Early Elementary Students’ Understanding of Complex Ecosystems: A Learning Progression Approach

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Received 13 July 2015; Accepted 25 May 2016

Abstract: Engaging in systemic reasoning about ecological issues is critical for early elementary students to develop future understanding of critical environmental issues such as global warming and loss of biodiversity. However, ecological issues are rarely taught in ways to highlight systemic reasoning in elementary schools. In this study, we conducted semi-structured interviews with 44 students from the first through fourth grades. Using an iterative process, we developed an empirically grounded learning progression that captures how elementary students use systemic reasoning to explain interactions in ecosystems. This learning progression contains five reasoning patterns: anthropomorphic reasoning, concrete practical reasoning, simple causal reasoning, semi-complex causal reasoning, and complex causal reasoning. The results also show that many students exhibited mixed-level reasoning, meaning that they used reasoning patterns at multiple levels to construct a single response. We discuss the implications of the study for learning progression research and teaching ecosystems at early elementary grades.

Keywords: learning progressions; ecosystems; systemic reasoning

Introduction

Understanding critical environmental issues such as global warming and threats to biodiversity require thinking about how different systems work and interact with each other. The National Research Council (NRC) framework and the Next Generation Science Standards (NGSS) identify Interdependent relationships in ecosystems as part of a disciplinary core idea in life sciences and systems and system models as a crosscutting concept that makes connections across disciplinary boundaries (NGSS Lead States, 2013; NRC, 2012). In the context of ecosystems, systemic reasoning fuse the above mentioned core idea and crosscutting concept. Systemic reasoning is the kind of reasoning used to understand essential features of open dynamic systems such as socio-economic systems and ecological systems (Chandler & Boutilier, 1992). In relevant literature, open dynamic systems are often called as complex systems and systemic reasoning is often labeled as systems thinking or systems reasoning (Hmelo-Silver, Marathe, & Liu, 2007; Hogan, 2000; Wilensky & Resnick, 1999). While we draw on the research in all of these
concepts, in this study, we use the terms used by Chandler and Boutilier because we drew heavily upon their work.

Although being a critical basis for future understandings about global warming and the effects of decreasing biodiversity (Lauro, 2012), systemic reasoning about ecological issues is rarely taught in early elementary school (Sweeny & Sterman, 2007). This means that as students move to upper grades, they may not have formal instruction on this topic and teachers may not know what students can do and understand. To address this need, we use a learning progression (LP) approach to explore ways in which early elementary students reason about interactions in ecosystems. Learning progressions are “descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time” (NRC, 2007, p. 219). Our goal is to develop a learning progression for systemic reasoning for early elementary students. Accordingly, our research question is: How do elementary students (first through fourth grades) reason about population interactions and relationships in an ecosystem? To answer this question, we conducted an interview study to develop an empirically grounded LP that captures common reasoning patterns of elementary students. This study is important given the need to investigate systemic reasoning in domain-specific contexts and the paucity of LP research at the early elementary level. We elaborate this point in the paragraphs that follow.

Literature Review

Teaching and Learning of Systemic Reasoning

Ecosystems are complex open systems, and understanding interdependent relationships in ecosystems (a component of a core idea in life sciences) requires systemic reasoning. Systemic reasoning is also part of the reasoning to understand the crosscutting concept of systems and system models. The NRC Framework emphasizes that “...thinking about systems in terms of component parts and their interactions, as well as in terms of inputs, outputs, and processes, gives students a way to organize their knowledge of a system, to generate questions that can lead to enhanced understanding” (NRC, 2012, p. 93). In this section, we first discuss the challenges that students encounter when using systemic reasoning to understand interactions in ecosystems. Then, we explore the possibility of teaching systemic reasoning at elementary or even early elementary levels.

An important aspect of understanding complex systems is to identify patterns at the system level and connect those patterns to behaviors and interactions of constituent components (Capra, 1996; Chi, 2005). In many situations, the patterns at the system level are “emergent,” meaning that the patterns are caused by the interactions and collective behaviors of constituent components (Chi, 2005). Empirical studies suggest that identifying system level patterns in ecosystems is very challenging for students. Eilam (2012) conducted a study, in which ninth grade students studied a live ecosystem and manipulated variables in a lab. The results suggest that students seldom connected individual processes of matter transformation and energy transformation at a molecular level with patterns of matter cycle and energy flow processes at the level of ecosystems.

Another aspect of systemic reasoning is feedback loop reasoning. The Framework (NRC, 2012) defines feedback loop reasoning as “any mechanism in which a condition triggers some action that causes a change in that same” (NRC, 2012, p. 99). Sweeny and Sterman (2007) found that middle school students do not readily use feedback loop reasoning to interpret relations and interactions among organisms in ecosystems. Based on their findings, they further concluded that explicit instruction is required to help students develop and reason with feedback loop concepts.
Similarly, Hogan (2000) conducted a study to explore 11-year-old students’ understanding of food webs. She found that very few students understood the predator–prey feedback loop relationship. Similarly, Hokayem, Ma, and Jin (2015) found that elementary students were rarely able to reach the highest level of learning progression for feedback loop reasoning of predator-prey relationships.

Given the learning difficulties confronting students, one may question whether systemic reasoning is appropriate for early elementary students to learn. Empirical studies have suggested that given appropriate scaffolding, students are able to learn to reason systemically. Several studies found that explicit teaching of systems significantly promoted middle school students’ understanding of interactions in ecosystems. Assaraf and Orion (2010) and Evagorou, Korfiatis, and Nicoloae showed that software programs coupled with explicit instruction about systemic reasoning produced successful results in teaching middle school students about ecosystems. Computer modeling was also successfully utilized to support students understanding of an “emergent property” of general systems such as traffic jams (Resnick, 1996; Resnick & Wilensky, 1998; Wilensky & Resnick, 1999). Moreover, Plate (2010) showed that middle school students who received explicit teaching about systems were better able to demonstrate how various factors affected a system and construct more complex connections in ecosystems. At the elementary school level, two studies provided promising results about teaching systemic reasoning. Roberts (1978) found that fifth and sixth graders significantly improved their systemic reasoning after the explicit teaching about feedback loop models and were able to identify underlying structures of models and demonstrate understanding of the factors that allowed the system to change. Hill and Redden (1985) found that third and fourth graders who were exposed to explicit teaching of systemic reasoning performed better at complex system tasks than those who did not receive systemic instruction. The above evidence suggests the potential benefit of teaching systemic reasoning at elementary or even early elementary school levels.

