between the pools. The comparisons offer insight into possible mechanisms that might be operating within each system. Scientists qualify the results of these types of experiments with knowledge of the limits that they involve, for instance that the depth of the water is different than in a real pond or that the macro-level interactions are limited. Even in cases where scientists situate mesocosms in lakes simulating the depth, as in the Stechlin LakeLab experiments[1], they recognize the limits of long columns of water. In EcoXPT, students configure one to four pools with experimental factors, collect measurements, and assess their outcomes. Eventually, they may discover that a pool with algae has higher dissolved oxygen than one without algae (See Fig. 2).

Tracers offer a means for ecosystems scientists to understand the movement of matter within the broader spatial lay-out and topology of an ecosystem. This is especially important to understanding the movement of chemicals within a watershed. They provide the opportunity to understand how substances may move through parts of the ecosystem in non-obvious and non-visible ways. They also offer the opportunity to test for multiple and distributed sources that may contribute to outcomes in an ecosystem. For instance, it may be difficult to notice the contribution of distributed sources that each are below a certain threshold, but that converge to have a noticeable impact on the environment. In EcoXPT, students may use chemical markers to show the movement of matter in the environment. For instance, by adding tracers to bags of fertilizers lets students test how the spatial layout and topography affect fertilizer runoff when it rains (See Fig. 3).

Associated Thinking Moves

In order to learn the thinking inherent in moving from seeking patterns to analyzing causality, we have introduced accompanying Thinking Moves with the experimental tools. These thinking moves are designed to help students understand the kinds of questions that ecosystems scientists might as they explore the potential causal dynamics of an ecosystem. (See Appendix A.)

Deep Seeing encourages students to consider the natural history of the ecosystem and to engage in careful observation of what is there. It asks them to look while being careful to set their assumptions aside.

Evidence Seeking encourages students to collect evidence from multiple sources, to seek corroborating evidence, and to evaluate the sources of their evidence.

Pattern Seeking encourages students to notice patterns in the on-going processes and steady states of the system and to notice how certain variables change together or not.

Analyzing Causality asks students to use experimental evidence and intervention to try to impact change in the patterns in an effort to discern the underlying mechanisms at work.

[1] http://www.lake-lab.de/index.php/concept.html

Constructing Explanations encourages students to develop the best "story" or explanation that they can from the available evidence. It asks students to look for gaps in their explanation ad to assess their explanations against rival explanations.

Accompanying thinking moves include *Time Traveling* which encourages students to think backwards and forwards in time and to move beyond event-based reasoning as they explore the changes over time in an ecosystem. Students are also encouraged to use *Virtual Binoculars* to see beyond what is currently in their attentional space and to consider what may be distant and thus non-salient to them.

NEXT STEPS AND CONCLUSIONS

We are currently in the process of conducting formal classroom studies of EcoXPT and the impact of introducing epistemologically authentic experimentation into ecosystems science learning through an immersive, virtual simulation. A pilot study conducted in the Spring of 2016 suggests some positive outcomes. Following pre- and post-testing, students participated in a 2.5 week curriculum based upon the EcoXPT immersive world. Content knowledge was assessed using a previously validated ecosystems-science instrument. Seventh grade students ($n = 189$) nested within 4 teachers in one school system in the Northeast participated. Students showed statistically significant gains from pre- to post- ($t = 9.5045(188)$, $p < 0.001$), scoring, on average, 1.5 points higher on the post-test than on the pre-test, a medium effect size of 0.5 standard deviation units. No teacher-level effects were detected via multiple regression, thus the findings held across teacher.

Understanding the methodologies of ecosystems science and how they link to insights about the dynamics of the world around us are important understandings for the next generation. The NGSS call for developing these understandings, however, the resources available to teachers to do so are limited and the challenges are great. This work draws upon the practices of ecosystems scientists to develop a vision for forms of experimentation in ecosystem science that students might learn and shares how these are represented in EcoXPT in ways that honor the systems aspects of ecosystems. Further study will illuminate how these practices impact student learning of ecosystems despite the limitations of the classroom.

