Science Education International
34(4), 339-346
https://doi.org/10.33828/sei.v34.i4.9

ORIGINAL ARTICLE

Learning Progression of Students' Reasoning about Life Cycles

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ABSTRACT

This study explored elementary students' reasoning about the life cycles of various organisms, including insects and amphibians. The study took place in a private school in Lebanon with 24 fifth-grade students. Students participated in a life cycle unit with pre and post-written assessments about what they learned and interviews to help determine their reasoning about life cycles. Using our findings, we suggest a learning progression (LP) approach to guide students over time in their learning about life cycles and their importance for species persistence within an ecosystem. Two LPs were developed from this study: Reasoning about the cyclic nature of life and comparison of life cycle stages. Overall, students improved their understanding of the cyclical nature of life, but comparing organisms' structures, stages, and life cycles proved to be more challenging. These LPs have direct implications for elementary instruction about life cycles, organisms, and species.

KEY WORDS: Elementary students; learning progressions; life cycle; reasoning

INTRODUCTION

Complex systems in science contain multiple variables that interact and affect each other, including processes and patterns in the system. Studies of complex systems investigate change, adaptations, and processes within them. Systems are studied in various science fields such as biology, chemistry, computer science, earth science, ecology, physics, physical science, and engineering (Yoon et al., 2018). This systematic thinking is a holistic view of science, biology, and ecology. Ecosystems in ecology are an excellent example of complex systems. Not only are there a multitude of organisms interacting ecologically, but there are underlying micro-processes that may not be seen but have implications for the community and ecosystem. Most studies of complex systems focused on three significant characteristics: Structures, processes, and stages (Yoon et al., 2018). Life cycles depend on specific structures, processes, and stages for organisms to grow and reproduce for species, food webs, and ecosystems to persist. Therefore, to meaningfully understand the life cycle, students need to look at the whole cycle, including relating the structure and function of the organism to its life cycle stage.

As described by Next Generation Science Standards (NGSS Lead States, 2013), the life cycle is a core idea in the life science standards describing the relationship between molecules and organisms and structures and processes. The NGSS suggests students learn about the life cycles of different species and identify the different stages within the life cycles, along with the changes in structure and function between stages. Life cycles are important for students to learn about because this is the course of organism development in relation to how species persist in a community, which ties into more significant ideas of ecology. Students also need to learn about life cycles and how they engage them in the natural world around us. These NGSS standards are supported in the literature investigating students learning about life cycles (Duncan et al., 2017). Throughout instruction, students should learn important concepts about life cycles, such as organisms having diverse life cycles and similarities such as birth, growth, reproduction, and death. Another important understanding is that life cycles are a description of a single organism to grow and reproduce and for species to persist. After establishing this understanding, students can work to learn about how life cycles help species continue after an organism's death or compare the life cycles of different species.

In elementary school science instruction, insects and plants are commonly used for students to investigate life cycles in action (Barrow, 2002; Chen and Cowie, 2013; Shepardson, 2002; Zangori and Forbes, 2014). The National Research Council (1996) suggests that these organisms are excellent for students to learn about structure and function processes. While these are good examples, students should be exposed to various life cycles so their learning is not constrained or context dependent on the organisms they encounter. Exposure to multiple species will help students see the typical patterns of birth, growth, reproduction, and death. Previous studies have found that some students' understanding of insects and life cycles is constrained by classroom instruction and informal experiences with the organisms (Barrow, 2002; Shepardson, 1997).

Despite some literature concerning students learning about life cycles, little is known regarding how students reason about different life cycles and how they compare them. This study used a learning progression (LP) approach to develop a fine-grained description of student reasoning about life cycles. LPs are hypothetical models showing how students scaffold knowledge and ideas to understand concepts better over time. Learning is naturally a progression, and this construct gives checkpoints by grade, level, or other hierarchical organization to build up big ideas or concepts in science. These progressions begin with a concept students need to learn, followed by researching how students reason about these ideas and build knowledge. Using the LP for life cycles, we evaluated students' learning outcomes of an inquiry unit about life cycles.

We consider the cyclical nature of the life cycle and compare different cycles as our progress variables as we pose the following research questions:

1. How do students reason about the cyclical nature of the life cycle? And how does that differ after formal instruction?
2. What are students' levels of reasoning (LP) when comparing different life cycles? And how does that differ after formal instruction?

