Three-Dimensional, Problem-Based Instruction in Middle School: Do students Need to Get Down and Dirty to Learn Ecology?

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Abstract

This study analyzes 143 6th-grade students' open-ended responses prior to and following their participation in a three-dimensional, problem-based ecology curriculum unit. By the end of the unit, students were more likely to make accurate claims about the direct ($p = 0.003$) and indirect effects ($p = 0.000$) of a decrease in size of a top predator population. In addition, on a near-transfer assessment question, students were more likely to articulate long-term effects and feedback loops that reflected systems reasoning on the post-test as compared to the pre-test ($p = 0.015$). Students were also more likely to make comparisons between graphs on the post-test than pre-test ($p = 0.000$). There was evidence of far-transfer learning in regards to the mediating effect of food abundance on a predator population, but not in regards to the influence of an abiotic factor on populations. In light of these findings, ecology learning progressions may need to be more fine-grained to distinguish between students' ability to identify and reason about specific cause and effect relationships in ecosystems. The findings also suggest three-dimensional problem-based learning provides an effective alternative to field-based ecology curriculum in K-12 classrooms.

Introduction

Ecology is an important area of study starting in elementary school for a variety of reasons. Ecological study contributes to the development of systems reasoning skills and conceptual understanding of environmental energy flow, positive and negative feedback cycles, evolutionary change, and interconnectedness (Furtak, 2012; Gotwals & Songer 2013; Hokayem & Gotwals, 2016; Ruth, 1993). When students understand key concepts in ecology they understand how changes in abiotic and biotic factors affect multiple ecosystem components (Gotwals & Songer, 2013; NGSS Lead States, 2013). In addition, ecology provides students an opportunity to develop systems reasoning skills that are useful in domains outside of ecology and science (Wilensky & Resnick, 1999). For example, system reasoning is utilized when considering how individual behavior will directly and indirectly affect other people's behavior, environmental health, and the economy (Byrne, 2016).

Given the importance of ecology-related concepts and skills for subsequent learning, there is a real need to identify effective ecology-based curricula. Many ecology-related interventions have involved hands-on, field-based experiences for students (e.g., Alexander, 1982; Baumgartner & Zabin, 2008; DiEnno & Hilton, 2005). Field-based curricula may better support learning gains as compared to a traditional lecture-based environment (e.g., DiEnno & Hilton 2005). However, field-based curricula are often difficult to broadly implement due to school location and instructional time constraints. Therefore, there is a need for student-centered ecology-related curriculum that is practical and easy to implement without requiring extensive outdoor experiences. The need is particularly notable at the middle school level where ecology misconceptions are prevalent and systems reasoning skills are difficult to foster (Evagorou, Korfiatis, Nicolaou, & Constantinou, 2009; Gotwals & Songer, 2010; Hogan, 2000).

More students now have the opportunity to begin learning ecological concepts at an early age, particularly in states that have adopted the Next Generation Science Standards (NGSS, National Research Council [NRC], 2012; NGSS Lead States, 2013). The NGSS begin to address concepts associated with interdependent relationships in ecosystems in the second grade. The NGSS emphasize the importance of learning science concepts ('disciplinary core ideas' or DCIs) within the context of 'science and engineering practices' (SEPs) and 'crosscutting concepts' (CCCs). For example, curricula that provide students the opportunity to *analyze and interpret data* and *construct explanations* can support a progression of ecology-related learning that fosters conceptual understanding as well as greater proficiency in key science practices (Gotwals & Songer, 2013). *Patterns* and *cause and effect* are two CCCs especially germane to ecology-related instruction as they underlie systems reasoning skills (Hovardas, 2016). It is important to implement curriculum that supports growth in all three dimensions since students' ability to recognize patterns and reason about systems is dependent upon content knowledge (Jacobson & Wilensky, 2006).

Problem-based learning (PBL) has been shown to be an effective pedagogical strategy in science education (Akinoğlu & Tandoğan, 2007; Hmelo-Silver, 2004). PBL lends itself to three-dimensional ecology-based instruction since it engages students in authentic scientific work that undergirds the SEPs. In addition, PBL can help students identify pertinent CCCs since units tend to extend over several class periods and integrate multiple concepts (Akinoğlu & Tandoğan, 2007; Baumgartner & Zabin, 2008; Hmelo-Silver, 2004). In the present study, we examined the extent a three-dimensional, problem-based ecology curriculum supports student learning within all three dimensions without additional field experience.

Literature Review

Students who understand ecology grasp not only on core ideas, more traditionally known as science concepts, but also relevant scientific practices and CCCs (NRC, 2012). Although all of the NGSS SEPs and CCCs are germane to ecology-related learning, the present study focused on two SEPs (*analyzing and interpreting data* and *constructing explanations*) and two CCCs (*patterns* and *cause and effect*) which are both components of the NGSS Middle School (MS) Life Science (LS) 2-1 Performance Expectation (PE). We also focus on DCIs associated with this PE, which include the ideas that (a) organisms and populations depend on biotic and abiotic factors in their environment; (b) the growth of organisms and populations is limited by access to resources; and (c) predators may reduce the number of organisms. In our review of the literature we examine what is known about student learning and understanding of these DCIs in the context of food chains and webs, and the two SEPs and CCCs relevant to this study. In addition, we review the literature on PBL and demonstrate how it naturally lends itself to three-dimensional learning outlined by the NGSS.

Disciplinary Core Ideas

Much of the K-12 ecology-related research has focused on student understanding of species interactions in the context of food webs that include predator-prey interactions (e.g., Alexander, 1982; Griffiths & Grant,

1985; Gallegos, Jerezano, & Flores, 1994; Gotwals & Songer, 2010; Hogan, 2000). Early research unearthed several common misconceptions (e.g., Alexander, 1982; Gallegos et al., 1994; Griffiths & Grant, 1985). For example, elementary and middle school students often classify organisms as herbivores or carnivores based upon the organisms' size and perceived ferocity rather than actual feeding behavior (Gallegos et al., 1994). This proclivity to misclassify small or seemingly passive organisms as herbivores can make it difficult for students to correctly interpret food webs or make predictions about ecosystem changes (Gallegos et al., 1994). In their study with 200 10th-graders, Griffiths & Grant (1985) found that up to 16% of students believed a change in one population would not affect other populations unless it was directly related as predator or prey. In addition, 6% of the students believed a change in the size of a prey population would not affect the predator population. Such misconceptions can be difficult to overcome and may be amplified when assessment questions include unfamiliar contexts and organisms (Gotwals & Songer, 2010; Hogan, 2000). Recent efforts to identify a learning progression for student understanding of ecology-related concepts has not yielded straightforward results (Gotwals & Songer, 2010; Hokayem & Gotwals, 2016). This is largely due to the fact that ecology concepts are intertwined with two crosscutting concepts; *cause-effect* relationships and *patterns* across ecosystems.

Crosscutting Concepts

Within ecological systems, *cause and effect* relationships abound (NGSS Lead States, 2013). These relationships may be within or between biotic and abiotic factors. As described above, a lot of research that has examined K-12 ecological learning has examined students' understandings about food-related energy transfer in ecosystems (e.g., Gallegos et al., 1994; Griffiths & Grant, 1985; Gotwals & Songer, 2010; Hogan, 2000). *Cause and effect* relationships within a trophic context can be simplified by only considering a single chain, or made more complex by considering a larger web of feeding relationships. When the larger context, or system, is considered, the stepwise consideration of *cause-effect* relationships supports systems reasoning (Jacobsen & Wilensky, 2006; Hokayem, 2016). The ultimate goal of ecology education is to enable students to identify complex and indirect effects when one component of an ecosystem changes and to engage in systems reasoning (Byrne, 2016). Unfortunately, students have difficulty identifying indirect cause effect relationships and to reason about an entire system (Evagorou et al., 2009; Griffiths & Grant, 1985; Hogan, 2000; Wilensky & Resnick, 1999). In addition, efforts to identify a learning progression for ecology-related systems reasoning has not identified a clear trajectory to inform curricular scaffolds and interventions (Hokayem & Gotwals, 2016). Furthermore, even when students develop a greater ability to reason about a single system, they have trouble transferring their reasoning skills to new contexts (Gotwals & Songer, 2010; Hovardes, 2016). This suggests students do not readily recognize *patterns* in *cause and effect* relationships across multiple ecological systems.