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For more information, visit: http://ecolearn.gse.harvard.edu

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FIGURES

Figure 1: EcoXPT virtual pond

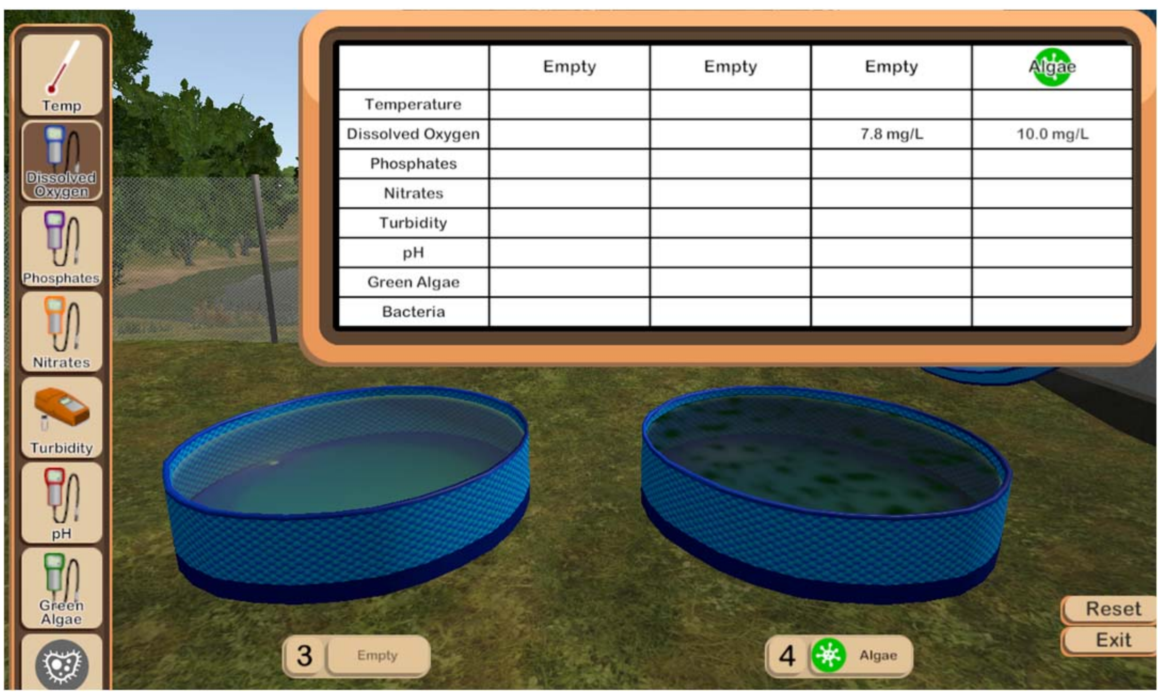

Figure 2: Mesocosm tool

Figure 3: Tracer tool

APPENDIX A

Thinking Moves Scientists Use	Try this:	Ask:
Deep Seeing *Scientists look deeply to understand an ecosystem.* They do their best to see what is really there. They use their past experience as a guide about what to expect but are careful not to make assumptions. They try to notice things that are unusual or different from what normally happens.	-Look closely -Look small and big. Attend to both the microscopic and macroscopic world. -Look for what is out of the ordinary -Look for what is hard to notice -Look for longer than you normally would. -Look for subtle things in thinking about what is known and what may be unusual. -Compare to the usual physical, biological, and chemical aspects of the ecosystem. -Keep your mind open. Try not to make assumptions.	-What do I see? -Are there any assumptions that I am making that prevent me from seeing what is really there? (Ex: If I think leaves are only green, I may miss the other colors.) -What is already known about the ecosystem and the regular patterns that happen over time? -Is there anything that is surprising? - What do I notice when I engage in deep seeing in the ecosystem at different times? Are there any patterns that seem to be constant? Do I see any subtle changes?
Evidence Seeking *Scientists seek evidence to support their claims.* They integrate evidence from multiple sources in order to develop well-supported arguments. They keep an open mind and look for evidence that supports and evidence that is against their claim.	-Support your claims with evidence. -Evaluate others' claims against evidence. -Look for evidence *for* and *against* a claim. -Support your claim with different types of information. -Give your reasoning for a claim using evidence and logic (instead of just saying that it is so). -Try not to jump to conclusions. (Instead, think about what *might* be so and what evidence may support it.)	-Have I collected evidence from multiple and varied sources to support my claim? -Have I looked for confirming and disconfirming evidence for my claim? -Have I looked for patterns or relationships related to the claim? -Was there anything that I missed the first time in my explorations that going back in time helped me to see?
Pattern Seeking *Scientists study patterns to understand the connections in a system.* They look for patterns to notice relationships between different parts of a system. (For ex. one population might go up while another goes down or both might go up at the same time.)	-Look for patterns as evidence for what *might* be going on. -Don't jump to conclusions about what patterns mean. -Keep your mind open to other possibilities, even if you think you know the reason for a pattern, -Check out patterns across time and over space. -When you see something unusual, time travel to look before it and after it to see if there is a pattern. Use Virtual Binoculars to look near and far from it. -Look for patterns in things you see in the world, in	-Do I notice anything that seems to change a little bit each day? …or that seems to change back and forth? …or some other pattern? -When I look at the numbers of the populations of different organisms, what patterns do I see? -Do I see patterns where both lines of the graph move up together or right after one another? …or move down together or right after one another? Are there patterns in the lines of the graphs where one thing goes up as another goes down?

