Middle School Students' Learning in Energy flow and Matter Cycling in the Ecosystem

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Abstract: An ecosystem is a complex system, including multiple layers of organization, complex interconnections among components, and invisible dynamic processes. Research shows that learners' often see energy and matter in ecosystems as mostly a linear, not cyclic, pattern. This study examined 35 students' energy and matter models at three points (pre, mid, and post) and interviews from 7 students during a Compost unit focused on ecosystems. We coded the models to examine students' understanding of energy and matter over time and included excerpts to show students' ability to identify system components and understand energy flow and matter cycling. We found that more students explained energy flow by including observable and non-observable organisms and process. Even though more students explained matter cycling as cyclic by including invisible process (decomposition), this was mostly at a superficial level. Students also conflated the terms "matter" and "energy", often using them interchangeably. This indicates a need to better assist students explicitly understand the two processes and how they are connected.

Key words: complex system, energy flow, matter cycling

Introduction

Complex systems consist of interactions between multiple components at different levels of organization as well numerous patterns that emerge from these interactions (Ladyman et al., 2011; Yoon et al., 2018). Although complex systems commonly occur in the physical and natural world, students find it difficult to comprehend their non-linear, dynamic, and sometimes invisible nature (Wilensky & Resnick, 1999). Being able to recognize and reason how these patterns emerge and behave is critical to understanding ecosystems (Hmelo-Silver et al., 2017). Instead, students tend to recognize visible, linear relationships among components of an ecosystem (such as a predator-prey relationship), as opposed to understanding invisible and cyclic relationships (Hayes et al., 2017). Making sense of the more complex, non-linear, invisible, relationships are fundamental for understanding the dynamic nature of ecosystems.

Liu & Hmelo-Silver (2019) found that virtual models can help students focus on the interdependencies among the different components in a complex system. Instructional supports, such as a combination of virtual and physical models, could assist students in focusing on the important aspects while the learning content is complex (Puntambekar et al., 2020). For our study, we developed a 14-week, design-based "Compost" unit combining virtual and physical models, aimed at helping students understand energy transfer (manifest in the macroscopic process) and matter cycling (a microscopic process) in an ecosystem. We investigated students' understanding of the relationships between the different ecosystem components. Our research questions were: 1) How did students' understanding of energy flow and matter cycling change over time? and 2) How did students illustrate their understanding of the ecosystem components?

Methods

Context of the research

Thirty-five eighth-grade students in one science teacher's classes from a midwestern middle school in the United States participated in this study. Students participated in cycles of inquiry to iteratively learn about the science of decomposition and ecosystems to solve a design challenge to create a compost that broke down quickly and contained a lot of nutrients. Students built a physical compost bioreactor, where they input materials (such as food scraps) and observed how their compost broke down (or not), based on what they added to the bioreactor. They also used a compost simulation to isolate, investigate, and visualize how specific abiotic factors (such as water, particle size, and carbon to nitrogen ratio) impacted the microorganisms in compost ecosystems, thereby affecting decomposition.

Data sources and analysis

<u>Energy and matter models</u>
Students drew models to show how matter and energy flow at three points: before, at a midpoint, and at the end of the unit. Students included concepts such as sun (S), producers (P) (i.e., different plants), consumers (C) (i.e., different animals), dead organic matter (M), decomposers (D), and other abiotic factors. We created a coding scheme to assess students' models, with five levels of connections. A higher-level connection indicated an understanding of more complex connections between observable and non-observable elements. For example, the PMDP connection in level 3, PCMDP and SPMDP connections in level 4, and SPCMDP connection in level 5 showed that students understood the cyclical nature of how matter *cycles* through an ecosystem, i.e., decomposers break down dead organic matter down to its constituents, which is then available as nutrients in the soil for plants to uptake. Lower-level connections showed students' understanding of the linear relationships in the complex system, such as SP or PC.