LITERATURE REVIEW

Students struggle to understand complex systems' structures, processes, and stages because most interactions and processes are non-linear (Ghazal and Hokayem, 2023; Gotwals and Songer, 2010; Hokayem, 2016; Hokayem and Gotwals, 2016). Understanding linear relationships between two organisms or two variables is less challenging than reasoning about non-linear relationships with three or more variables. Studies have found that students understand the function of individual structures but struggle when reasoning how multiple structures in systems are related and interconnected and how structures influence functions within the system (Ben-Zvi Assaraf and Orion, 2010; Hmelo-Silver et al., 2007). The structures are easier to identify than the behaviors and processes of the structures in the system (Hmelo et al., 2000; Hmelo-Silver and Pfeffer, 2004; Hmelo-Silver et al., 2007). New curricula and tools have been created for complex systems, but more focus should be placed on how students learn about these systems and understand the components and their relationships. Yoon et al. (2019) call for LPs to help students understand complex systems and align with the NGSS that calls for more learning pathways to guide instruction and curriculum in a developmentally coherent way.

Gotwals and Songer (2010) used a LP approach to investigate students reasoning about food chains, focusing on the students' intermediate levels of knowledge or those that had some knowledge but lacked a complete understanding. When moving from a lower anchor to an upper anchor of thinking, there is often a "messy middle," as students may have multiple pathways and types of knowledge while moving to a more sophisticated level of thinking. In this study, students reasoned about the complex situations in a food chain and how disturbances in an ecosystem affect the food chain or food web. The study found that students may know the content knowledge but fail to apply the knowledge to scientific explanations. This finding supports the "messy middle" idea that students understand some parts but not the whole. It is easy to make an endpoint for students to reach but difficult to guide them on pathways to the end when not all paths are the same.

Shepardson (1997) investigated first graders' ideas about the life cycle of insects, specifically butterflies, and mealworms. He found that students held three models of understanding insect life cycles. The first is the non-metamorphosis, or one-staged model, where students believe that the animal only grew larger over time. The two-staged model demonstrated students' belief that insects pass from the larva to the adult stage, which skips the pupae phase. Last, with the three-staged model, students believed the insect changed from larva to pupa to adult and did not include the transformation from the egg to the larva. The third model was the most common and may result from students' lack of exposure to the egg stage of the life cycle. Other studies have also shown that students' understanding is constrained to the organisms demonstrated during classroom instruction, lack of exposure or observation of stages, and informal experience with the organisms outside the classroom (Barrow, 2002; Chen and Cowie, 2013; Shepardson, 2002).

Shepardson's (1997) study in determining three models of understanding was influential in laying the terrain of students' reasoning. Still, more details are needed to explain students' reasoning about the life cycle and how they compare different life cycles. The instruction constrained student understanding of life cycles to the organisms used, such as beetles and butterflies. This context affected their ability to compare life cycles between organisms because students related all life cycles to these two insects. Another study investigated K-6 students' knowledge about insects and found that overall, students did not understand life cycles and that <25% understood the differences between complete and incomplete metamorphosis (Barrow, 2002). This finding differed from Shepardson's (1997) study; however, one second-grade student in Barrow's (2002) study identified the egg as a life cycle stage, which Shepardson did not find in his third model. The researchers believed that this was due to students' informal experience with the organism, which can be positive during instruction. Turning informal experiences into meaningful education is attributed to the teacher, who plays a vital role in mediating students' everyday experience with formal instruction because these experiences influence knowledge construction in the classroom (Driver et al., 1994).

A study concerning life cycles emphasized modeling practices to investigate how students understood plant life cycles, specifically a modeling practice that allowed students to provide evidence-based explanations (Zangori and Forbes, 2016). This study also found that when students lacked the knowledge of life cycle stages to compare them to other organisms, they tended to anthropomorphize plants or animals, which means that they compared their life cycles to humans. This tendency can lead to misconceptions and shows the importance of investigating student reasoning about the life cycle to help students reach a more informed understanding. While communicating with scientists about the life cycle concept, the idea of the cycle continuing through another organism in the species and correctly classifying an organism was also important. Instruction needs to place more importance on life cycles for not only the single organism but also the species as a whole and community dynamics up to the ecosystem level. These dynamics are foundational concepts in ecology that can be applied to higher levels of thinking about the dynamics of a community or ecosystem. Therefore, we argue that more research is required to identify the students' different reasoning levels concerning life cycles.