They pay attention to the short-term (what "just happened") but are careful to think about it in the longer term (what has been going on).	numbers, and in graphs. -Notice events that tell that something changed, BUT also notice what has been going on before and after the event. -Compare to what is known about the ecosystem in terms of its regular patterns—this is part of its natural history. -Consider how the scale of time that you pay attention to (days, months, years) impacts what you understand about the patterns in the system.	-Do I see any patterns across the terrain/space? …when I look near? …when I look far? -Do I see any patterns over time?
<u>Analyzing Causality</u> *Scientists find ways to intervene on a pattern to see if it changes the outcome.* They conduct a variety of experiments to help them to understand what causes what. Experimenting within the environment is important because it tells how certain factors interact with others.	-Figure out if relationships are causal or just correlational. -Do an experiment to see what it causes to happen. -Try changing just one thing at a time to see what happens. -If you think that more than one thing is responsible for the outcome, test them together. -Consider multiple causes. Don't assume that one cause is responsible for an outcome. -Consider whether it is important to test at different scales to understand what is going on.	-Have I tried to impact the pattern by intervening on it? …doing an experiment to test the claim? -Have I tried to isolate the factors so that I know how they individually contribute to what happens? -Have I considered how factors may interact to lead to the outcome? -Have I thought about how the details of the surrounding environment might interact with what happens?
<u>Constructing Explanations</u> *Scientists try to develop explanations that account for as much of the evidence as possible.* They try to explain the patterns. They try to tell what causes the things that happened and how. They check carefully to make sure that there are no gaps (unexplained connections) in their explanation.	-Make sure there is evidence for each part of your explanation. -Even after you have a possible explanation, consider other possible explanations with an open mind. -Tell your explanation to someone else and have them ask questions about it to help you find gaps. -If you like a certain explanation, work extra hard to notice other possibilities to help your brain consider them openly.	-Have I tried to connect my evidence into a story of what happened? -Have I made sure that there is evidence for all of the connections or links in my story? -Have I considered whether there are other plausible stories and considered them as rival explanations? -Have I tried to make a causal link for each of the connections in my explanation?