Foregrounding Behaviors and Functions to Promote Ecosystem Understanding

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The ability to analyze complex systems is fundamental to ecology literacy (Jordan, Singer, Vaughan, & Berkowitz, 2009; Sabelli, 2006). Yet deciphering ecosystems is challenging because, like all complex systems, they transcend spatial, temporal, and cognitive boundaries (Pickett, et al, 1997) and necessitate understanding how different components and processes are interconnected (Covitt, Gunckel, & Anderson, 2009; Jacobson & Wilensky, 2006; Jordan et al., 2009; Mohan, Chen, & Anderson, 2009). Furthermore, complex systems are comprised of multiple interrelated levels that are dynamically related, making it difficult even for experts to understand and to predict (Simon, 1996).

The very nature of this complexity makes it challenging for learners to grasp associations and interactions among a system's components (Ben-Zvi Assaraf & Orion, 2005; Gallegos et al 1994; Penner, 2000). Often, learners focus on simple linear relationships and visible components of an ecosystem (Hmelo-Silver, Marathe, & Liu, 2007; Hogan, 2000; Hogan & Fisherkeller, 1996; Leach et al. 1996; Reiner & Eilam, 2001). For example, when asked to draw or name components of an aquarium system, novices tended to emphasize visible components, such as fish and rocks, and rarely mentioned invisible components, such as oxygen, nitrogen, and bacteria (Hmelo-Silver, Marathe, & Liu 2007; Hmelo-Silver & Pfeffer, 2004). Grotzer & Basca (2003) also report that student explanations favor single causal and linear connections between system components.

In this paper, we present the results of a technology-intensive classroom intervention designed to support middle schools students' understanding of an aquatic ecosystem. The goals of our intervention are to help learners develop deep understanding of ecosystems and to use tools that make the relationships between a system's structures, behaviors, and functions explicit.

Aquariums as Models for Learning

To help students understand complex systems, we implemented a two-week aquarium unit that was designed by a team of learning scientists, middle school classroom teachers, and ecologists. The technology consisted of a suite of computer tools: a function-oriented hypermedia (Liu & Hmelo-Silver, 2009), simulations of macro- and micro-level processes (Liu & Hmelo-Silver, 2008; Gray et al. 2008), and the Aquarium Construction Kit (ACT; Goel et a. 2010; Vattam et al. in press).

Our instructional approach builds upon structure-behavior-function theory (Goel et al., 1996; Goel et al., 2009). The structure-behavior-function (SBF) approach is useful to explain dynamic systems with multiple components and levels (Goel et al., 2009; Liu & Hmelo-Silver, 2009). We view SBF theory as providing a conceptual representation that is consistent with both canonical explanations in biological systems and with expert understanding (Bechtel & Abrahamson, 2005; Hmelo-Silver et al., 2007). In addition to helping students organize their system knowledge, the SBF representation provides a scaffold for overall knowledge organization.

In a biological system, structure refers to components of an ecosystem that have form, such as fish or cells. Behaviors represent the processes within systems. These refer to mechanisms such as photosynthesis or nitrification. Functions refer to the outputs of a system or the role(s) of a particular structure within a system. An example of a function would be that fish produce energy.

Technology Support for Learning about Complex Systems

It is difficult for learners to understand many aspects of ecosystems because they have not had opportunities to engage with those processes that are dynamic and outside their perceptual understanding (Jacobson & Wilensky, 2006). In addition to helping students organize their system knowledge, the SBF representation also provides a scaffold for overall knowledge organization because it helps learners consider the relationships among form and function as well as the causal behaviors and mechanisms. We make SBF explicit through the use of hypermedia, organized in terms of SBF (Figure 1), through NetLogo simulations that make behaviors visible (Figure 2a and b) and through the ACT tool (Figure 3a and b), which makes SBF explicit as students build models using the language of the SBF conceptual representation.