Jacobson and Wilensky (2006) conducted an extensive literature review about teaching systemic reasoning in science. They acknowledged the usefulness of computer simulations and a top down approach of explaining system structures in teaching students about complex systems. However, they also emphasized the “bottom up” approach of gradually supporting students in reasoning about emergence and feedback in complex systems. This wide range of instructional strategies suggests that more research is needed to develop the best practice of teaching systemic reasoning. Our study will help to identify various levels of systemic reasoning, which will have implications for curriculum and instruction. Moreover, understanding whether age plays a role in systemic reasoning also contributes to our understanding of when we can introduce systemic reasoning in ways that help students understand complex systems.

In this effort, we reviewed relevant literature to understand how researchers study students’ systemic reasoning across domains. We found that extensive research has been conducted to explore students’ reasoning across a variety of complex systems. Many of those studies identify alternative ideas that students use to understand specific phenomena of complex systems such as the V-shape of goose flocks and traffic jam (Raia, 2005; Wilensky & Resnick, 1999). A few researchers used a framework to explore student reasoning behind their alternative ideas. For example, Hmelo-Silver et al. (2007) used structure-behavior-function framework to compare the expert-novice differences (Hmelo, Holdon, & Kolodner, 2000; Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver et al., 2007). They found that experts make more connections among structure, behavior, and function than novices. We argue that the framework approach is important for the development of in-depth understanding of student thinking. As will be elaborated later, we
developed a framework that allows us to examine students’ systemic reasoning in a specific content context—interdependent relationships in ecosystems. By doing so, our study and resulting LP describes student systemic reasoning in a domain-specific context.

Learning Progression Research

A LP usually contains a lower anchor, an upper anchor, and several intermediate levels (Duncan & Hemlo-Silver, 2009). The lower anchor stems from students’ informal reasoning. The upper anchor aligns with the scientific explanation of the phenomenon. The intermediate levels express a mixture of informal and scientific ideas that increasingly progress to reach the scientific idea. Smith, Wiser, Anderson, & Krajcik (2006) explained that LPs bridge the gap between standards and what students know through empirically documenting the various stages of learning of “big ideas.” Recently, researchers have developed LPs for matter (Johnson & Tymss, 2011; Mohan, Chen, & Anderson, 2009; Stevens, Delgado, & Krajcik, 2010), energy (Jin & Anderson, 2012; Neumann, Viering, Boone, & Fischer, 2013), genetics (Duncan, Rogat, & Yarden, 2009; Todd & Kenyon, in press), biodiversity (Songer, Kelcey, & Gotwals, 2009), natural selection (Furtak, 2012), and modeling (Forbes, Zangori, & Schwarz, 2015; Lehrer & Schauble, 2012a; Schwarz et al., 2009). Many researchers also used LPs to guide curriculum development and classroom teaching and teacher professional development (Furtak, 2012), and assessment of teacher knowledge (Jin, Shin, Johnson, Kim, & Anderson, 2015). Based on a comprehensive review of LP literature, we identified two important aspects of LP research, which have important implications for the design of our study. These two aspects are different types of LPs and the grain size of LPs.

First, Duschl, Maeng, and Sezen, (2011) distinguish between two types of LPs: A “validation” LP describes a logical sequence of ideas and concepts and sometimes associated common errors to be fixed through instructions (e.g., Alonzo & Steedle, 2009), whereas an “evolutionary” LP describes how informal ideas evolve and develop into scientific ones (e.g., Mohan et al., 2009). Duschl et al. (2011) call for developing more evolutionary LPs, as these LPs help teachers use students’ informal ideas as resources for learning.

Second, an important issue in the LP research is grain size—the breadth of content covered and length of time included in the LP. The LP literature exhibits considerable variation in choosing grain sizes. For example, some LPs cover a broad span from elementary, through middle and high school (e.g., Mohan et al., 2009; Smith et al., 2006), while others focus on a single grade span, such as upper elementary level, middle school level, or high school (e.g., Johnson & Tymss, 2011; Neumann, Viering, Boone, & Fischer, 2013). The grain sizes of content topics also vary. Some LPs cover broad content areas, for example, energy in carbon-transforming processes (Mohan et al., 2009). Other LPs focused on a narrower content topic, for example force and motion (Alonzo & Steedle, 2009).

To date, most LP studies have used ideas of upper elementary or middle school students as a lower anchor. There are a few notable exceptions, for example, in their work on a LP for plant nutrition from first through sixth grades, Alonzo et al. (2009) found that students varied in their levels of understanding even when they have not formally learned about how plants make food (i.e., photosynthesis). Also, Lehrer and Schauble (2012b) developed a LP for elementary students’ understanding of modeling practice using evolution and ecology starting from the first grade to the fifth grade. In a recent commentary on LPs, Lehrer and Schauble (2015) stress the importance of fine-grained LPs that provide practical guidance for teachers’ day-to-day instruction. In agreement with Lehrer and Schauble and with recognition of lack of LP research with younger children, we recognize a need for developing LPs with a fine grain size, especially those for lower elementary students.
Metz (2011) points out the importance for science educators to recognize younger student’s capabilities and use students’ informal ideas as resources for learning more complicated science concepts. Along the same line, we argue that an in-depth understanding of students’ informal ideas is the foundation to develop evolutionary LPs. Existing research has mostly investigated students’ ideas during or after formal instruction. Studies on LPs before formal instruction are rare. To bridge the gap, we developed an evolutionary LP with a small grain size for systemic reasoning in ecology and lower elementary grade bands. By including students from early elementary level (grades 1–4) and the specific topic of interactions in ecosystems, we were able to develop a fine-grained description that captures a range of students’ informal reasoning patterns. This LP will provide valuable information about younger students’ reasoning and therefore will be useful for researchers and teachers to design learning activities that use students’ informal ideas as resources for learning.