CONCEPTUAL FRAMEWORK

We adopt LPs as our theoretical framework to understand students' reasoning about life cycles. LPs are "descriptions of 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. 214). LPs describe students' thinking from a naïve to a more sophisticated level of reasoning, including several intermediate levels. In a recent literature review of LPs, which spanned work from 2006 to 2018, the authors recognized the importance of LPs in describing students' reasoning from intuitive to scientific thinking (Jin et al., 2019). The authors revealed the need to develop more LPs for use in classrooms and investigate more LPs of the core ideas. Thus, research implications for how to teach life cycles stem from how students' thinking develops. According to Shepardson (1997), the main challenge for student reasoning scientifically about the life cycle is the physical constraint which prevents students from seeing how the organisms really "transforms" from one stage to another. His recommendation was to involve students in more observations of the different life cycle stages of representative organisms and have them analyze what they observe at each stage.

So far, much of the LP work stemmed around matter, energy, ecosystems, genetics, force and motion, and astronomy as core ideas (Alonzo and Steedle, 2009; Duncan et al., 2009; Plummer and Maynard, 2014). Other work on LPs involved modeling practices (Hokayem and Schwarz, 2014; Songer *et al*., 2009; Schwarz et al., 2009). For example, Schwarz et al. (2009) developed a LP using modeling to generate predictions and scientific explanations and examine how knowledge models change according to students' understanding. In addition, the researchers developed instructional activities to track students' improvement across the levels, ranging from students explaining one phenomenon based on observation to using models across various contexts. However, this LP considering modeling practices is difficult to project onto students' reasoning about life cycles. Although life cycles account for structural variations among organisms, it is more concerned with individual and population organizational levels. In contrast, the modeling practices (Schwarz et al., 2009) involve more abstract concepts (molecular level). Thus, an LP on life cycles should focus specifically on the cyclic nature and transformative processes. These processes include structural and functional transformations among the same or different organisms. Therefore, we use the LP framework to determine students' lower, intermediate, and higher reasoning levels based on their responses about the life cycles. Specifically, we map students' reasoning levels about the cyclic nature of life cycles and how students compare life cycle stages among different organisms. The reason for selecting these two criteria is that (a) the continuity of a life cycle is one of its main features and (b) determining similarities and differences among various life cycle stages between organisms reveals students' stepwise thinking of how this complex process occurs.

METHODS

Context and Participants

The life cycle is a core idea for students to learn about in elementary school (NRC, 2012). The participants in this study were 24 fifth-grade students (ages 10 and 11 years) in a private school[1] in Beirut, Lebanon. There were fourteen males and ten females[2]. The first author taught all students the life cycle unit developed by the researcher. The native language of the students was Arabic, and English was their second language. However, they learned science and mathematics in English.

Data Sources

The data sources consisted of pre/post-written assessments and pre/post-semi-structured interviews carried out by the researcher.

Pre/post-written assessment

We designed the written assessment with eleven short answer questions. Each question tried to capture what students understood about the cyclic nature of life cycles (research question 1) or how they could compare different life cycles (research question 2). For example, one question asked students why different living or non-living things (e.g., frogs, ladybugs, and erasers) have a life cycle. Other questions asked students to define a life cycle and use a model to describe a particular life cycle. We asked specific questions about differences in the life cycles of frogs and butterflies to address students' reasoning about comparing life cycles.

Pre/post-interviews

The interviews also targeted both research questions. We designed the pre-interviews into two parts: (a) General

1. This private school served middle socio-economic middle class students. It's the school where the first two authors know well, and so building relationship with the students facilitated teaching the unit and created a positive atmosphere of learning.
2. Consent forms were signed by the parents and all ethical procedures were followed according to IRB.

questions about the life cycle to understand if/why students think of the life cycle as a cycle and (b) questions about pictures of different life cycle stages. These pictures included stages of three organisms (butterfly, frog, and mealworms) in one envelope that students arranged into different life cycles. The post-interview consisted of the same pre-interview questions but included questions about two new organisms they did not learn about in class (salamander and cockroach) to determine if the students could transfer their knowledge after instruction.