Science Practices

The science practices *analyzing data* and *constructing explanations* are crucial to the field of ecology. Ecologists regularly need to construct explanations for observed phenomena based upon data. Although separate practices, *analyzing data* and *constructing explanations* are often complementary because the

meaning identified in data through analysis is used to develop, support, and complement explanations (Roth et al., 1999). Ecologists often relay their data, and accompanying explanations, in the form of inscriptions (e.g., graphs, tables) accompanied by complementary text (Roth, Bowen & McGinn, 1999). While scientific explanations describe causal mechanisms for phenomena by providing the *how* or *why* a phenomenon happened (Lombrozo, 2006; NRC, 2012; Zangori & Forbes, 2014), data analysis reveals *what* happened (NRC, 2012; Zangori & Forbes, 2014).

Analyzing data presented in well-constructed graphs should be an integral component of any ecology curriculum (Roth et al, 1999). Graphs allow ecologists to display data and convey patterns (Roth et al, 1999). Therefore, as three-dimensional standards and curricula seek to engage students in authentic scientific work, data analysis through graph interpretation is essential. Unfortunately, research demonstrates students have difficulty interpreting graphs in ecology as well as in other science disciplines (Mokros & Tinker, 1987; Shah & Hoeffner, 2002). However, a curriculum that incorporates graphs within instructional contexts wherein students are asking scientifically oriented questions, collecting data, constructing explanations, and using graphs to convey or devise meaning can foster greater graph interpretation skills (Roth & Bowen, 1994; Shah & Hoeffner, 2002; Wu & Krajcik, 2006).

Although children construct explanations at a very early age as they naturally seek to identify *why* or *how* something has happened, explanations developed from incomplete prior knowledge may impede learning (Hickling & Wellman, 2001; Lombrozo, 2006). Thus, science education should provide students with opportunities to develop sound conceptual knowledge that can be used when constructing explanations (Lombrozo, 2006). Furthermore, the act of constructing explanations supports conceptual understanding and transfer of learning to new contexts (Aleven & Koedinger, 2002; Ryoo & Linn, 2014; Rittle-Johnson, 2006). Therefore, constructing explanations and conceptual knowledge development are intricately intertwined in science education (Aleven & Koedinger, 2002; Lombrozo, 2006; Ryoo & Linn, 2014). Unfortunately, science teachers are often unaware of the value of explanation construction in knowledge development and therefore do not provide many opportunities for students to engage in this practice (Zangori, Forbes, & Biggers, 2013; Zangori & Forbes, 2014).

Approaches to Ecology Education

As a result of student difficulties in ecology, there have been efforts over the last few decades to implement exciting, hands-on curricula that might lead to greater student engagement and learning (e.g., Alexander, 1982; Baumgartner & Zabin, 2008). In particular, most associated studies have looked at the effects of curricula or educational experiences that engage students in collecting data in outdoor settings. For example, Alexander (1982) supported students' understanding of saltmarsh food webs through specimen collection and subsequent stomach content analysis. In another study, 9th-grade students spent a semester engaging in fieldwork to document and understand intertidal biodiversity (Baumgartner & Zabin, 2008).

In a rare comparison study, DiEnno & Hilton (2005) examined learning outcomes between two groups of high school students learned about invasive plants and their effects on the ecosystem. The treatment (18 students) worked daily in collaborative groups conducting investigations on a nature preserve while the control (18 students) learned the material through traditional lecture. The treatment group had higher learning gains than the control group suggesting fieldwork increases ecology related learning (DiEnno & Hilton, 2005). These curricula are exciting, but fieldwork is often difficult to broadly implement due to school location and instructional time constraints.

In contrast to field-based instruction, PBL is a pedagogical strategy that can support student learning in science (Akinoğlu & Tandoğan, 2007; Baumgartner & Zabine, 2008; Hmelo-Silver 2004; Kolodner et al., 2003; Schmidt et al., 2011; Sterling, Matkins, Frazier, & Logerwell, 2007). Problem-based learning is defined by instruction that (a) provides an open-ended problem to students; (b) includes a problem that has multiple solutions; (c) includes opportunities for student collaboration; and (d) engages students in scientific practices (Hmelo-Silver, 2004). In general, PBL in science is accomplished at the unit level, extends over a period of time, and incorporates student-centered strategies including inquiry-based instruction (e.g., Baumgartner & Zabin, 2008; Kolodner et al., 2003). Studies suggest that PBL promotes student learning because it fosters situational interest, which results, in part, from student engagement in scientific practices (Baumgartner & Zabin, 2008; Hmelo-Silver, 2004; Schmidt, Rotgans, & Yew, 2011). It is possible that PBL may stimulate ecology-related learning in the confines of the classroom, providing an alternative avenue for effective instruction that does not include field-based exploration and investigation.

Rationale For Study

This study was designed to address several voids in K-12 ecology education research. First, to our knowledge, there has not been a study published that examines three-dimensional, ecology-related learning in K-12 education. As more states adopt the NGSS and implement three-dimensional curricula, the extent to which such curricula can actually foster ecology-related learning needs to be explored. Second, little is known about how a curriculum can support students' ability to reason about ecological systems (Gotwals & Songer, 2013; Jacobsen & Wilensky, 2006). The intervention took a novel approach to fostering systems reasoning by focusing on two cross cutting concepts; *cause and effect* and *patterns*. We sought to determine the extent a unit that explicitly identified *cause and effect* relationships in multiple ecological contexts could support systems reasoning in near- and far-transfer learning scenarios. The third reason for this study is the need to determine the extent a PBL unit implemented within the confines of the classroom can evoke outcomes similar to that achieved by field-based ecology curricula. Problem-based instruction that takes place within the classroom in other science content domains has been effective in fostering learning (Kolodner et al., 2003; Schmidt et al., 2011). However, there seems to be an assumption that ecology instruction needs to be field-based to evoke maximum student interest and learning (Alexander, 1982; Baumgartner & Zabin, 2008; DiEnno & Hilton, 2005). Although DiEnno and Hilton (2005) determined that students who conducted fieldwork learned more than the classroom-bound students, it was unclear what component(s) of the treatment led to greater learning gains. The treatment

differed from the control on at least three variables; location, student collaboration, and pedagogy. If a PBL unit implemented within the confines of the classroom is effective, teachers potentially have another, more practical model to draw from when implementing ecology-related instruction.

Within these broader goals, we sought to determine whether a three-dimensional, problem-based ecology unit could support 6th-grade students' ability to:

1. Make claims and construct explanations regarding simple cause and effect relationships within ecosystems;
2. Engage in systems reasoning;
3. Analyze and interpret graphs.

Methods

This qualitative study utilized data in the form of student responses to select questions on a pre- and post-assessment. Data were analyzed to infer understanding of and proficiency in DCIs, SEPs and CCCs addressed by the intervention. Details on the curricular intervention, participants, assessment, and data analysis are provided in the sections below.