Conceptual Framework

Ecosystems are open complex systems because matter and energy constantly flux into and out of ecosystems, and ecosystems dynamically interact with surrounding environments (Odum, 1992). Scientists have developed multiple approaches to study open complex systems. Bertalanffy (1968) was the first to develop a general systems theory applicable to open systems. He asserted that a key concept in biology is “organization”—the interactions and connections among parts produce a whole that is more than the sum of its parts. For example, human body systems have characteristics that allow them to perform functions different from individual cells. Similarly, ecosystems have characteristics of energy flow and species interaction that are at a different level from a single organism’s need. An open complex system can reach stability, a state of dynamic equilibrium that nevertheless keeps the system functioning through the flow of materials (Odum, 1992).

Chandler and Boutilier (1992) took this a step further by developing a model that contains four properties of systemic reasoning:

- **Systemic synthesis** refers to predicting change across the whole system when a small change happens to one element within the system. In other words, a disturbance in one of a system’s elements results in a large scale influence at the system level.
- **Systemic analysis** refers to identifying elements in a system and differentiates the essential elements from non-essential ones.
- **Dynamic recycling** refers to understanding how the recycling of matter make a system sustainable.
- **Circular connectivity** refers to recognizing feedback loops in a system. A complex system can be internally regulated by one input producing an output, which in turn becomes an input of the same system. For example, the presence of grass (input) will allow more herbivores to increase (output). The increase in herbivores will in turn allow more carnivores to increase, in which a previous output becomes an input. These output and input linkages constitute the food web.

We used Chandler and Boutilier’s model as a framework to guide the design of our initial LP. In particular, we used the four properties of systemic reasoning as progress variables for the LP for systemic reasoning. We elaborate the progress variables below.

- **Systemic Synthesis (SS):** This progress variable characterizes student understanding of how an increase or a decrease in one population (e.g., primary consumers, secondary consumers, or top predators) influences the food web in the ecosystem.
- Systemic Analysis (SA): This progress variable characterizes the extent to which students recognize the unique and crucial role of the energy source (sun) and producers (photosynthetic plants) in an ecosystem.

- Dynamic Recycling (DR): This progress variable characterizes matter recycling in ecosystems. In particular, we are interested in students’ explanation of decay and decomposition of dead bodies of animals and plants—what happens to the organic matter of the dead bodies.

- Circular Connectivity (CC): This progress variable characterizes students’ ability to construct an ecosystem. More specifically, we examined how students choose populations to make up a viable ecosystem.

Methods

Participants

This study took place in a Midwestern Suburban school, where 71% of the students were white, 11% were Hispanic, 8% were African American, 5% were Asian, and 5% were American Indian, American Hawaiian or a mixture of two races. Each class (grades 1–4) included approximately 24 students. To ensure certain variance in responses, we asked the teachers to identify students at different performance levels. For the first and second grade students, teachers based the rating on their experiences with students in the class. For the third and fourth grade students, teachers based their ratings on their science scores (e.g., low level was below 70%, middle level was between 70% and 85%, and high level was above 85%). This effort was made to include a wide range of ideas from students for the development of the LP. The first author conducted interviews with all students. We used a specific approach to ensure data saturation—the point in qualitative research where data become repetitive and no new patterns or themes appear (Bogdan & Biklen, 2007; Strauss & Corbin, 1998). After collecting a small sample of 6–8 interviews, we analyzed the interview data and identified patterns from the sample. Data saturation was reached after interviews with eight students in each class (32 interviews). To ensure that we included enough students, we interviewed two to four additional students in each class. Altogether, we conducted interviews with 44 participants (N = 44). (See Table 1). Each interview took place in a quiet room and lasted 35–45 minutes.

Systematic Validation of the LPs

Anderson (2008) suggests considering three qualities to enhance the validity of LPs. First, LPs must have conceptual coherence—the LP provides a logical story of how “initially naive students can develop mastery in a domain” (p. 3). Secondly, LPs must have compatibility with current research and build on findings about learning in the given domain. Finally, LPs must involve some process of empirical validation based on data from real students or teachers. We used Anderson’s guidelines to enhance the validity of the LP.

Table 1

Information about interviewees

<table>
<thead>
<tr>
<th>Grade level</th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade 1</td>
<td>4</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Grade 2</td>
<td>6</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Grade 3</td>
<td>5</td>
<td>5</td>
<td>10</td>
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<tr>
<td>Grade 4</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>20</td>
<td>24</td>
<td>44</td>
</tr>
</tbody>
</table>

Journal of Research in Science Teaching
To ensure the conceptual coherence of our LP, we modified the four components of a conceptual model of systemic reasoning (Chandler & Boutilier, 1992) and used the modified components as the progress variables of the LP. The four progress variables therefore entail different but related aspects of a model of systemic reasoning.

To achieve the compatibility with current research and the empirical validation, we adopted a research approach that contains a top-down process and a bottom-up process. In the top-down process, we first developed a hypothetical LP based on ideas from the literature about students’ systemic reasoning (e.g., Griffiths & Grant, 1985; Grotzer & Bell, 2003; Leach, Driver, Scott, & Wood-Robinson, 1995; Lehrer & Schauble, 2012b; White, 2000) to ensure the compatibility of the LP with current research. In addition, we consulted an ecologist about the conceptual framework and an earlier version of the LP. Based on the feedback from the ecologist, we revised the framework and the levels of the LP.

Next, in a bottom-up process, we used interview data from students to enhance the empirical validity. In particular, we conducted two studies, including a pilot study and the present study reported in this article. The data from the pilot study were used to revise the interview tasks and the LP. In addition, a professor in ecology reviewed the interview tasks and the LP. Based on the review feedback, we further revised the interview tasks and the LP. In the present study, we used the revised interview tasks to collect data; we also used the LP as an initial LP to analyze the interview data. As will be elaborated below, this initial LP was continuously revised and refined in the process of data analysis.