The Life Cycle Unit

Regarding the unit, we used the constructivist approach to involve students in activities, analysis, and reasoning about the life cycle of various organisms. The unit lasted for ten periods and was implemented over 3 weeks. Students learned about the butterfly and frog life cycles in earlier grades, and we wanted to determine how much they understood the concepts surrounding these organisms. In a designed-based approach (Collins et al., 2004), the first author implemented the unit in the classroom following the inquiry model, and as such, she made some modifications depending on the needs of the students. For example, after finding out in the pre-interviews that the students did not understand the idea of the life cycle, the first author adjusted the unit to start the unit with a discussion of what a cycle means, how they can find examples of different cycles in the world, and explain why they are cycles. Following this introduction, the unit consisted of activities, observations, discussion, and extraction of patterns about various organisms. The organisms under study were the frog, the butterfly, the mantis, the mealworms, and the humans. During this session, participants worked in groups (cooperative learning) to classify and group pictures of the life cycles of different organisms. They also physically investigated the different stages of a particular organism (the mealworm). This investigation followed the scientific method to understand the transformation of mealworms in the life cycle. We introduced the mealworms as a new organism they were unfamiliar with to examine their understanding. The class worked in six groups, and each group had mealworms they observed, measured, and recorded daily observations about to note any occurring changes for discussion with the rest of the class. They also engaged in group and classroom discussions after watching videos, grouping stages of life cycles, and interacting with the mealworms.

For the frogs and other insects, the students experienced videos and discussed the changes happening for those organisms. For the human life cycle, we collected pictures from all students at different stages of their lives, their parents' lives, and their grandparents' lives. We then had each group represent the life cycle of humans and discuss the similarities/differences of the human life cycle with the other organisms. The unit ended with a research project where each group selected an organism of their choice, researched its life cycle, presented it to the class, and then compared it with an organism they learned about in class.

Data Analysis

We transcribed all interviews verbatim. We analyzed the pre/post-assessments and pre/post-interviews similarly. First, the authors looked at two pre-test assessments, and using the constant comparative method (Strauss and Corbin, 1998), they derived general initial codes about both the reasoning levels about the cyclic life cycles and how students compared different life cycles. Upon agreeing on the initial set of themes, the researchers independently coded different responses on the pre-test. They discussed the codes again and revised them following a second round of coding to generate the most appropriate levels (Collins et al., 2004). The researchers returned to the data, re-coded students' answers accordingly, and then refined our codes in an iterative process consistent with the LP approach (Collins et al., 2004). The authors settled all disagreements through discussion.

Reliability

We established the reliability of the results through inter-rater agreement at the beginning of the pre-assessment analysis. First, the researchers discussed and practiced analyzing the student's responses. Then, we picked one pre-test randomly, and the researchers read it question by question together, depicting the reasoning level based on the developed codes of reasoning for the cyclic nature of life cycles and the comparison between different life cycles.

Then, following this practice, two pre-assessments were randomly selected, and each rater analyzed them independently. After comparing their results, the researchers noted common and different findings. The inter-rater reliability was calculated to be 90%. Since there was no considerable difference between the raters (interrater reliability was more than 85%), the researchers moved on to the second step, with a full analysis of all the assessments and interviews completed by the researchers. The researchers outlined the reasoning categories related to students' ideas about the cycles and their thinking levels as they reasoned about the similarities and differences between various cycles.

RESULTS

Students' Reasoning about the Cyclical Nature of the Life Cycle

Concerning the first research question about students' reasoning about the continuity of life cycles, we identified three levels. Table 1 describes each level and provides an example.

We assessed students' understanding of this progress variable using the pre/post-assessments. The bar graph below (Figure 1) shows the number of students who answered one question, which targeted the continuity of life cycles before and after instruction. The question was: "Using a model, show what a human's life cycle looks like. Models can include pictures, words, labels, etc. Add as much detail as possible. Describe what is happening."

As shown in the graph, no students recognized the cyclical nature of the life cycle in the pre-test. However, in the post-test, 16 students out of 24 recognized the cyclical nature of the life cycle. This was manifested by showing a linear model in the pre-test while showing the cyclical nature by drawing the arrow, which goes back to the fetus/baby (Figure 2).