Curricular Intervention: “Our Changing Ecosystems” Unit

In response to demand for NGSS-aligned middle school curricula, a team of curriculum developers, teachers, and scientists in one state are developing and implementing units that address the three dimensions of the NGSS standards within a coherent framework. These units incorporate the PBL elements outlined above (open-ended problem, problem with multiple possible solutions, student collaboration, authentic scientific work). In each lesson, students explore concepts and practices of science or engineering disciplines in a given context, and then elaborate on their newfound understanding by applying these concepts and practices to a problem that extends throughout the unit, called the *unit challenge*.

The “Our Changing Ecosystems” unit was designed to support students' understanding of interactions between species and how changing access to resources affects species interactions and population sizes. Students constructed this understanding through engagement in SEPs, with a particular emphasis on *analyzing and interpreting data* and *constructing explanations* (Table 1). The *unit challenge* was contextualized within White Pine forests, an ecosystem familiar to students and native to the state they live in. Through the *unit challenge*, groups of students identified with a specific species in the White Pine forest ecosystem to understand the White Pine forest as a model within which to examine ecological interactions. The unit also drew on data and examples from other ecosystems in the state to illustrate the predictable ways organisms of different trophic levels interact with each other, both directly and indirectly, and to provide students multiple opportunities to analyze and interpret data. By examining data from

multiple ecosystems the unit permitted students to repeatedly identify *cause and effect* relationships and *patterns*, the two CCCs addressed by the unit (Table 1).

Table 1 DCIs, SEPs, and CCCs in “Our Changing Ecosystems” Unit Relevant to this Study

DCIs	SEPs	CCCs
Organisms and populations of organisms are dependent on their environment both with other living things and with nonliving factors (MS-LS2-1, part a)	Analyze and interpret data to provide evidence for phenomena (science practice 4, LS2-1)	Cause and effect relationships may be used to predict phenomena in natural or designed systems (LS2-1)
Growth of organisms and population increases are limited by access to resources (MS-LS2-1, part b)	Construct an explanation that includes qualitative or quantitative relationships between variables that predict phenomena (science practice 6, LS2-2)	Patterns can be used to identify cause and effect relationships (LS 2-2)
Predatory interactions may reduce the number of organisms or eliminate whole populations of organisms (MS-LS2-1, part c)		

Note: The unit addressed additional NGSS standards that are beyond the focus of the study.

The unit included 12 lessons that were implemented over the course of eight weeks. Each of the standards in Table 1 was addressed in multiple lessons (Table 2). Lessons two, four, six, and twelve were especially pertinent to the standards investigated in this study and each of these lessons is summarized below.

Lesson two. In lesson two, students collected and analyzed data on yeast population growth. Students gave yeast samples varying quantities of sugar and left the samples to reproduce overnight. Students organized their data into graphs and then analyzed their graphs to determine that food quantity is a limiting factor for population size. Students elaborated on this idea by researching the resources needed by their assigned White Pine forest species and predicted how changes in the accessibility of resources would affect populations of their species.

Lesson four. In this lesson, students watched a video about wolves and a prey species (elk). After watching the video, students were asked to consider what would happen to the wolf population if there were no elk, and what would happen to the elk population if there were no wolves. Students subsequently used a computer simulation (<http://cashmancuneo.net/flash/fc44/foodchain.swf>) to investigate how changes in one species affect the population size of another. Simulation activities were scaffolded by first having students examine a food chain with only two species (lynx and hares) and then with three species (foxes, rabbits and plants). Students completed worksheets that guided them to analyze and interpret graphs depicting population size for each species under investigation. For example, one question on the worksheet asked, “Looking at just the line for hares, what is happening to the hare population when the line goes down?” During the investigation with foxes, rabbits, and hares, students were also asked to *construct explanations* based upon the observed changes in each population. In this lesson students specifically had to confront the common misconception that a change in a population only affects its immediate prey or predator (Griffiths & Grant, 1985).

Lesson six. During lesson six, students considered the effects of the abiotic environment on organisms through several investigations. Students first analyzed maps depicting average annual snowfall and deer densities in the state to arrive at the conclusion that snowfall amounts and deer densities are inversely related. Students then examined a graph of deer populations over 40 years and provided an explanation, based upon their previous investigation, for the increase in deer population in the state. Students and teachers discussed other important abiotic factors that mediate population sizes including fire. Finally, students examined data describing wolf and moose populations over 50 years in the state. In addition to the predator/prey effects, students examined how weather, parasites, and disease affected each species' population size.

Lesson twelve. In this final lesson, students used the knowledge they gained throughout the unit to recognize that the same types of biotic and abiotic interactions occur in various ecosystems, not just the White Pine forest ecosystem. Working in groups, students created a model of one of five ecosystems; dunes, wetlands, lakes, rivers, or urban forests. Student groups identified important biotic and abiotic factors in their ecosystem and presented their ecosystem models to their classmates. During their presentations, students also had to communicate at least one prediction about how a change in one part of the ecosystem would affect additional ecosystem components. This extension afforded students an opportunity to recognize the CCC *patterns* as they saw the same types of predatory and prey relationships in diverse ecosystems and how changes in abiotic and biotic factors have predictable effects on other populations.

Table 2 *Standards Covered in Relevant Lessons in "Our Changing Ecosystems" Unit*

NGSS standard	Lesson 2	Lesson 4	Lesson 6	Lesson 12
DCI: MS-LS2-1, part a		X	X	
DCI: MS-LS2-1, part b	X	X		
DCI: MS-LS2-1, part c		X	X	
SEP: Analyze and interpret data	X	X	X	
SEP: Constructing explanations	X	X	X	
CCC: Cause and effect	X	X	X	
CCC: Patterns		X	X	X

Note: An "X" denotes NGSS standard coverage.

Pre-Teaching. Teachers implemented approximately two weeks of pre-teaching before beginning the unit. This instruction was not contextualized within a PBL unit. The purpose of the pre-teaching was to provide students with conceptual knowledge they would have had exposure to if the unit were implemented at the usual time in the academic year based upon district curriculum maps. Due to practical constraints imposed by the broader curriculum development project, "Our Changing Ecosystems" unit needed to be implemented earlier in the year than teachers would normally have addressed the content contained within it. To prepare for the unit, students were introduced to the concept of food chains and webs using a computer simulation and card sorts. Students were also introduced to the terms "abiotic" and "biotic" factors and identified examples of each within certain ecosystems. Finally, students were introduced to the concept that energy flows through ecosystems via feeding patterns. Understanding of this

foundational conceptual was necessary for students to appreciate how *changes* within an ecosystem have subsequent outcomes, the actual focus of the DCIs addressed in the unit.

Participants

Three teachers (pseudonyms, Ali, Mary, India) implemented the “Our Changing Ecosystems” unit between November 2015 and February 2016 as part of the piloting phase for a larger curriculum development project. The teachers volunteered to pilot test the unit and therefore participants represent a sample of convenience. Ali and India taught at the same school (school 1) located in a large district, while Mary taught within a smaller district (school 2) (Table 3). Ali (57 students total) and Mary (54 students total) each implemented the unit in two 6th-grade classes. All the students from Ali’s and Mary’s classes were included in data analysis. India taught three classes. However, data from only two of her classes were used during data analysis (n = 60 students total). These classes were chosen at random. India reported no major differences between classes that might have affected outcomes. By selecting two of India’s courses at random for data collection, the study collected data from approximately the same number of students taught by three different teachers. A subset of students did not complete both the pre-and post-test and were excluded from the final analysis. As a result, the final sample size was 143 students (Ali: n = 47; Mary: n = 45; India: n = 60). The teachers had a range of teaching experience: Ali had 13 years, Mary 4 years, and India had 28 years.