**Interview Protocol**

We used interviews to elicit these students’ reasoning about complex ecosystems because in order to develop an empirically grounded and fine-grained LP. Many researchers agree that interviews produce a wealth of information about students’ reasoning (Southerland, Smith, & Cummins, 2000). For example, Stromen (1995) compared two methods of eliciting first graders’ ideas about forests, drawings and interviews, and found that interviews produced richer data than drawings. Smith and Brown (2014) emphasized the preferable validity of semi-structured interviews with younger students who have not mastered reading and writing skills yet. They explained that semi-structured interviews allowed for more credible responses because the interviewer could: (i) engage students more efficiently, (ii) probe further students’ way of reasoning and discard irrelevant answers, and (iii) use concrete materials such as pictures or physical objects to understand their reasoning. Given our sample of early elementary students and our goal to generate in-depth understanding of students’ reasoning about complex ecosystems, we adopted the semi-structured interview method.

As described above, the interview tasks used in the present study were revised based on the data collected in a pilot study. We present the final version of the interview tasks in this article. The interview questions were built around two scenarios. As presented in Table 2, each variable is assessed by a question set that contains one or more questions. Each Question Set contains one to six major questions that elicit student thinking.

Scenario I presents a picture showing a forest and lake. It has animals such as a frog, insect, opossum, wolf, fish, mouse, owl, small black bird. The picture was used from Dagher, Hajjar, Safi, and Sabeh (1999). We developed three question sets around this scenario in order to elicit students’ reasoning about three of the variables, including SS, SA, and DR. Table 3 presents two exemplar questions within each question set.

Scenario II consisted of giving students 15 pictures of biotic elements of plants (flowers, bush, shrub, tree), and animals (frog, squirrel, fish, bee, snake, robin, crab, millipede, cardinal, spider, rabbit, worm). In addition we gave them a picture combining abiotic elements (sun, clouds, land, Journal of Research in Science Teaching
water). We used this scenario to probe students’ understanding of circular connectivity (CC variable). In particular, Question Set 4 asked students to select pictures and use the pictures to construct a food web. The question set for this scenario was modified from an interview task originally developed by Leach et al. (1995). The original task included two sub-tasks: choosing six organisms that could live together for a long period of time without needing anything external, and choosing the population that is largest in size. In the pilot study, we found that students were often confused by the instruction that restricted them to picking only six organisms. Therefore, in the present study, we used the same organisms but allowed students to choose as many plants and animals as they wanted. In the interview, the pictures aforementioned were cut out and provided to the student. The first author then asked each student to choose as many animals or plants as the student wanted that can live in a place with sun, clouds, water, and earth. Next, the first author asked the student to justify his or her choices as the student was performing the task. After the student completed the task, the first author asked follow-up questions about plants or animals that were not chosen. These questions allowed the student to elaborate the rationales behind the student’s choices of organisms.

Data Analysis

We conducted interviews with 44 students from first through fourth grades. Each interview was transcribed and segmented into sections corresponding to the four progress variables (also the four question sets). We used the initial LP to score the interviews discuss the discrepancies in coding and revised and refined the LP to resolve the discrepancies. In this process of data analysis, we continuously revised the LP to enhance its validity. In particular, we found new patterns in the students’ responses that were not captured in the initial LP. Therefore, we conducted two major

<table>
<thead>
<tr>
<th>Progress variables</th>
<th>Interview scenario questions</th>
</tr>
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<tbody>
<tr>
<td>SS (Systemic Synthesis)</td>
<td>Scenario I: Six questions about the effect of changes in specific populations on other populations in the food web (Question Set 1)</td>
</tr>
<tr>
<td>SA (Systemic Analysis)</td>
<td>Scenario I: Two questions about the importance of producers and sunlight energy (Question Set 2)</td>
</tr>
<tr>
<td>DR (Dynamic Recycling)</td>
<td>Scenario I: Four questions about matter recycling through decomposition (Question Set 3)</td>
</tr>
<tr>
<td>CC (Circular Connectivity)</td>
<td>Scenario II: One question about constructing an interconnected food web (Question Set 4)</td>
</tr>
</tbody>
</table>

Table 2
Interview questions used to assess the progress variables

<table>
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<tr>
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<tr>
<td>CC (Circular Connectivity)</td>
<td>Scenario II: One question about constructing an interconnected food web (Question Set 4)</td>
</tr>
</tbody>
</table>

Table 3
Exemplar questions for scenario I

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>1. What would happen if all insects died?</td>
<td>1. What is the most important element that allows this system to be working properly?</td>
<td>1. If the fox died, what would happen to its body over time?</td>
</tr>
<tr>
<td>2. What would happen if all black birds died?</td>
<td>2. Do you think something is missing in this system?</td>
<td>2. If the fish died, what would happen to its body over time?</td>
</tr>
</tbody>
</table>
revisions of the LP. First, we found that some responses did not fit any level of the LP. Therefore, we created a new level to capture the emergent pattern in the data. For example, a second grader chose several organisms to build an ecosystem and explained that she chose those organisms “because we see those in nature all the time.” Responses similar to this one do not fit any levels of the initial LP. Instead, they suggest a new reasoning pattern that is captured in the final LP—“concrete practical reasoning”. The final version of the LP contains five levels. Second, some new patterns belong to the levels of the initial LP, but the descriptions of those levels are not specific enough to detail those patterns. To solve this problem, we created sub-categories within some levels to provide specific depiction of the new patterns. In brief, the strategies used to revise the LP include splitting levels, merging levels, and creating fine-grained sub-categories within a single level; these strategies are similar to those discussed in other articles about validation of learning progressions (Shea & Duncan, 2013).

Next, we performed two kinds of reliability checks. First, the first author trained a graduate student in science education on the coding scheme, and both the first author and the graduate student coded all 44 interviews separately. We performed Cohen kappa and obtained a score of 0.794 which is considered high enough to eliminate agreement occurring by chance. (Fliess, 1981). The agreement in coding was over 85% across all interview questions. Second, we used Cronbach alpha to check for the internal consistency across the interview questions within each variable. As elaborated above, each variable is assessed using a question set contains one to six questions: Question Set 1 (six questions) for the SS variable, Question Set 2 (two questions) for the SA variable, Question Set 3 (four questions) for the DR variable, and Question Set 4 (one question) for the CC variable. Since only one question assesses the CC variable, we did not calculate alpha for CC variable. The results suggests high consistency across the six questions for the SS variable ($\alpha = 0.725$), and the four questions for the DR variable ($\alpha = 0.702$), indicating the questions likely measure the same construct. However, the consistency across the two questions for the SA variable was low ($\alpha = 0.150$). Therefore, we considered the coding results for those two questions separately in the follow-up analysis.