As shown in the figure above, the student did not show either through text or diagram that the human life cycle is continuous in the pre-model. However, in the post-model, although the student provided fewer details about each stage, they indicated their comprehension that life cycles are repetitive using an arrow from the adult to baby stages. The pre/post-interviews also supported this data, where only two out of 14 students understood the cyclical nature of the life cycle in the pre-interview. However, in the post-interview, 10 of the 12 students discussed the cyclical nature of the life cycle. The following excerpt illustrates the pre/post-conversation (Table 2).

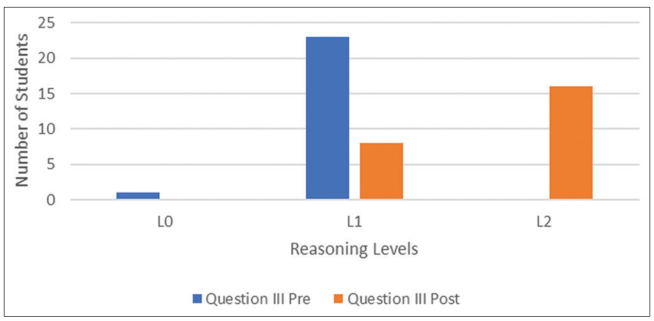

Figure 1: Students' reasoning levels for Question 3 in the pre and post-assessments

Concerning the second research question and progress variable of students recognizing the similarities and differences across different life cycles, the LP showed five levels (Table 3).

The LP generally ranged from students' ability to compare one stage of the cycle to identifying patterns among two or more stages. When students could align stages when a transformation in structure occurred, this idea reveals a higher reasoning level. Students identified similarities and differences among life cycles. For example, concerning the similarities, one student identified that the two organisms are born, grow, and reproduce for the cycle to continue. For the differences, the student recognizes the different body structures at different stages of life and relates that to the function of each life stage.

A sample question that illustrates this LP is question four, which requires students to list the similarities between the life cycle of a frog and that of a butterfly. The reasoning level results from question four are in the graph below (Figure 3).

As shown in the bar graph above (Figure 3), only one student responded at level 2 in the pre-test, whereas seven students had responses at levels 2 or 3 in the post-test. An example was a response from student 15, who moved on from saying that both the frog and the butterfly "are animals, lay eggs, and can be males or females" to saying in the post-test that "both change completely during their life cycle." Even though this is not a significant change, further probing during the post-interview indicated responses that showed that students recognized the structural differences of the stages rather than focusing only

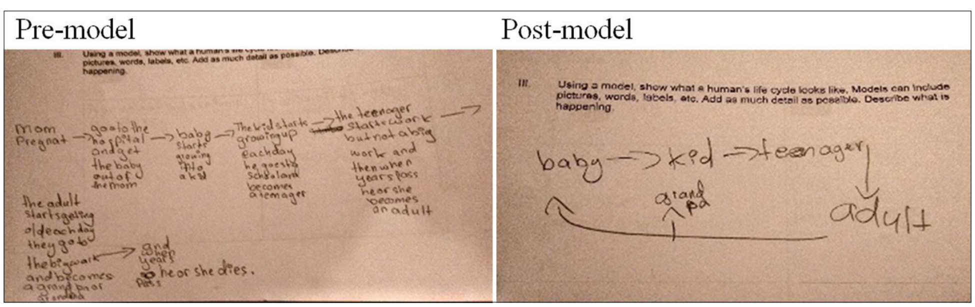

Figure 2: Student 22's responses about the human life cycle

Table 1: Students' reasoning levels about the continuity of life cycles

Level	Description	Example
L0	Students indicate no response or no understanding of the life cycle	A life cycle is a living thing *(the student provided an incorrect understanding of what a life cycle is)*
L1	Students identify that the life cycle of an organism includes a sequence of stages, ranging from birth to growth and then death.	The human is first an embryo when in his mom, then a newborn when his age is from 0 and 1 month, a child kid when 1–12 years old, a teenager from 13 to 19 years, and an adult when age is 20 till he *dies*. *(The student explained the different stages of the human life cycle (e.g., embryo, child, teenager, and adult) but does not indicate its continuity after death)*.
L2	Students identify the life cycle stages of an organism in addition to the repetition of the cycle through the offspring	First, there are eggs, then small mealworms, then bigger, and then a beetle, but if one of the beetles dies it doesn't mean the life cycle ended here because maybe before it dies it laid eggs, and these eggs will *continue* the life cycle. *(the student determined the life stages of a mealworm: mealworm, beetle, egg; and explained that the cycle continues)*