Figure 1. Function-centered hypermedia

Along with the hypermedia and ACT tools, students also used NetLogo simulations to learn about the behaviors and functions in an ecosystem (Wilensky & Reisman, 2006). Using these simulations, (Figure 2) students had opportunities to explore factors that would affect the dynamic balance in the aquarium. For example, the macro fish spawn simulation allowed students to manipulate different aspects of the ecosystem such as initial population, spawning rate, filtration level, and amount of food. Thus if the students overfed the fish, then the increasing ammonia (from fish excretion) in the water would affect water quality and have toxic effects on the fish, leading to mortality. This helped problematize water quality, which is a black box in the macro simulation. This created the need for students to identify some of the invisible components within an ecosystem. For example, using the micro-level simulation, students could observe how crucial the nitrification cycle is for the overall health of an ecosystem and understand the important role that bacteria play in converting toxic forms of nitrogen (ammonia) into less toxic forms of nitrogen.

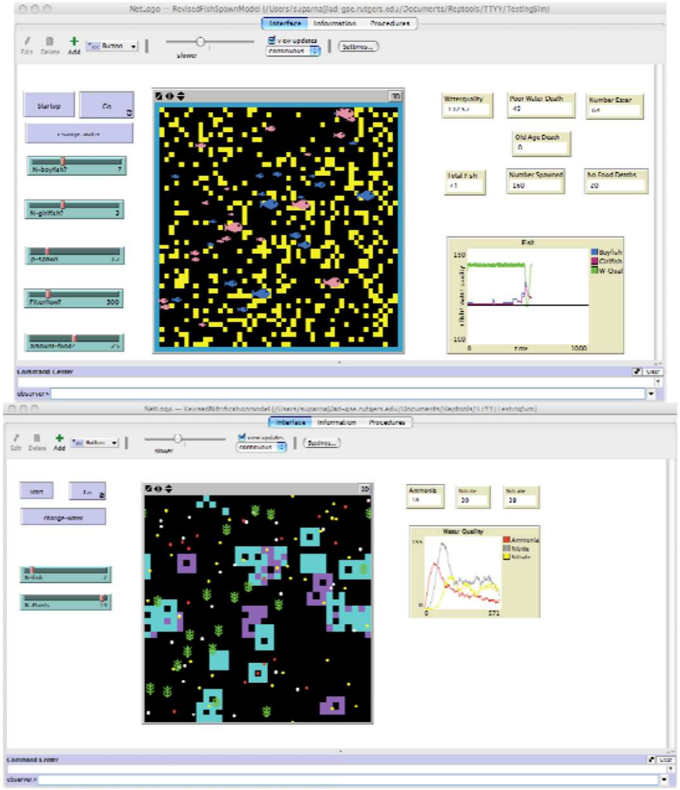

Figure 2. NetLogo Fish Spawn and Nitrification simulations

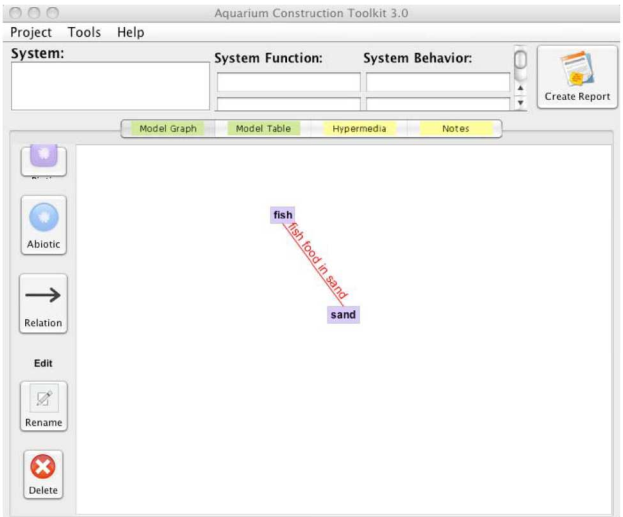

Figure 3a. ACT: A space to create models

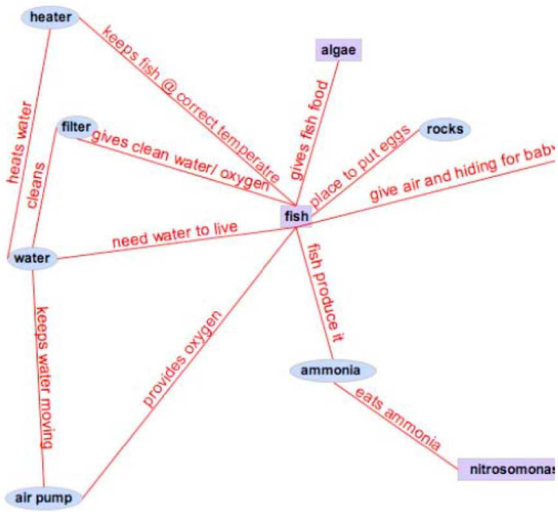

Figure 3b. ACT: Example of model created by a student.

Instructional Context

The science teacher introduced the unit by asking students to articulate their ideas about the functions of ecosystems. This allowed the teacher to gauge the students' prior knowledge. The teacher then moved on to the ACT modeling tool and asked the students to represent their thoughts about ecosystems as structures behaviors and functions. The students recorded their ideas in a table within the ACT tool (Figure 4).

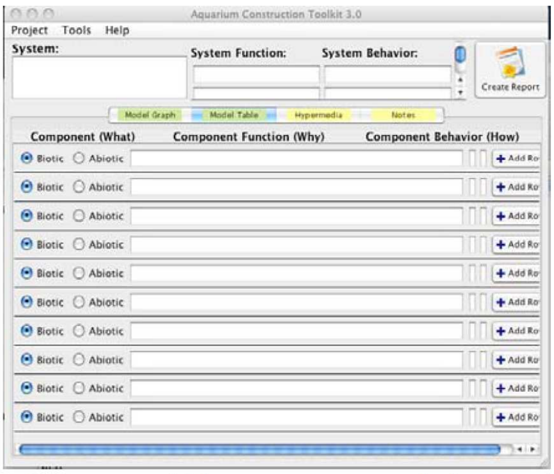

Figure 4: ACT table where students record ideas as structure, behavior, and function