Finally, we used the rank correlation method (Cohen, Cohen, West, & Aiken, 2003) to investigate to what extent students’ proficiency, as measured by the LP, is linked to grade level. In particular, individual students’ proficiency is represented in the five levels of the learning progression for each variable (or question) described above.

Results

In this section, we first describe the levels of the LP. Then, we explain “the mixed-level reasoning,” a pattern emerging from our analysis of the interview data. Finally, we present the correlation analysis results.

Levels of the Learning Progression

We developed an empirically grounded LP based on the interview data. The LP consists of five levels across the four progress variables: anthropomorphic reasoning, concrete practical reasoning, simple causal reasoning, semi-complex causal reasoning, and complex causal reasoning. Table 4 shows the five general levels across four progress variables. In this section, we discuss each level in detail. More examples for each progress variable at each level are provided as a supplementary material.

Level 1: Anthropomorphic Reasoning. Level 1 is the lower anchor of the LP. Level 1 responses are defined as anthropomorphic reasoning because students reason about interactions in ecosystems based on personal feelings. At this level, students do not refer to any objective
<table>
<thead>
<tr>
<th>Level</th>
<th>SS (systemic synthesis)</th>
<th>SA (systemic analysis)</th>
<th>DR (dynamic recycling)</th>
<th>CC (circular connectivity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Identifying human characteristics or aesthetic reasons as effects to the change of population without any reference to external mechanism.</td>
<td>Identifying an irrelevant element in the ecosystem as the most important due to the feeling of power/identifying the missing element due to personal liking.</td>
<td>Relating what happens to a dead animal to spiritual or human feelings.</td>
<td>Relating their choice of populations to the personal liking of those populations.</td>
</tr>
<tr>
<td>2</td>
<td>Identifying concrete or practical effects to population change/e.g., relating poison to the death of the animal that consumes it only.</td>
<td>Identifying an important element because they see a lot of it in nature/identifying elements that are missing because they are part of the nature they see everyday.</td>
<td>Relating what happens to a dead animal to what they see in real life, such as disappearing, or rotting without further elaboration.</td>
<td>Relating their choice of populations to being part of the nature they see in their everyday life.</td>
</tr>
<tr>
<td>3</td>
<td>3a-identifying a direct effect on ONE population that feeds on the removed population/relating the effect of the poison to the loss of food source of other animals OR death of the animals the eat the poisoned animal. OR Identifying the direct effect on the ONE population that they themselves feed on.</td>
<td>Identifying a reason that is logically sound (e.g., plants giving oxygen) but is not related to energy for the importance of plants or another population.</td>
<td>Relating what happens to a dead animal to ONE external factor such as soil or predation by another organism.</td>
<td>3a-relating their choice to the habitat that the populations live in. 3b-relating their choice to a ONE way eating relationship like squirrel eats nuts. A⇒B</td>
</tr>
<tr>
<td>4</td>
<td>4a-identifying the effect of a population removal to more than one population that feed on it. OR Identifying the effect of a population removal to more than one population that it feeds on.</td>
<td>Identifying two reasons to justify their choice of the importance of plants on another populations. OR Identifying two populations with a logical reason for each.</td>
<td>Relating what happens to a dead animal to more than one factor such as worms and fungus or soil and air.</td>
<td>Relating their choice to the habitat they live in AND the organisms they feed on.</td>
</tr>
</tbody>
</table>

**Table 4**

Final learning progression for ecological systemic reasoning
<table>
<thead>
<tr>
<th>Complex causal reasoning (reasoning that considers a network of relations which recognizes the complexity in an ecosystem).</th>
<th>Level</th>
<th>SS (systemic synthesis)</th>
<th>SA (systemic analysis)</th>
<th>DR (dynamic recycling)</th>
<th>CC (circular connectivity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relating the effect of the poison to the death of other animals that eat the poisoned animal AND loss of food source for other animals.</td>
<td>4b- Identifying the effect of population removal to the population that feeds on it AND the population that it feeds on OR Identifying of a mutualistic relation that benefits both populations.</td>
<td>Identifying the web-like relationship in the ecosystem and that one change in one population will influence all other populations in the ecosystem.</td>
<td>Identifying the critical importance of sunlight and plants because they are the primary producers of energy in the ecosystem.</td>
<td>Relating what happens to a dead animal to the breakdown of matter that can be used by other organisms or can be recycled in the ecosystem.</td>
<td>Relating their choice to the network of feeding relationships of populations of the organisms that constitute a food web in the ecosystem.</td>
</tr>
</tbody>
</table>

![Diagram](https://via.placeholder.com/150)

Relating the effect of the poison to being transferred in the whole food web from one population to another.
mechanism or cause. One excerpt from an interview with a third grader is provided below to illustrate Level 1 for systemic synthesis. The student used human feelings (i.e., sadness and care) as the reason of the changes in populations.

Interviewer: What would happen if all foxes die?
Student: The foxes have families too, and whoever cares about them they would be sad.
Interviewer: Will other animals be affected?
Student: If the possum tells his family tells about it, that would be very sad.

Level 2: Concrete Practical Reasoning. Unlike students relying on Level 1 reasoning, students using Level 2 reasoning do not use personal feelings to explain changes in ecosystems. Instead, they explain phenomena using obvious patterns identified based on their everyday experience with the material world. Students relying on Level 2 reasoning are not able to identify invisible or hidden mechanisms. It appears that these students tend to think “concretely.” Therefore, we define Level 2 as concrete reasoning. The excerpt below was from an interview with a first grader. It focuses on the systemic synthesis variable. The student described a pattern based on her experience with life cycle—the insects just get born again and again.

Interviewer: What would happen if all insects died?
Student: New ones will come.
Interviewer: How?
Student: They just get born again and it keeps repeating over and over.
Interviewer: And if they did not have babies?
Student: We wouldn’t see any more insects because they’re dead.
Interviewer: Anything else may happen?
Student: No.

The response above shows that the student considers not seeing the insects as the only major result on the environment if insects were removed. This is the kind of reasoning considering practical concrete observations without any reference to a causal mechanism.