Table 2: Excerpt from Student 21's pre- and post-interview

Pre-interview with Student 21	Post-interview with Student 21
Do we have an LC, as humans?	I want to ask you what is the life cycle
Yes, first, we are in the womb, then we become babies after birth, and we grow.	It is the life stages that stages that stay repeating.
And where's the cycle? What happens when we grow older?	Like what?
We will die.	Humans have different stages, but they repeat.
And how does the cycle happen?	How?
Every animal will die.	First baby, then kid, teenager, adult, then grandpa and grandma.
So, why do we call it a cycle? Do you know what a cycle is? It continues. Do you think this is an LC?	How does it repeat? Does the grandpa die, for example?
No.	When he is an adult, he will have a baby that will continue the life.

Table 3: Learning progression on students' reasoning about life cycles

Level	Description	Example of student response
L0	Students indicate no response or limited understanding of life cycles	I do not know "When a frog is a tadpole and a butterfly a caterpillar, they look exactly the same." *(the student has a limited understanding about life cycles, as tadpoles and caterpillars are distinctly different despite potential superficial similarities in their appearances during this stage)*
L1	Students recognize ONE aspect (a similarity or difference) of different life cycles (e.g., habitat or change in body structure)	"They both [tadpole and caterpillar] hatch from eggs." *(the student identifies a similarity between one stage of the life cycles which is hatching from eggs).*
L2	Students recognize TWO aspects (similarities/differences) of different life cycles (e.g., Habitat and change in body structure)	"I think they [the grasshopper and butterfly life cycles] are different because the grasshopper does not hide in a cocoon and be a butterfly he will not be a caterpillar, but both hatch from eggs." *(the student identified two similarities and differences: a) hatching from eggs and b) the cocoon stage that is unique to a butterfly's life cycle)*
L3	Students recognize THREE aspects (similarities/differences) of different life cycles: (e.g., habitat and change in body structure)	"Both of them walk [grasshopper and beetle] but the difference is that the grasshopper jump and the beetle do not. Both hatch from an egg, and both of them are small at first then grow, both of them have six legs." *(a) The student compared the similarities and differences in the adult phase, such as walking or jumping and having similar physical features: six legs. (b) The student identified similar stages in their life cycle: hatching from eggs and c) growing in size to reach a later stage*
L4	Students recognize the structural/functional differences of the life cycles at EVERY stage	No student reached this level.

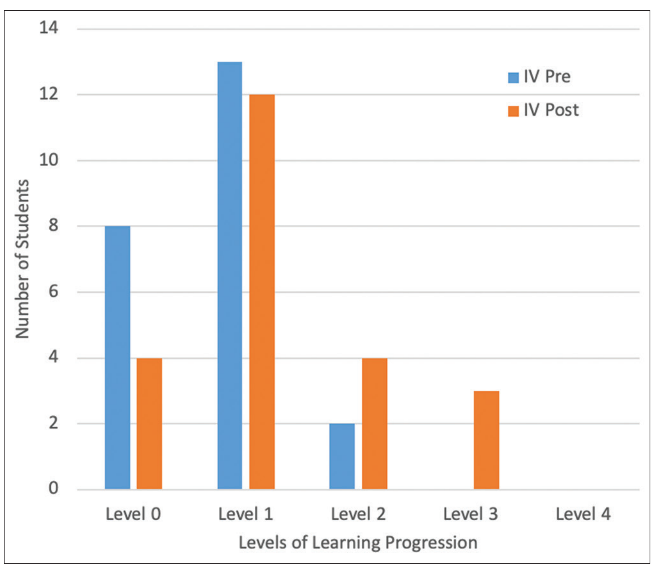

Figure 3: Students' learning progression levels for Question 4 in the pre- and post-assessment about similarities and differences between life cycles

on the organism's habitat. For example, all students in the interview were thinking of either habitat or some structural difference when changing a state (level 2), and four of the interviewed students were thinking of changing or more than one difference and even included the technical terms "complete/incomplete metamorphosis" (level 3). However, no students reached level four, where they could identify all the structural differences of the various stages of the different organism's life cycles.