The teacher also encouraged the students to use the hypermedia to build on their ideas about the ecosystems. The teacher then asked students explore the NetLogo simulations. In the simulations, students could manipulate various ecosystem components (e.g., number of fish, amount of food, number of plants) in order to maintain a healthy ecosystem (Eberbach & Hmelo-Silver, 2010). The students worked in groups and had opportunities to refine their models. At the completion of the two-week period, students presented their models to the rest of the class.

Methods

Participants

Fifty-four seventh grade students from a suburban public middle school in the northeast United States participated in this study during their regular science instruction.

Data Sources

The students completed tests before and after the intervention. In each pre and post-test, students drew components of an aquatic ecosystem and were asked to show relationships between these components. In addition, students answered open-ended questions about different parts and processes of an aquatic ecosystem as well as solved problems related to ecosystems.

Coding for pre and post tests

The scoring criteria for the pre and post tests are summarized in Table 1. All of the questions (17) were coded based on two different scoring schemes. The first examined student explanations of relationships between structures and their related behaviors and functions. The codes were assigned to the answers/explanations on a four-point scale, shown in the upper part of Table 1. Each response was scored for the complexity of the SBF relationship the student identified.

We also coded for whether the students were able to identify and explain relationships between micro and macro elements within an ecosystem. Only eight of the 17 questions were coded for Macro and Micro (MM) level because only these questions provided opportunities for students to explain both micro and macro level connections. The other questions on the assessment were specific to either macro or micro elements within an ecosystem. The micro-macro relationship score was assigned as shown in the lower part of Table 1.

The following student response on the importance of 'waste' to the aquatic ecosystem illustrates how these scoring schemes were applied. The student wrote:

> Waste is normally produced by organisms such as fish. It contains ammonia. Through the nitrogen cycle, bacteria breaks it down into nitrite then nitrate (which is a less toxic form of nitrogen), which is then used for plant growth.