Level 3: Simple Causal Reasoning. At Level 3, students are able to explain how external factors cause changes in ecosystems. However, students’ thinking is at a simple causal level, meaning that they identify single rather than multiple factors. For example, they often identify only one external factor that influences ecosystems, or only one population or other ecosystem component that is influenced by a certain change. When explaining the effect of changing one population on other populations within a system, students only identify the population directly feeding on that population. When explaining decomposition, students only identify one physical
factor. At this level, sub-levels exist for the systemic synthesis variable and the circular connectivity variable. Those different sub-levels represent qualitatively different ways of reasoning within the simple causal reasoning category. For example, for the systemic synthesis variable, some students recognize the mutualistic relationship between birds and plant. This mutualistic relationship is different from predator–prey feeding relationships. Therefore, we assigned the explanation using mutualistic relationship to a sub-level different from the sub-level where explanations are based on feeding relationships. A common theme across the sub-levels within level 3 of the systemic synthesis variable is that students are considering one external factor in their answers; they do not consider multiple factors that influence the ecosystem. Here we illustrate this level by the following two examples. The first example is from a third grade female.

Interviewer: What would happen if all black birds died?

Student: The fox will probably eat more possum.

The response above shows that the student is considering a simple cause effect relationship to reason about how one population feeds on another population directly related to it in the food chain.

The second example is from a second grade male:

Interviewer: What would happen if all black birds died?

Student: No flowers because they make more flowers each time they eat the nectar.

This second example shows a causal relationship that considers the mutualistic and not a predator/prey relationship between the birds and the flowers which is another sub-category of this level.

In addition, for the dynamic recycling variable, four students (out of 44) mentioned that there was a reason for rotting, but none of them knew the reason. Because these students recognize the existence of physical factors, we scored their responses as level 3. One example is provided below.

Interviewer: What will happen to the body of the fox when it dies?

Student: It will get rotten.

Interviewer: How?

Student: It will be really old and super hard to eat.

Interviewer: What will happen to it after one year?

Student: It will turn into soil, the bones kind of disappear and turn into soil and the skin gets eaten by worms and it disappear.

Interviewer: How will it disappear?

Student: I don’t know how it disappears, but I know that bones disappear in the soil. I really don’t know the reason. I’m still trying to learn that.

Journal of Research in Science Teaching
Level 4: Semi-Complex Causal Reasoning. Responses at Level 4 take into account multiple external factors affecting an ecosystem. Students at this level begin to consider the complex interactions in the ecosystem by reasoning about various causes and effects. Only beginning with this level, students’ responses suggest an early awareness of the complexity of ecosystems. More specifically, students recognize that changes in one population may influence more than one population in the ecosystem. For example, a student recognizes that if insects are removed from the ecosystems, several populations are affected such as the frogs and the birds. They are also able to identify multiple external factors for decomposition. However, students do not recognize that a change in a population can influence many more populations that do not have direct feeding relationship with that population which in turn influences the whole ecosystem. We illustrate this level by an example by a second grade male:

Interviewer: What would happen if all insects died?
Student: Frogs, beavers and black birds would have no food and they would die.

The above response shows the reasoning is considering more than one population that are being affected by the insect.

One may argue that level 4a of the systemic synthesis variable is similar to 3a because both consider the influence of direct predator–prey relationships. However, responses at level 3a in Table 4 recognize the effect on only one population, while responses at level 4a considered the relationships among several populations (level 4a in Table 4). Griffiths and Grant (1985) would group these two types of responses into one level because they require the same skill (recognizing only the effect on direct populations). It is important to note that Griffiths and Grant’s study was done with 10th grade students, whereas our study was conducted with lower elementary students, who have not received any formal instruction. For research on lower elementary students, teasing apart one reasoning pattern into more fine-grained sub-levels is important because it provides rich descriptions of students’ reasoning that is less influenced by instruction, and therefore less familiar to science researchers and educators.

Level 5. Complex Causal Reasoning. At this level, students recognize a network of relations in an ecosystem, which reveals a more advanced understanding of the complexity of ecosystem than level 4 understanding. This is the level where students consider the interdependency among organisms and recognize effects on multiple elements which resulted from a specific change happening to one element. Students consider changes in the system as a whole and not as separate entities. This means that students begin to reason systemically (note: we did not see any level 5 seconds for dynamic recycling). We illustrate this level by a response from a grade four female:

Interviewer: What would happen if all plants died?
Student: If plants died, all animals would die, first it’ll be the bugs, then the ones that eat the bugs, then the ones that eat small animals and then the big animals and then and we would die too because we have no food.

The above response shows a chain of reaction that influences all the system. Note that we considered two perspectives when defining level 5. Grotzer and Bell (2003) claim that the recognition of the “domino-effect” factor—any changes in one population influence all other populations, is a sophisticated view. However, Robertson et al. (2012) warn us about considering any kind of population change detrimental and resulting in collapsing the whole ecosystem: “[t]he
nature of interconnectedness of systems is overstated, for example, removal of one species leads to system collapse” (p.349). Therefore, we solicited an ecologist’s perspective. Below is the ecologist’s analysis on the above students’ responses, which we initially thought could be scored as level 5:

It’s exactly the kind of response that could lead you in either direction, right? On the one hand, this response could be interpreted as “everything linked to everything else”, but on the other — I’m inclined to think it’s relatively a sophisticated 4th grader. The reason I’m more inclined to believe the latter is because she articulates the nature of the connections. I think that when students truly don’t understand, and employ the “everything connected to everything” strategy as a response, you’re far less likely to see them explain “why” everything would collapse — they’re likely to say “it just would” with no indictment of mechanism. In this response, the student is clearly showing her knowledge of trophic structure for this community. Thus, her reasoning is clear, but it is narrow b/c it is focused only on food, and not other interactions that shape ecosystem structure. (T. Long, Personal communication, June 12, 2012).

Therefore, we define level 5 responses as those that not only recognize the interdependency among organisms, but also include reasoning that justifies the interdependency.