DISCUSSION

This study revealed two significant results: The idea of the cycle in the life cycle requires explicit instruction, and the idea of recognizing and comparing different stages of life cycles is a difficult concept for students to grasp. Even when students could draw a cycle from memory, they could not, when probed further, understand how this cycle continued when the organism died. After the explicit instruction about the cycle, most students could realize that the life cycle refers to the species and not to one organism. Moreover, even when students could list the stages of the life cycle, the in-depth interview showed that students could not compare the life cycle stages in the same way as scientists do. Instead, students simply talked about behavioral differences, and after instruction, they could talk about the number of stages or the difference between stages. Only a few could relate the structure to the function (e.g., the mealworms), which could help students see how the organisms "transform" from one stage to another (Shepardson, 1997) and move students toward a higher reasoning level (Level 3).

This finding calls for more explicit instruction to relate the life cycles to the bigger idea of the structures and processes, which is what NGSS calls for. Whereas the life cycles of frogs and butterflies are standard in instruction, this constrains students' reasoning to just those organisms. We believe that more work is needed to think of the life cycle as a generic concept that can cut across the various organisms even if they do not have prior knowledge, as Shepardson (1997) notes.

This study has important implications for curriculum and instruction. The reasoning framework on the cyclic nature of life cycles suggests a need to explicitly teach that life cycles are repetitive. Instruction should point out that even though an organism dies, the species continues with newborn generations. Our results showed that students struggled to understand that the life cycle could continue with new offspring rather than one organism that died. This indicates that students should comprehend that life cycles involve several organisms of the same species. Even if one organism dies, the cycle could continue with younger generations. Therefore, textbook diagrams should include life cycles with several organisms at different developmental stages. This study contributes to the literature supporting the use of students' ideas and reasoning when planning instruction and creating curriculum (Driver et al., 1994).

CONCLUSION

The LP on the similarities and differences between life cycles also has implications for curriculum and instruction. For example, if students hold a level 1 of reasoning, teaching should compare every stage in different life cycles (e.g., egg stage, baby stage, adult stage) to move students to L2. Next, to promote students understanding from L2 to L3, teachers should explicitly point out that organisms develop differently and that not all resemble human development, where the organism keeps similar structural and functional features throughout. Thus, students would realize that some organisms transform, that is, some structural organs, and their functions change throughout the life cycle. Finally, to progress to L4, students should relate the similarities and differences among different life cycles to having a cyclic trajectory of events. In other words, a systemic, holistic comparison of the life cycles, including their stages, should be examined and not focus only on a few. Therefore, the curriculum should include comparative diagrams showing complete cycles independent of one another and the details of the similarities and differences in every stage of these cycles to provide both a holistic and detailed understanding. In the end, the aim is for students to develop a relationship between different levels of organizations: Structures, organs, individuals, and population levels.

LPs aim to guide students' understanding as they progress through science concepts. There need to be more LPs produced to give an overarching structure of how students reason about various science concepts. Thus far, there are LPs about evolution (Lehrer and Schauble, 2012), ecology (Hokayem et al., 2015; Hokayem, 2016; Hokayem and Gotwals, 2016; Hovardas, 2016), genetics (Duncan et al., 2009), carbon cycling (Mohan et al., 2009; Jin and Anderson, 2012), celestial motion (Plummer et al., 2015; Plummer and Maynard, 2014; Plummer and Krajcik, 2010), and biodiversity (Songer et al., 2009). Most LP research pertains to the middle to the high school level, and there is a need for more LPs at the elementary level. LP research has come a long way in the past 15 years and is an excellent approach to help with crosscutting concepts from the NGSS. The field aligns well with complex systems reasoning and is an excellent approach to help students build an understanding of complex systems over time. LP research provides opportunities to help improve curriculum and instruction with learning pathways for various topics in different grade levels, but there is still a need for more research to provide coherence in science curriculum and instruction.

Ethical Statement

This study was approved and followed all the protocols and ethical research standards of TCU IRB M-1903-111-1904.

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