Table 3 *School District Demographic Data*

School	Students in District	Low SES (%)	White (%)	Black (%)	Hispanic (%)	Asian or pacific islander (%)	American Indian or native of Alaska (%)
School 1	7692	27.6%	87.8%	2.3%	3.4%	4.4%	0.4%
School 2	670	33.6%	93.3%	0.7%	1.3%	0.2%	0.9%

Assessment

Students took a 13-item assessment prior to and following unit implementation. Only two questions included in the assessment pertained to the constructs under investigation and were analyzed as part of this study. For simplicity, the two questions will be referred to as 1 (actually item 5 on the assessment), and 2 (actually item 6). Both questions had two subcomponents (i.e., 1a and 1b, 2a and 2b, Figure 1).

Assessment questions were selected based upon their alignment with the standards under investigation and the opportunities they provide for students to demonstrate learning in a near- and far- transfer question (questions 1 and 2, respectively). A team of curriculum writers alongside a content expert with a degree in ecology developed the second question using real-world data (Table 4). In addition, normative responses to question 2b required students to analyze data (SEP), recognize *cause and effect* and *patterns* (CCCs), and understand biotic and abiotic interactions in ecosystems (DCI). This three-

dimensional assessment question reflected the type of assessment that should accompany NGSS-aligned curriculum (Pellegrino & Wilson, 2014).

1. For over 50 years, scientists have been studying the predator-prey relationship between wolves and moose on Isle Royale in Lake Superior. The wolf population has been decreasing for many years, and it was reported recently that only three wolves remain on the island.

a) With the loss of wolves, explain what might happen to the number of moose on the island, assuming no other changes occur.

b) Moose depend on fir trees as an important food source on the island, especially during the winter. With the loss of wolves, explain what might happen to the number of fir trees on the island.

2. On the Galápagos Islands, there are several species of ground finch. These finches eat seeds. From the middle of 1976 until the end of 1977, it rained very little on the islands. Figure 1 below shows the amount of seeds on the islands from 1975 - 1978. Figure 2 shows population size of ground finches during the same time period.

a) Using the graphs, describe how the amount of seeds and size of finch population on the Galapagos Islands changed from 1975 – 1978.

b) How can you explain the observed changes in the amount of seeds and size of finch population?

Table 4 Assessments Questions and Their Alignment with NGSS Standards Addressed in the “Our Changing Ecosystems” Unit

	Question 1a	Question 1b	Question 2a	Question 2b
DCI: MS-LS2-1, part a Organisms and populations of organisms, are dependent on abiotic and abiotic factors	X	X		X
DCI: MS-LS2-1, part b Access to resources limits growth of organisms and populations				X
DCI: MS-LS2-1, part c Predatory interactions may reduce the number of organisms	X	X		X
SEP: Analyze and interpret data			X	
SEP: Constructing explanations				X
CCC: Cause and effect	X	X		X
CCC: Patterns				X

Note: An “X” denotes the question was analyzed to assess students for a specific standard.

Data Analysis

Each subquestion was treated as a separate question during analysis. A scoring rubric for each question was developed by initially identifying normative responses that focused on correct claims and

explanations. Additional codes were inductively developed by identifying patterns in incorrect responses using systematic data analysis (Miles & Huberman, 1984). Codes for non-normative conceptions were created only if two or more students expressed a specific idea. A codebook was developed by the first author, including code definitions and example student responses (Appendix A).

Student responses were ascribed a “1” if the answer reflected a particular code and a “0” if the answer did not reflect the code. Codes assigned to responses to a specific question were not mutually exclusive. The first and second author initially coded a subset (20%) of student responses. Any codes that had less than 85% inter-rater reliability were talked through and revised until 100% agreement was reached. The first author then coded the remaining data set with the revised codes (Table 5).

Differences in code frequencies from pre-to post-test were conducted using the McNemar test with alpha set at 0.05 for all tests. The McNemar test is most appropriate for comparing paired, dichotomously coded data (Adedokun & Burgess, 2012). In addition, data for all three teachers were combined to yield adequate power to detect pre to post differences since the McNemar test is insensitive when applied to univariate contexts (Westfall, Troendle, & Pennelo, 2010). Although aggregating data might prevent teacher-level differences from being discerned, our overall research questions were concerned with determining whether the intervention could support students’ growth in specific DCIs, CCCs, and SEPs. Combining student data to achieve sufficient power to detect change allowed us to best answer our research questions. Furthermore, weekly de-brief interviews and discussions with Ali, Mary, and India indicated the unit was implemented similarly and with fidelity by the three participants.

Table 5 *Assessment Question Codes (a priori)*

	Codes
Question 1a	Correct claim, Incorrect claim, Correct explanation, Incorrect explanation, Illogical/irrelevant, I don’t know/no answer, Systems reasoning
Question 1b	Correct claim, Incorrect claim, Correct explanation, Incorrect explanation, Illogical/irrelevant, I don’t know/no answer, Systems reasoning, Partial explanation
Question 2a	Cause/effect, Incorrect claim, Vague correct claim, Correct bird graph claim, Correct seed graph claim, I don’t know/No answer, Data only, Similar pattern in graph
Question 2b	Finches need seeds, Seeds need water, Drought caused fewer seeds, Fewer seeds caused fewer finches, Finches caused seeds to decrease, I don’t know/No answer, Illogical/irrelevant, Similar pattern in graphs

Note: Additional emergent codes are reported in the results section.

Results

Results for each question are summarized in tables that show the frequency of each code with exact *p* values that denote whether the change in frequency of dichotomously coded variables from pre- to post-test was significant. Exemplar student responses to specific codes are provided within the body of the results to aid interpretation of patterns and demonstrate student thinking/responses.

Near transfer question on how predator population changes affect prey populations (Q 1a). Students were significantly more likely to predict what would happen to the moose population when wolves

declined on the post-test (93.7%) compared with the pre-test (81.8%, $p = 0.003$). This would indicate that students, in this near transfer case, developed a normative understanding about what would happen to the immediate prey of wolves when the wolf population dropped dramatically (Table 6).

Table 6 *Frequency of Codes in Question 1a (Pre-/Post-test)*

	Pre (n=143)	Post (n=143)	Change (%) (Post-pre)	<i>p</i>
I don't know/no answer	1 (0.7%)	0 (0.0%)	-0.7%	1.000
Correct claim	117 (81.8%)	134 (93.7%)	11.9%	0.003
Incorrect claim	23 (16.2%)	8 (5.6%)	-10.6%	0.004
Illogical	2 (1.4%)	1 (0.7%)	-0.7%	1.000
Correct explanation	56 (39.2%)	62 (43.4%)	4.2%	0.532
Incorrect explanation	19 (9.8%)	5 (3.5%)	-6.3%	0.049
No explanation	71 (49.7%)	76 (53.1%)	3.4%	0.328
Systems reasoning	8 (5.6%)	21 (14.7%)	9.1%	0.015

Notes: Significant differences bolded, $p < 0.05$. Codes are not mutually exclusive therefore column sums do not equal 100%.

Although the question did not ask students to provide any reasoning to support their claim, nearly half of all students provided either a correct or incorrect explanation on the pre- (49%) and post-intervention (46.9%) tests (Table 6). Of the students who provided an explanation, many provided a correct explanation on both pre- and post- tests (39.2% and 43.4% of those providing an explanation, respectively). In all of these instances students specifically explained that the moose population would increase because there were fewer wolves to eat them. Several students, without being prompted, also took the opportunity to engage in systems reasoning on the pre- and post-tests. For example, one student wrote, "I think that they will repopulate and over flow the island, eat all the food and somehow die out" (1401253, pre-test). Another student explained, "The amount of moose will increase greatly and if there isn't enough vegetation then a bunch may die of starvation" (2957283, post-test). These instances demonstrate students' ability to think about long-term and indirect effects of the moose population increasing on other populations. The number of students who engaged in systems reasoning was significantly higher on the post-test (14.7%) compared with the pre-test (5.6%, $p = 0.015$).