Two researchers independently coded 23% of the data and achieved a 91.07% interrater reliability. The first author coded the remaining data. We used the non-parametric Friedman test to evaluate the overall differences from pre, mid, to post models. We then used the Wilcoxon Signed-Rank test to compare the connections that students made over time in each level, separately. We also examined the connections representing the cyclic nature of matter cycling.

<u>Student interviews</u>
Of the 35 students in this study, we conducted semi-structured interviews (about 30 minutes on average) with 7 students and asked them to interpret and explain their models. Excerpts from the transcribed interviews were grouped by three main topics: identifying system components, understanding energy flow, and understanding matter cycling.

Results

Changes in students' understanding of energy flow and matter cycling over time
We calculated the frequency of the number of correct connections between ecosystem components (e.g., SP, PCM, CMDP, etc.) in each level for all 35 students' pre, mid, and post models to examine learning over time. Using a Friedman test, we found that students included significantly higher-level connections in their models over time ($\chi^2_{(14, N=35)} = 362.97$, $p < .001$). Our follow-up pairwise comparisons using Wilcoxon signed rank tests, with a Bonferroni correction to control Type I error, showed students included significantly more level 5 connections from their pre to post, and mid to post models.

Students' connections of energy flow and matter cycling
As mentioned earlier, students often struggle to understand non-observable and cyclic aspects of complex systems. To understand how the Compost unit may have supported students' ability to recognize these relationships, we examined students' understanding of non-observable organisms and their interactions with other organisms in the ecosystem. The connections we examined are displayed in Table 1.

Table 1
Number of students who made connections at higher levels

Connections	Prior to curriculum	End of curriculum	Decomposition included or not	Linear or cyclic
SPCM (level 3)	10	19	No	Linear
PMDP (level 3)	0	10	Yes	Cyclic
SPCMD (level 4)	7	15	Yes	Linear
PCMDP (level 4)	3	13	Yes	Cyclic
SPCMDP (level 5)	2	12	Yes	Cyclic

When looking at students' connections related to energy flow at a visible and non-visible scale, we compared the number of SPMC (level 3) and SPCMD (level 4) connections students included in their models over time. Students made fewer SPCMD (level 4) connections than SPMC (level 3) connections both prior to and at the end of the unit. This indicates that understanding the direction of energy flow from matter to decomposers, which is unobservable in most cases, was challenging for students. However, when we compared the number of students who identified a SPCMD (level 4) connection prior to and at the end of curriculum, eight more students were able to incorporate these ideas into their model, showing that some students were able to build this understanding over time.

Next, we examined students' understanding of matter cycling as cyclic. We compared the number of students who made higher-level connections that incorporated the cyclic aspects of the complex system, PMDP (level 3), PCMDP (level 4), and SPCMDP (level 5) prior to and at the end of unit. We found that 10 more students included connections in each of these levels at the end of curriculum, showing that they made growth in understanding that matter cycling is a cyclic, rather than linear process.

Even though some students did make progress in understanding the cyclic aspects of the compost ecosystem, we found that the number of students who made linear connections was higher than students who were able to identify cyclic connections. Specifically, at the end of the curriculum, 19 students identified the SPCM (level 3) linear connection versus the 10 students identifying cyclical PMDP (level 3) connection; and 15 students identified the SPCMD (level 4) linear connection in comparison to 13 students with cyclical connection of PCMDP (level 4).

Students' explanations of their energy models

Students were generally able to identify system components within the ecosystem. However, we found that students had difficulty explicitly articulating what "matter" was. Further, some students conflated energy flow and matter cycling, using "matter" and "energy" interchangeably. For example, one student defined matter as "things that could be eaten, and the energy is compacted into food".