Mixed-Level Reasoning

Even though the word “progression” may imply a linear pathway to reasoning, this does not mean that students will necessarily pass from level 1 through 5 in a linear way. A student may be at level 2 and move straight to level 5. Most researchers agree that LPs describe a certain level of reasoning rather than delineating a linear learning trajectory for specific content. Heritage (2008) cautions that, “[w]hile the concepts and skills may have specific precursors, learning does not always take place in a linear trajectory” (p. 14). Johnson and Tymss (2011) empirically examined a learning progression on the concept of “substance” and found non-linear patterns. Our findings also suggest non-linearity—some responses in our data did not strictly belong to a specific level. For example, during the discussion about one specific question, a student may first provide Level 3 reasoning, and later used Level 2 reasoning. It appeared that some of our participating students were using “mixed-level reasoning.” Mixed level reasoning was indicated when a student switched between different levels of reasoning when responding to a single question. Table 5 shows the frequency of responses that indicate mixed-level reasoning for each interview question. Altogether, we found mixed-level reasoning in ten questions.

Table 5
Percentages of students using mixed-level reasoning to answering individual questions

<table>
<thead>
<tr>
<th>Progress variables</th>
<th>Questions</th>
<th>Number of students using mixed-level reasoning</th>
<th>Frequency of mixed-level reasoning (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>SS-Q1</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>SS-Q2</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>SS-Q3</td>
<td>10</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>SS-Q4</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>SA</td>
<td>SA-Q1</td>
<td>7</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>SA-Q2</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>DR</td>
<td>DR-Q1</td>
<td>9</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>DR-Q2</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>CC</td>
<td>CC-Q1</td>
<td>20</td>
<td>45</td>
</tr>
</tbody>
</table>

Journal of Research in Science Teaching
The highest frequency of mixed-level reasoning appeared in responses for the circular connectivity variable (almost 50% of students), where students were asked to create a viable environment. The question for the circular connectivity was very open, requiring students to build a system rather than analyzing an existing system. Under such situation, students could consider several factors for constructing their environment. For example, they could consider their personal liking or relate their choices to human characteristics. High frequencies of mixed-level reasoning also appeared in responses for the systemic synthesis variable (about 20–25% of students). In responses to the questions for the systemic synthesis variable, most mixed-level reasoning episodes contained responses at level 1 (anthropomorphic reasoning) and responses at level 2 (concrete reasoning). Table 6 in the supplementary materials provides examples of mixed-level reasoning episodes for each progress variable. An excerpt from an interview with a second grader is provided below as an example of mixed-level reasoning.

Interviewer: What would happen if all foxes died?

Student: Chickens will be safe and the farmers wouldn’t have to take care of the foxes anymore and the fish would be happy to survive but owls would still eat them. (Level 1; Level 4)

Interviewer: Is this good?

Student: No, because the foxes make sure there’s not too many chicken (Level 3).

The student’s responses in the above excerpt indicate several levels of reasoning. The response to the first question indicates levels 1 and 4 simultaneously because the student related human emotions to the animal, but at the same time recognized that the foxes influence many other populations up and down the food chain. The student’s response to the second question (Is this good?) suggests Level 3 reasoning because the student understood that the top carnivore keeps many other populations down.

Correlations Analysis Results

As elaborated in the methods section, we calculated the correlations between student proficiency and grade level. For each individual student, the proficiency is measured in terms of five scores: one score for SS variable (average score), two scores for SA variable (one for each question), one score for DR variable (average score), and one score for CC variable. The correlation results are provided in Table 6. As shown in Table 6, grade levels are correlated with student proficiency in SS variable. For other variables, there was no significant correlations between student proficiency and grade level or between student proficiency and gender. These results suggest that student understanding of interactions in ecosystems does not progress much over grade levels, although ecosystems is an important topic at elementary schools.

Table 6

<table>
<thead>
<tr>
<th></th>
<th>SS</th>
<th>SA-Q1</th>
<th>SA-Q2</th>
<th>DR</th>
<th>CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>0.374(*)</td>
<td>0.222</td>
<td>0.095</td>
<td>0.278</td>
<td>0.071</td>
</tr>
</tbody>
</table>

*Correlation is significant at the $p \leq 0.05$ (2-tailed).
Discussion

This study provides two implications for LP research: (i) the importance of considering grain size in defining a LP, and (ii) the importance of students’ mixed-level reasoning for defining LPs. Moreover, it has practical implications for how to teach systemic reasoning at lower grades.

Grain Size: Zooming in and Out of the Learning Progression

Researchers distinguish between large-grained LPs and fine-grained LPs (Alonzo, 2012; Mohan & Plummer, 2012). It is important to consider the purpose of the LP in determining the grain size: Broader LPs may serve to refine standards and large-scale assessment, while narrower LPs may serve to support curriculum and instruction and formative assessment in the classroom (Furtak, 2012; Lehrer & Schauble, 2015).

The LP developed in this study is fine-grained which distinguishes our study from other LP studies about the same content topic—interactions in ecosystems. Among studies about interactions in ecosystem, the study of Griffith and Grant (1985) provides a relatively small grain size. They categorized the food web model into “subordinate” and “super-ordinate” skills. Although they did not use a LP language, their study provides a progression that describes increasingly more sophisticated reasoning patterns. They found five hierarchical levels of students’ reasoning about food webs. The lowest level consisted of a reasoning pattern that considered the direct predator–prey effect. The highest level consisted of a reasoning pattern where students considered how changing one population in one food chain affected another population in a different food chain. Our LP provides an even more fine-grained distinction among younger students’ reasoning patterns. For example, we differentiated the understanding of predator-and-prey relationships into two levels: direct predator–prey relationship at level 3, and direct predator and several prey populations at level 4.

It is worth noting that our bottom-up approach honored students’ ideas. Gotwals & Alonzo (2012) emphasize the importance of a bottom-up approach in illuminating students’ ways of reasoning and teasing apart the middle levels that are usually hardest to identify. The bottom-up approach allowed us to differentiate various middle levels for lower elementary students. By doing this, we provide a fine-grained depiction of younger students’ informal ideas before they are formally exposed to the instruction. Using the bottom-up approach and incorporating students’ ideas, our evolutionary LP (Duschl et al., 2011) can provide teachers with rich depictions of students’ ideas which can be used as resources of learning.