Near transfer question on effects of predator population changes on producer abundance (Q 1b).

In addressing how wolf declines affect fir tree abundance, students provided more accurate claims and normative explanations in post- than in pre- tests (22.4% and 15.4% change respectively, Table 7).

Table 7 *Frequency of Codes in Question 1b (Pre-/Post-test)*

	Pre (n=143)	Post (n=143)	Change % (Post-Pre)	<i>p</i>
I don't know/No answer	5 (3.5%)	1 (0.7%)	-2.8%	0.063
Correct claim	104 (72.7%)	136 (95.1%)	22.4%	0.000
Incorrect claim	30 (21%)	6 (4.2%)	-16.8%	0.000
Illogical	5 (3.5%)	2 (1.4%)	-2.1%	0.063
Correct explanation	38 (26.6%)	60 (42.0%)	15.4%	0.006
Partial explanation	15 (10.5%)	34 (23.9%)	13.4%	0.007
No explanation	70 (49.0%)	39 (27.7%)	21.8%	0.000
Incorrect explanation	15 (10.5%)	10 (7.1%)	-3.4%	0.503
Systems reasoning	7 (4.9%)	17 (11.9%)	7.0%	0.064

Notes: Significant differences bolded, $p < 0.05$. Codes are not mutually exclusive therefore column sums do not equal 100%.

In addition, significantly more students provided partial explanations on the post-test (23.9%) compared with the pre-test (10.5%, $p = 0.007$). Partial explanations were coded for cases in which the student vaguely identified the moose as the causal agent of change without further elaboration. For example, one student wrote, "With the loss of the wolves there would be more moose repopulating and that would bring down the A game for the fir trees especially in the winter" (1260794, post-test). In this answer the student did not indicate that the moose eat fir trees which would be the specific reason for why a larger moose population would result in fewer fir trees. Instead, the student only referenced the increased moose population as causing a decline in the fir population without explicitly identifying the moose as a consumer of the fir trees.

As in question 1a, more students provided a response that demonstrated systems reasoning on the post-test (11.9%) compared with the pre-test (4.9%), but this was not significant ($p = 0.064$). These responses, and others coded for systems reasoning, included consideration of long-term effects and feedback loops caused by increased predation by the moose on the fir trees, including a decline in the moose population. One exemplary student response that demonstrated systems reasoning was:

"The fir trees will decrease because with the wolves gone the moose will repopulate. With more moose eating the fir trees there will be less of them. (Even though with it growing less and less there will be less and less for moose making them die and fir trees come back)." (1240395, post-test)

Another student wrote, "The fir trees would keep getting eaten on, so the population of the moose would go down because they would have nothing to eat" (2597533, post-test).

Incorrect claims students most often made on the pre-test were that the fir population would either increase (10 students, 7.0%) or would stay the same (14 students, 9.8%) when the wolf population was drastically reduced. These incorrect claims significantly decreased by the post-test (Table 8). Non-normative reasoning addressed only one line of thought in the pre- and post-tests: that wolves do not have anything to do with fir trees therefore a decline in the wolf population would not affect the fir tree population (3.5% pre, 0.7% post respectively, Table 8).

Table 8 *Frequency of Incorrect Claims and Explanations on Question 1b (Pre-/Post-test)*

	Pre (n=143)	Post (n=143)	Change % (Post-Pre)	<i>p</i>
Incorrect claims				
Fir trees increase	10 (7.0%)	2 (1.4%)	-5.6%	0.039
Fir trees stay the same	14 (9.8%)	1 (0.7%)	-9.1%	0.001
Incorrect explanations				
Wolf population size has not effect fir trees	5 (3.5%)	1 (0.7%)	-2.8%	0.219

Note: Significant *p* values are bolded, $p < 0.05$.

Graph interpretation (Q 2a). Students were more likely to explicitly point out the pattern was the same for both the seed and finch graphs on the post-test (55.6%) than the pre-test (32.9%, $p = 0.000$). Fewer students made incorrect claims on the post-test compared with the pre-test (0.7% and 5.6% respectively). In addition, all students answered the question on the post-test, whereas 6.3% did not answer the question on the pre-test (Table 9). Students tended to make more cause and effect statements on the post-test (26.1%) compared with the pre-test (18.9%), but this difference was not significant ($p = 0.185$). In responses with cause and effect statements, students did not necessarily indicate the overall pattern in either graph, but indicated that changes observed in one graph resulted in the changes in the other graph. For example, one student wrote, “When the population of the seeds decreases so does the population of the ground finch” (1510469, post-test). Another student responded, “If the seeds go down so do the finch (1766758, post-test). Finally, a third student indicated, “When the seeds decreased so did the finch, and with the finch decreasing they made more seeds and then the finch start eating them again” (2499275, post-test).

Table 9 *Frequency of Codes in Students Answers to Question 2a (Pre-/Post-test)*

	Pre (n=143)	Post (n=143)	Change % (Post-Pre)	<i>P</i>
IDK/No answer	9 (6.3%)	0 (0%)	-6.3%	0.004
Data only	12 (8.4%)	4 (3.8%)	-4.1%	0.057
Cause/effect statement	27 (18.9%)	37 (26.1%)	7.2%	0.185
Incorrect claim	8 (5.6%)	1 (0.7%)	-4.9%	0.039
Vague correct claim	29 (20.3%)	17 (12.0%)	-8.3%	0.059
Correct bird graph claim	72 (50.3%)	68 (47.9%)	-2.4%	0.804
Correct seed graph claim	83 (58.0%)	81 (57.0%)	-1.0%	1.00
Graph comparison	46 (32.9%)	79 (55.6%)	22.7%	0.000

Notes: Significant *p* values are bolded, $p < 0.05$. Codes are not mutually exclusive therefore column sums do not equal 100%.

Question on the relationship between changes in an abiotic resource, producer population, and consumer population (far transfer, Q 2b.) This question asked students to provide causal explanations for the observed patterns in two graphs. The pertinent evidence, gleaned from the graphs and the supporting text, was that when the seed population declined so did the finch population and both were precipitated by a drought. There were three cause/effect statements students could make: (a) drought caused fewer seeds; (b) fewer seeds caused fewer finches; and (c) finches caused seeds to decrease. To defend these cause and effect statements students could reason that seeds need water and finches eat seeds.

Almost all students attempted a response to this question on the post-test (98,6%) compared to 84.6% on the pre-test. As in 2a, more students compared the graphs on the post-test (39.9%) than the pre-test (25.2%, $p = 0.013$). Only one of the cause/effect statements changed significantly. On the post-test, more students indicated that a decline in seeds resulted in a decline in finches, and that finches needed seeds to survive (14.7% and 15.4% change respectively, Table 10).