Energy flow in the ecosystem

We found that all 7 students were able to explain both the microscopic and macroscopic scales of organisms in the ecosystem (i.e., SPCMD) when discussing energy flow in their models, such as:

> "I started with the sun...our main source of energy for the producers sun goes to the producer ... grass gives energy to the cow...the consumers eat the producers and it's in chemical energy form, ... and then it goes as the consumers transfer energy ... I have some bacteria up here that ... could get energy from a decaying apple, and it eats part of it, and that's how it gets its energy"

In this example, the student explicated the process of energy being transferred from producers to consumers and further transferred to decomposers by breaking down (dead) plants/animals or leftovers from humans. While this student did not discuss breakdown of matter and uptake of these nutrients by plants, other students (incorrectly) discussed that energy is directly reused by plants at the end of the decomposition process.

Matter cycling in the ecosystem

Unlike in their descriptions of energy flow, where all students included information about the macro and microscopic scales, students' discussions about matter cycling as a cyclical process varied (see Table 2 for examples). In general, in more successful examples, students were able to articulate how matter was broken down by decomposers so that it could be used again by plants to start another cycle; Whereas, in less successful examples, students did not explain this. Further, even if students discussed matter cycling, their explanations were often vague and inaccurate.

Table 2
Examples of students' discussion of cyclic nature of matter cycling during interview

More Successful	Less Successful
"the matter is what humans, they eat it, and then what's left over that goes into the compost and then, earth worms and mold...eat that matter and then whatever is left that others things can't really eat is, um, is good for the soil and then producers can use it."	"when things die…the mold eats the matter, the dead matter, and the matter is mostly like it eats these because it's not like from the sun to the plants…[matter] is an actual thing, and it's not like just an energy flow. It's like the dead things...it's really hard to explain"

Discussion

We found significant gains in the complexity of students' understanding of these dynamic processes by including more components from mid to post models, demonstrating that some students could understand their interconnections. The students' increasing ability to see relationships between the ecosystem components revealed that their understanding of energy flow and matter cycling changed from simple to complicated over time. These findings are in line with prior studies which have suggested that students find it challenging to understand interconnections between components of complex systems (Grotzer & Basca, 2003; Hmelo-Silver et al., 2007)

We also observed that students could explain energy flow through both the observable and unobservable organisms in the ecosystem in their interviews. As other researchers have noted, students in this study found it less challenging to make connections between observable organisms and their interactions with the biotic and abiotic factors, as was evidenced by the frequency of level 1 and 2 connections made in their models. However, in line with Hayes et al., (2017), we found that a deeper understanding of the invisible processes such as the decomposition was less prevalent in students' written models. This highlights the importance of scaffolding students to see both the structures and dynamic changes in the systems (Opitz et al., 2017) to help them link the components to the processes.

Even though we made the unobservable processes of decomposition more observable via the compost simulation, many students did not include explanations about how matter is recycled and conserved (Grotzer et al., 2017). Similar to Lee & Liu's (2010) findings, few students included the highest-level connection (SPCMDP), between multiple levels of organisms in the ecosystem in their models and most were also unable to discuss connections at this level during their interview. Understanding decomposition at the microscopic scale is important for explaining the cyclical nature of matter cycling in the ecosystem.

Conclusion and Future Work

The combination of a physical bioreactor and a compost simulation in this unit may have helped students notice and learn about the unobservable processes (i.e., decomposition) occurring in ecosystems, since they showed a better understanding of decomposers' role in the ecosystem as well as the interrelationships among multiple organisms over time. Although some student's explanations showed growth in understanding energy flow, this was only a part of understanding the complex and interrelated nature of ecosystems. This indicates a need to better assist students in developing a more sophisticated understanding of the macro and microprocesses underlying the complex relationships between energy flow and matter cycling in ecosystems, specifically about decomposers' role in breaking down matter during decomposition. To help all students achieve a deeper level of understanding, more supports that enable students to explore and understand the role of decomposers and matter are needed. In future work, our aim is to understand how the compost simulation could better support students' understanding of the unobservable phenomena in an ecosystem, and how the simulation can be better integrated with the physical experiments.

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