Explanations of Mixed-Level Reasoning

When examining students’ ideas, we found many instances of mixed-level reasoning, with implications for defining LPs. Although LP researchers, in general, agree that learning is not linear, there is an assumption that a specific level can be assigned to an individual student. However, Lehrer and Schauble (2009) note that students exhibit variation in their reasoning, and thus locating a student strictly to one level is not authentic. Alonzo and Steedle (2009) found that students’ responses to assessments about the same underlying ideas in force-and-motion concept did not always fall into the same level and Gotwals & Songer (2010) identified instances of different levels of student reasoning about food web interactions depending on the context. Our evidence similarly suggests that defining LPs as having clear-cut levels might be problematic.

In our study, students who reasoned at levels 3, 4, or 5 often also showed reasoning at lower levels such as level 2 and level 1 all while reasoning about a single question. As described in the results section, the highest frequency of mixed-level reasoning occurred for the circular connectivity reasoning (the question which required students to construct a viable ecosystem).
One reason may be that the question was very open, allowing students to consider many different factors for constructing the ecosystem. However, this mixed-level reasoning also existed in other questions. A major pattern showed that students tended to reason at Level 1 and Level 2 simultaneously when responding to one question. For example, students mentioned that if a predator population died, the prey would not be eaten and it would be happy and some students mentioned that, if the fox died, its body would rot, and its family would be sad. These responses include both simple causal reasoning (Level 2) and anthropomorphic reasoning (Level 1). We propose two possible explanations for using anthropomorphic and simple causal reasoning within one episode.

The first explanation is based on Piaget’s (1966) distinction between the world of the child and the world of scientists. A child’s world is full of intentions and subjectivity in what Piaget calls “transductive” reasoning, while the world of the scientist largely depends on “physical determinism” or “deductive” reasoning. Piaget classifies the stages that the child passes through to reach “objective” causality. The child first starts with subjective reasoning (e.g., A pebble is heavy because he thinks so), moves to reciprocity (e.g., the pebble is light for the child himself, but heavy for water), and to relativism (i.e., relating the concept to others such as relating the density of one object to the density of another object). However, even as a child moves to a later stage, the child may return back to egocentric ideas in some situations. It is possible that the students who exhibited mixed-level reasoning in our study demonstrated an “adherence to subjectivity,” while developing understanding of the material world.

The second explanation of mixed-level reasoning draws on conceptual change theories in science education. Zohar and Ginossar (1998) found that high school students often used anthropomorphic explanations because it was easier to communicate ideas, not, necessarily, because they were thinking at lower levels. Vosniadou (2007) coined the term “synthetic models” to refer to students’ schemas when they assimilate school science knowledge into their existing naïve frameworks. She points out that although the synthetic models are not exact scientific models, they do indicate development in students’ knowledge. In our study, the mixed-level reasoning could be likened to “synthetic knowledge” where students are developing more sophisticated reasoning (rather than reverting to lower levels as Piaget suggests). Alonzo (2010) considered that using mixed-level reasoning may be one way for students to use everyday language as they learn a scientific discourse (also see Mohan et al., 2009). These findings suggest that the theory of “knowledge in pieces” (diSessa, 1996) could be used to define levels of a LP (e.g., students demonstrate more coherence in their reasoning over time). It is possible that students hold a set of loosely connected ideas, and these ideas can be activated based on the context. When at a lower level, students demonstrate more incoherence in their reasoning; when they learn more formally about the topic, they can apply ideas more consistently.

Thus, rather than thinking of a LP as having pure levels, one might think of a hypothetical LP that takes into account mixed-level reasoning by including a measure of consistency in reasoning. This type of LP may be used to illustrate the non-linear way of students’ reasoning. A gold standard for LP research requires longitudinal studies with the same students (Corcoran, Mosher, & Rogat, 2009). Because these longitudinal studies have not been completed, the idea of mixed-level-reasoning could be considered as a way to help us understand how early elementary students reason about scientific phenomena.

**Practical Implications**

This study showed that young students, as early as first grade, were able to begin systematic reasoning about interactions in ecosystems. Our findings suggest that students may enter the
classroom with anthropomorphic ideas, but that even young students were often able to articulate concrete and simple causal reasoning. This suggests that it is possible (and important) to provide students with opportunities to make sense of ecosystems in order to lay the foundation for future learning. Other researchers have found that computer simulations and modeling are productive tools to support students’ systemic reasoning in early grades (Assaraf & Orion, 2010; Evagorou et al., 2009). For example, teachers may use computer simulations to have students identify several components of general systems, and identify relationships (structure, behavior function as advocated by Hmelo-Silver et al., 2007) as a first step. Jacobson and Wilensky (2006) also agree with beginning with this approach and emphasizing the importance of supporting students in reasoning about the emergence and feedback loop in complex systems. Grotzer and Bell (2003) found that modeling population interactions with third graders promoted systemic reasoning. Similarly, Lehrer and Schauble (2012b) report on the LP across elementary grades when using students’ ideas to model changes that happen in the ecosystem.

The second implication for curriculum and instruction is related to the mixed-level reasoning results. Knowing that many students move back and forth between levels for specific concepts, promoting discourse in the classroom is critical for both allowing students to learn more sophisticated systemic reasoning and also for teachers to support these new types of ideas by providing feedback to students (e.g., see Wright & Gotwals, in press). When teachers hear mixed-level reasoning, they can work with students on ways of talking “like scientists” and the importance of disciplinary-specific ways of reasoning (e.g., see Cervetti, Barber, Dorph, Pearson, & Goldschmidt, 2012). Similarly, if the LP could capture ways in which mixed-level reasoning moved from less to more sophisticated, teachers may be able to use the LP to guide the types of formative assessment opportunities they provided and the feedback that they gave to students (Furtak & Heredia, 2014). This idea of making students’ thinking visible suggests that future research could investigate the ways in which teachers used the LP to support student learning about systemic reasoning in different ecosystems.

We would like to thank Dr. Hui Jin for her feedback on earlier versions of this manuscript.

Note

1 By mutualistic relationship, we refer to a relationship that benefits two populations: for example, insects use flowers to feed on their nectar, but at the same time, they help pollinate other flowers which help in their reproduction.

References