Table 10 *Frequency of Codes in Student Answers to Question 2b (Pre-/Post-test)*

	Pre (n = 143)	Post (n = 143)	Change % (Post - Pre)	<i>P</i>
I don't know/No answer	22 (15.4%)	2 (1.4%)	-14.0%	0.000
Illogical/irrelevant	17 (12.0)%	22 (15.4%)	3.4%	0.441
Graph comparison	36 (25.2%)	57 (39.9%)	14.7%	0.013
Finches need seeds	26 (23.6%)	52 (36.4%)	12.8%	0.019
Seeds need water	6 (4.2%)	6 (4.2%)	0%	1.0
Drought caused fewer seeds	9 (6.3%)	15 (10.5%)	4.2%	0.180
Fewer seeds caused fewer finches	28 (19.6%)	50 (35.0%)	15.4%	0.004
Finches caused seeds to decrease	12 (8.4%)	20 (14.0 %)	5.6%	0.186

Notes: Significant p values are bolded, $p < 0.05$. Codes are not mutually exclusive therefore column sums do not equal 100%.

There was a difference in the likelihood students would make certain cause/effect statements on both the pre- and post-tests. Students were more likely to mention the cause/effect statement *fewer seeds caused fewer finches* than the *drought caused fewer seeds* on both the pre- ($\chi^2 = 16.03$, $p = .000$) and post-test ($\chi^2 = 37.67$, $p = .000$). Students were also less likely to identify the possibility the *seeds declined due to predation from the finches* compared with the idea that *fewer seeds caused fewer finches* on both the pre- ($\chi^2 = 11.37$, $p = .001$) and post-tests ($\chi^2 = 27.68$, $p = .000$). These cause/effect frequency differences indicate student responses tended to overlook the initial effect of the drought on the seed population. For example, one student wrote, "There was a lot of seed so finch population increased and they ate all the seeds so then they had nothing to eat and the finch population decreased" (8254097, post-test). Similarly, another student indicated, "There were less seeds to eat for the finches so finches decreased. Finches were eating too much and the seeds were getting low so the finches would have no food and it is decreasing" (6993647, post-test). These responses demonstrate how students were likely to focus on the role of a food source (seeds) in mediating changes in the predator populations and overlook abiotic factors.

Summary of Findings

Significant conceptual change was evidenced in the near transfer question (question 1), especially in part b that addressed indirect effects on producer populations when a top predator declined. Importantly, on the pre-test a higher percent of students made a correct claim involving a direct prey effect (81.8%, part a) than the percent of students who made the correct claim in regarding indirect effect (72.7%, part b). This difference was eliminated on the post-test where the correct claim was made by more than 90% of students in parts a and b. In both parts of question 1, students were also more likely to provide an explanation to support their claims on the post-test than the pre-test without being prompted to do so. In

addition, students were more likely to identify feedback loops and engage in systems reasoning on the post-test compared with the pre-test, especially when considering the effect of a declining wolf population on moose. Students were more likely to identify the role of a food source (seeds) in affecting predator populations than they were to discuss the role of the abiotic factor (rain) in affecting food (seed) abundance. This proclivity was evident on the pre- and post-test, but became even more pronounced on the post-test. Finally, students were more likely to indicate the graphs in question 2 showed a similar pattern on the post-test.

Discussion

This study sought to achieve three outcomes. The first goal was to determine the extent a three-dimensional, problem-based learning (PBL) unit could support student understanding of the effects of changes in biotic and abiotic factors in ecosystems in the absence of fieldwork. A second goal was to determine whether a three-dimensional unit could support systems reasoning. Finally, we sought to determine whether a three-dimensional, PBL unit could support far transfer learning related to the mediating effects of biotic and abiotic factors in controlling population sizes. The studies' findings are discussed in light of each of the three NGSS dimensions.

DCIs

The DCI under investigation (MS-LS2-1) focuses on population sizes and how biotic and abiotic factors control them. Within the DCI, concepts including predation, abiotic factors, and resource availability are identified as unique variables that affect populations. In the near transfer questions, students made significant learning gains in regards to understanding the role of predation in determining how the moose and fir populations might change. Importantly, the largest gains (pre- to post-) were made on the indirect predator effect question (1b). This significant gain is important in light of the documented tendency for students to believe that producer populations are not affected when a consumer population changes, especially if it is not the immediate prey (Griffiths & Grant, 1985; Hogan, 2000). Previous curricular interventions have found this misconception difficult to change (Hogan, 2000). At least within the familiar context, students developed normative understandings about direct and indirect effects of predation on other populations in the ecosystem.

There was some evidence of far transfer learning. Within the new context presented in question two, more students provided responses that included the cause/effect statement that *fewer seeds caused fewer finches*. This indicates students recognized that food is a limited resource and mediates the population size of organisms that consume it. However, students were not any more likely to recognize the role of drought on reducing both seed and finch populations. Therefore, the findings suggest students made far transfer learning gains in regards to biotic, but not abiotic factors.

One possible explanation for why students may have overlooked the causal relationship between the drought and fewer seeds pertains to how the question was constructed and information presented. The information regarding the drought was embedded in text and was not supported by any graphical data

which may have encouraged a certain level of response bias and was not necessarily consistent with how students interacted with data in graphical or tabular forms during unit lessons. For example, in lesson six students were provided maps with snowfall data and deer density data to analyze to develop possible causal relationships between an abiotic factor (snowfall) and deer population density. Students may not have read the text in the test question carefully or identified important information that would help them to fully interpret the graphical data and the impact of drought. Future research should investigate the possible tendency of students to recognize some ecosystem-related cause and effect relationships more readily than others using a variety of test questions that minimize bias. If there are predictable patterns in cause/effect relationships students overlook, there are implications for how students reason about complex systems.

Another explanation for why students provided explanations that focused differentially on one cause and effect relationship pertains to cognitive load. Recent research has demonstrated that the context in which students are creating explanations is predictive of the quality of the explanations. In particular, if the context is unfamiliar to students, there is higher intrinsic cognitive load placed on the student (Osborne, Henderson, MacPherson, Wild, & Yao, 2016; Sweller, Merriënboer, Paas, 1998; van Merriënboer, & Sweller, 2005). As a result of limits to cognitive load, students focus their cognitive abilities on understanding the context, and not on developing explanations, when the context is unfamiliar (Osborne et al., 2016). Perhaps the relationship between food availability and population size is most familiar to students, therefore puts the least demand on cognitive load, and led to more students providing an explanation for the data that focused on that relationship.

The differential identification of certain variables in question 2b is important in light of current efforts to identify a learning progression in ecology which have not yielded clear trajectories (Gotwals & Songer, 2010; Hokayem & Gotwals, 2016). These learning progressions assume students place equal value and similarly identify biotic and abiotic factors in mediating populations (Hokayem & Gotwals, 2016). Many ecology learning investigations also refer to student understanding of “predator/prey” relationships without attending to the possibility that students are more likely to focus on the prey than the predator in an ecosystem as mediating population sizes (Hokayem & Gotwals, 2016; Hovardas, 2016). Our findings suggest that ecological learning progressions may need to consider not only complexity, but also the “types” of environmental factors that influence population sizes and relationships.

CCCs (*Cause and Effect and Patterns*)

In both the near and far transfer questions more students recognized *cause and effect* relationships on the post-test than on the pre-test. In addition, students provided answers to the direct, near transfer question that showed systems reasoning more often on the post-test. We are encouraged by these outcomes since several previous studies have indicated that students struggle to identify cause/effect relationships and feedback loops even after an intervention (Evagorou et al., 2009; Hogan, 2000).

There are several possible explanations for why the unit supported students’ ability to identify *cause and effect* relationships to a greater extent than in some previous interventions. First, the intervention was

longer in duration than most others. *Our Changing Ecosystems* unit extended over approximately eight weeks whereas other interventions only lasted a few class periods (e.g., Evagorou et al., 2009). Another reason students may have developed the ability to identify *cause and effect* relationships in diverse ecosystems may have been a result of the large number of graphs and real-world data sets students encountered, especially in lessons two, four, and six. Furthermore, in lesson four students used a computer simulation to graph populations that demonstrated feedback loops as a result of species interactions. Hovardas (2016) speculated that students need to examine graphs that show population oscillations in order to reason about population dynamics accurately.