The response indicates the presence of multiple structures, such as fish, ammonia, bacteria, nitrites and nitrates. We considered "waste" as a structure; we coded "bacteria breaks it down" as behavior and "which is then used for plant growth" as its function. We assigned this response an SBF relation score of 4 as the student has identified at least one structure in relation to behaviors and functions. In addition, we assigned this response the maximum score of 3 for the micro-macro coding it as reflects connecting macro (waste) and micro (ammonia, nitrogen cycle) level structures and processes. Inter-rater reliability was calculated by having two independent raters code 20% of the sample. The overall reliability was 87% agreement.

Table 1. Scoring criteria for pre and post test

SBF Relation	Explanation	Score
No Answer		0
S	Identifies structure **without connecting** to other structures, behaviors, or functions. Ex: "An aquarium has fish, gravel, and bacteria." Ex: A drawing with no connections (written or drawn).	1
S:S	Identifies some relationship **between** structures. Ex: "Bacteria are in the gravel." Ex: A drawing with connections but no elaboration (written or drawn).	2
S:B or S:F	Identifies structures in relation to behaviors **or** functions. Ex: (B) "Fish eat the food." (F) "Fish get energy." Ex: A drawing with connections and elaboration (written or drawn).	3
S:B:F	Identifies structures in relation to behaviors **and** functions. Ex: "The fish eats food to get energy." Considerations: -Students may include many individual SB's and SF's, but to code an answer as SBF, the all three must reflect some relationship to each other. -SBF thinking is not necessarily represented in one sentence as the example here.	4
Micro/Macro Level	**Explanation**	**Score**
No Answer		0
Macro or Micro	Identifies **only** macro **or** only micro structures or processes.	1
Macro + Micro	Identifies **both** macro **and** micro structures or processes.	2
Macro ⇆ Micro	Identifies some **relationship between** macro and micro structures or processes.	3

Results

All pre and post tests were compared using a paired t-test. Overall, we found significant gains on all measures from pre to post test as show in Table 2. The maximum score for the SBF relationship is 68 and for macro-micro is 24. We found that students reached near ceiling at posttest on both coding schemes, with moderate to large effect sizes.

Table 2. Results for Pre and Post Tests (*n*=56)

	SBF relationship	Macro – Micro score
Pretest Mean (SD)	50.07 (24.68)	15.23 (6.48)
Posttest Mean (SD)	64.30 (17.75)	22.71 (6.62)
$t(55)$	3.43*	5.99*
Effect Size	0.66	1.14

*$p < 0.001$

Discussion

The results show that using SBF as a tool for instruction helps students deepen their understanding of relationships within a system. Post-instruction, the relationships that students identified were more complex. Students were more likely to identify relationships between the parts and the mechanisms of the system. In addition to considering relationships across different levels of the system (i.e., across structures, behaviors, and functions), students, post-intervention, were more likely to generate ideas at both macro to micro levels, connecting the visible to the invisible. Indentifying more invisible structures and relations is not surprising as it is a major focus of our instruction, but the connections across different scales of a system, we contend, are a robust consequence of SBF oriented instruction.

The SBF language provides students with the opportunity to develop a conceptual framework where multiple levels and non-linear phenomena can interact. Traditionally, such integration about ecosystem abstractions has been difficult for students. As Linn and Hsi (2000) argue, students' ideas are often distinctly linked to particular contexts and experiences, and confronting novel ideas can cause cognitive conflict. In addition, if students are generating ideas about complex systems in pieces (as suggested by DiSessa, 1993), requiring the students to see the relevance of these pieces or cognitive resources when encountering a problem may be a fruitful approach. Although this remains to be tested, perhaps the SBF framework provides students with a "glue" to link ideas not only about the system being studied but also to the cognitive resources they already hold. Certainly SBF-oriented instruction has resulted in more sophisticated reasoning about problems related to complex systems (e.g., Liu & Hmelo-Silver, 2009). Our future directions include an investigation into the potential for SBF instruction to result in students' ability to transfer ideas from one complex system to another.

Acknowledgements

We thank Swaroop Vattam for his contributions to earlier parts of this research. This research was funded by the Institute for Education Sciences under Grant # R305A090210. Opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of IES.

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