There was little evidence students recognized *patterns* in new contexts. Question 2b provided students an opportunity, in a far transfer question, to draw parallel cause/effect statements to those they made in questions 1a and b. For example, explaining that the seed population would go down as a result of finch predation is similar to predicting the fir tree population would go down as a result of moose predation. In terms of this specific relationship between an herbivore and its prey, there was no evidence that more students recognized the relationship, and hence the *pattern*, on the post-test in the far transfer question.

One challenge to being able to identify cause and effect relationships and engage in systems reasoning across ecosystems is that a certain level of conceptual knowledge is required about the context (Jacobsen & Wilensky, 2006). Therefore, conceptual knowledge and the ability to effectively reason about possible effects when abiotic and biotic factors are altered in an ecosystem go hand in hand. This poses a challenge to students who are exposed to ecology-related concepts infrequently.

Science Practices (*Analyzing and Interpreting Data and Constructing Explanations*)

Graphs are an essential means of data representation in ecology-related research (Roth et al., 1999). In addition, most often graphs are grouped together in ecology-related research to allow readers to draw comparisons (Roth et al., 1999). Therefore, this study's question asking students to consider data on two graphs (question 2b) reflected real-world use of graphs in ecology research (Roth et al., 1999). The finding that students drew comparisons between the graphs more often on the post-test than pre-test indicates that the intervention resulted in an increase in desirable graph interpretation skills (Roth et al., 1999). Students are seldom shown more than one graph at a time during ecology education (Roth et al., 1999). The positive results for this question are therefore promising and indicate that students can move from explication of patterns in each graph to synthesizing and comparing patterns across graphs in the matter of a few weeks when ample opportunities for practice are given. In the unit *Our Changing Ecosystems* students analyzed a variety of graphs in lesson 2, 4, and 6 and had opportunities to use data from more than one graph (lesson 6) and to process multiple lines of data on a single graph (lesson 4). Another important feature of the unit that may have supported growth in graph analysis skills was the inquiry-based context in which the graphs were used. Graphs were not simply projected on a screen. Instead students analyzed graphs to answer research questions. Previous research has indicated an inquiry-based context supports data analysis skills and the current study confirms these findings (Roth & Bowen,

1994; Wu & Krajcik, 2006). Our study extends these findings by demonstrating the investigations do not necessarily need to be hands-on or field-based.

Students created more explanations on both the near and far transfer questions on the post-test compared with the pre-test. This growth is important since explanation construction, while its own science practice, is also foundational to argumentation (McNeill, 2011; Osborne et al., 2016). Students demonstrated an improved ability to construct explanations within two different science contexts; questions 1a and b involved students constructing explanations from a hypothesized scenario without any data while question 2b required students to construct explanations from provided data. It is important to remember that in questions 1a and 1b students were not actually asked to provide an explanation. Nonetheless, significantly more students provided explanations for these questions on the post-test than the pre-test. This pattern indicates that students developed “habits” of providing explanations for predicted or observed phenomena during the intervention. One indication of proficiency and expertise in a field is unconsciously and seamlessly engaging in certain behaviors without apparent effort (Borko & Livingston, 1989; Gladwell, 2005). The increased propensity for students to make comparisons between graphs and provide explanations without prompting, suggests students, through the unit, developed a certain level of comfort with these scientific practices that resulted in their unprompted use on the post-test.

Future Research and Limitations

The findings of the study provide numerous and diverse possible avenues for future research. One primary limitation of the study was the lack of additional contextualizing information. In particular, interviews with students could greatly help illuminate why students focused on seeds in mediating the finch population and overlooked other interactions in question 2b. It would be valuable to know the extent to which patterns in student responses were an artifact of how the information was presented or a result of tendency to focus on certain interactions regardless of the question format. Abiotic changes in our environment affect many facets of ecosystem dynamics and human lives. If middle school students have difficulty identifying them, curriculum should be designed to help students recognize them as readily as biotic factors. For example, rainfall and temperature influence plant growth and therefore food resources for herbivores and predators. If students do not recognize these indirect effects stemming from changes in abiotic factors they will have trouble making informed decisions and thinking critically about the relative importance of certain ecosystem factors (Byrne, 2016).

Future research should also investigate students’ ability to reason about ecosystem interactions by using assessment questions that provide a greater range of contexts surrounding problems. In the current study, questions 1a and 1b allowed for pre to post growth most likely due to the fact that the white pine forest ecosystem that was featured throughout the unit. It is possible question 2b was so dissimilar (new organisms and new ecosystem) and complex (biotic and abiotic factors) it limited the opportunity for learning transfer (Pellegrino & Wilson, 2014). It would be useful to have additional questions that vary on

single variables to allow for comparison and determine a trajectory for transfer of reasoning skills and understanding of ecosystems.

Conclusion

An assumption underlying the Next Generation Science Standards (NGSS) is that students will learn concepts more deeply when curriculum is three-dimensional. Evidence of deeper learning can be provided by students' ability to demonstrate their understanding within new contexts. It is anticipated that ability to apply learning to new contexts will be greater for those students who experience three-dimensional learning opportunities than for students who do not have such opportunities. Our findings suggest three-dimensional, problem-based learning (PBL) curricula support the development of at least two scientific practices; *analyzing and interpreting data* and *constructing explanations*. In addition, "Our Changing Ecosystems" unit resulted in a greater number of *cause and effect* statements on the post-test compared with the pre-test for questions that referenced familiar and unfamiliar ecosystems. However, there was little evidence students made growth in recognizing *patterns* of familiar biotic relationships across ecosystems. Furthermore, students showed significant learning gains for some components of the relevant DCI's but not for all. For example, there was no evidence students recognized the importance of abiotic factors in influencing populations despite examining the effect of snowfall on deer density within the unit. However, students were significantly more likely to recognize the importance of biotic factors (predator and prey population sizes) on other organisms. In addition, students more readily identified long term-effects and feedback loops when a population's size changed within a familiar ecosystem on the post-test compared with the pre-test.

Together these findings suggest that an eight-week long NGSS-aligned PBL unit can support learning within the confines of the classroom, but some of the challenges to achieving far transfer evidenced in other studies persisted (Evagorou et al., 2009; Gotwals & Songer, 2010; Hogan, 2000). Greater emphasis may need to be given to the role of abiotic factors in curriculum addressing population dynamics. As the DCI is currently written, student understanding of biotic and abiotic factors is linked. However, students may find it easier to recognize the role of biotic factors in mediating population sizes. This suggests a progressive understanding of and reasoning about ecosystems that moves from biotic to abiotic factors and may be an effective component of learning progression related to ecology-related learning and reasoning. Our study demonstrates students can improve their understanding of and ability to reason about population dynamics during three-dimensional problem-based learning without ever getting wet or dirty! There are practical options for curriculum developers, researchers, and teachers to explore as ecological and environmental education is becoming increasingly important to support general systems reasoning skills, within and outside of ecological systems.

Declarations

- Ethics approval and consent to participate

This study was approved by Michigan Tech's Internal Review Board

- Consent for publication

There are no names or identifiers in the manuscript requiring consent. Names have been deidentified with pseudonyms.

- Availability of data and material

The datasets generated during and/or analysed during the current study are not publicly available due to the ongoing nature of the project. They are available from the corresponding author on reasonable request.

- Competing interests

There are no competing interests to report

- Funding

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- Authors' contributions

ALG was primary collector/analyzer of data and drafting of manuscript

BGB was secondary on data analyses by providing IRR and validity. She also contributed to the manuscript

JH contributed to the writing of the manuscript

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References

- Akinoğlu, U., & Tandoğan, R. O. (2007). The effects of problem-based active learning in science education on students' academic achievement, attitude, and concept learning. *Eurasia Journal of Mathematics, Science & Technology Education*, 3, 71-81.
- Aleven, V., & Koedinger, K. R. (2002). An effective metacognitive strategy: learning by doing and explaining with a computer-based cognitive tutor. *Cognitive Science*, 26, 147-179.
- Alexander, S. K. (1982). Food web analysis: An ecosystem approach. *The American Biology Teacher*, 44(3) 186-190.

- Baumgartner, E., & Zabin, C. J. (2008). A case student of project-based instruction in the ninth grade: a semester-long study of intertidal biodiversity. *Environmental Education Research*, 14(2), 97-114.
- Byrne, L. B. (2016). Learner-centered teaching activities for environmental and sustainability studies. In *Learner-centered teaching activities for environmental and sustainability studies*. Pp.1-24 Springer International Publishing: Switzerland.
- DiEnno, C. M., & Hilton, S. C. (2005). High school students' knowledge, attitudes, and levels of enjoyment of an environmental education unit on nonnative plants. *The Journal of Environmental Education*, 37(2), 13-25.
- Evagorou, M., Korfiatis, K., Nicolaou, C., & Constantinou, C. (2009). An investigation of the potential of interactive simulations for developing system thinking skills in elementary school: A case study with fifth-graders and sixth-graders. *International Journal of Science Education*, 31, 655-674.
- Furtak, E. M. (2012). Linking a learning progression for natural selection to teachers' enactment of formative assessment. *Journal of Research in Science Teaching*, 49(9), 1181-1210.
- Gallegos, L., Jerezano, M. E., & Flores, F. (1994) Preconceptions and relations used by children in the construction of food chains. *Journal of Research in Science Teaching*, 31(3), 259-272.
- Gotwals, A. W., & Songer, N. B. (2010). Reasoning up and down a food chain: Using an assessment framework to investigate students' middle knowledge. *Science Education*, 94(2), 259-261
- Gotwals, A. W., & Songer, N. B. (2013). Validity evidence for learning progression-based assessment items that fuse core disciplinary ideas and science practices. *Journal of Research in Science Teaching*, 50(5), 597-626.
- Griffiths, A. K., & Grant, B. A. C. (1985). High School students' understanding of food webs: Identification of a learning hierarchy and related misconceptions. *Journal of Research In Science Teaching*, 22, 421-436.
- Hickling, A. K., & Wellman, H. M. (2001). The emergence of children's causal explanations and theories; evidence from everyday conversations. *Developmental Psychology*, 37, 668-683
- Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn? *Educational Psychology Review*, 16(3), 235-266.
- Hogan, K. (2000). Assessing students' systems reasoning in ecology. *Journal of Biological Education*, 35, 22-28.
- Hokayem, H. & Gotwals, A. W. (2016). Early elementary students' understanding of complex ecosystems: A learning progression approach. *Journal of Research in Science Teaching*, 53 (10), 1524-1545.

- Hokayem, H. (2016). Patterns of Reasoning about Ecological Systemic Reasoning for Early Elementary Students. *Science Education International*, 27(1), 117-135
- Hovardas, T. (2016). A learning progression should address regression: Insights from developing non-linear reasoning in ecology. *Journal of Research in Science Teaching*, 53(10), 1447-1470.
- Jacobson, M. J., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *The Journal of the Learning Sciences*, 15(1), 11-34.
- Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., Puntambekar, S. & Ryan, M. (2003). Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting learning by design™ into practice. *The Journal of the Learning Sciences*, 12(4), 495-547.
- Lombrozo, T. (2006). The structure and function of explanations. *TRENDS in Cognitive Sciences*, 10(10), 464-470.
- Miles, M. B., & Huberman, A. M. (1984). Drawing valid meaning from qualitative data: toward a shared craft. *Educational Researcher*, 13, 20-30.
- Mokros, J. R. & Tinker, R. F. (1987). The impact of microcomputer-based labs on children's ability to interpret graphs. *Journal of Research in Science Teaching*, 24, 369-383.
- National Research Council (2012). *A framework for K-12 science education: Practices, cross cutting concepts, and core ideas*. Washington, DC: The National Academies Press
- NGSS Lead States. (2013). *Next Generation Science Standards*. National Academy Press: Washington, DC.
- Osborne, J. F., Henderson, J. B., MacPherson, A., Wild, A., Yao, S. (2016). The development and validation of a learning progression for argumentation in science. *Journal of Research in Science Teaching*. DOI: 10.1002/tea.2136
- Pellegrino, J. W., & Wilson, M. R. (2014). *Developing assessments for the next generation science standards*. Washington, DC: National Academies Press.
- Rittle-Johnson, B. (2006). Promoting transfer: the effects of direct instruction and self-explanation. *Child Development*, 77, 1-15
- Roth, W.M., Bowen, G. M., McGinn, M. K. (1999). Differences in graph-related practices between high school biology textbooks and scientific ecology journals. *Journal of Research in Science Teaching*, 36(9), 977-1019.

- Roth, W. & Bowen, G. M. (1994). Mathematization of experience in a grade 8 open-inquiry environment: An introduction to the representational practices of science. *Journal of Research in Science Teaching*, 31(3), 293-318.
- Ruth, M. (1993). Core Concepts in Ecology. In *Integrating Economics, Ecology and Thermodynamics* (pp. 35-47). Springer: Netherlands.
- Ryoo, K., & Linn, M. C. (2014). Designing guidance for dynamic visualizations: Generating versus reading explanations. *Journal of Research in Science Teaching*, 51, 147-174.
- Schmidt, H. G., Rotgans, J. I., & Yew, E.H.J. (2011). The process of problem-based learning: what works and why. *Medical Education*, 45, 792-806.
- Shah, P., & Hoeffner, J. (2002). Review of graph comprehension research: Implications for instruction. *Educational Psychology Review*, 14(1), 47-69.
- Sterling, D. R., Matkins, J. J., Frazier, W. M., & Logerwell, M. G. (2007). Science camp as a transformative experience for students, parents, and teachers in the urban setting. *School Science and Mathematics*, 107, 134-148.
- Sweller, J., van Merriënboer, J. J. G., & Paas, F. G. W. C. (1998). Cognitive architecture and instructional design. *Educational Psychology Review*, 10, 251-296.
- van Merriënboer, J. J. G., & Sweller, J. (2005). Cognitive load theory and complex learning: Recent developments and future directions. *Educational Psychology Review*, 17, 147-117.
- Westfall, P. H., Troendle, J. F., & Pennello, G. (2010). Multiple McNemar Tests. *Biometrics*, 66(4), 1185–1191.
- Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic systems approach to making sense of the world. *Journal of Science Education and technology*, 8(1), 3-19.
- Wu, H., Krajcik, J. S. (2006). Inscriptional practices in two inquiry-based classrooms: A case study of seventh graders' use of data tables and graphs. *Journal of Research in Science Teaching*, 43(1), 63-95.
- Zangori, L., & Forbes, C. T. (2014). Scientific practices in elementary science classrooms: Third grade students' scientific explanations for seed structure and function. *Science Education*, 98(4), 614-639.
- Zangori, L., Forbes, C. T., Biggers, M. (2013). Fostering student sense making in elementary science learning environments: Elementary teachers; use of science curriculum materials to promote explanation construction. *Journal of Research in Science Teaching*, 99, 1-29.

Figures

Figure 1

Changes in abundance of seeds

Figure 2

Changes in finch population size