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Technology-Supported Inquiry for Learning about Aquatic Ecosystems

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Understanding ecosystems is challenging, but important for becoming environmentally-literate citizens of today's society. People have difficulty considering how different components, mechanisms, and phenomena, both visible and invisible, are interconnected within ecosystems. This research presents both the design and initial testing of an innovative and technology-intensive classroom intervention. This intervention was designed to support middle school students' understanding of an aquatic ecosystem through encouraging explicit Structure-Behavior-Function (SBF) conceptual representation of ecosystems. The technology support included hypermedia organized around SBF, NetLogo simulations, and an SBF modeling tool. Our study analyzed pre- and post-test data coded for SBF relationships generally, and relationships between Macro- and Micro-level (M-M) structures, behaviors, and functions, using 311 students in the classrooms of four science teachers. We found moderate to large effects of our intervention with students' understanding of SBF relationships and recognition of M-M level relationships increasing over time. The increased consideration of relationships derived from the SBF intervention is important for a more sophisticated understanding of ecosystems in middle school science classrooms. Additionally, by using the SBF framework, micro-level systems phenomena might be made more salient for young learners.

Keywords: Conceptual representation; ecosystems; modeling; Structure-Behavior-Function; technology

INTRODUCTION

Systems thinking is quickly becoming a requisite for science literacy and is part of the cross cutting concepts in the Next Generation Science Standards (National Research Council, 2012). Furthermore, being able to analyze complex ecosystems is fundamental for becoming ecologically-literate citizens (Jordan, Singer, Vaughan, & Berkowitz, 2009; Sabelli, 2006); and therefore, considerable effort in the life sciences is focused on the development of tools to support complex biological system reasoning. Here, we build on current innovations in K-12 systems thinking development (see Jacobson & Wilensky, 2006; for a review), by providing students with a language for the development of conceptual representations which can accompany tools intended to scaffold students' understanding of ecosystems.

Making sense of 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, mechanisms and phenomena are interconnected (Covitt, Gunckel, & Anderson, 2009; Jacobson & Wilensky, 2006; Author, 2009; Mohan, Chen, & Anderson, 2009). Furthermore, complex

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State of the literature

- Systems thinking is an important aspect of science and ecological literacy and is a component of new science standards but they are challenging for students to understand, with particular difficulties in thinking about micro-level phenomena and systems behaviors and function, and the relationships across system levels.
- Experts consider structures, behaviors, and functions and their inter-relations in their thinking about complex systems.
- Structure-behavior-function theory is a conceptual representation that has been fruitful in creating hypermedia for teaching about systems.

Contribution of this paper to the literature

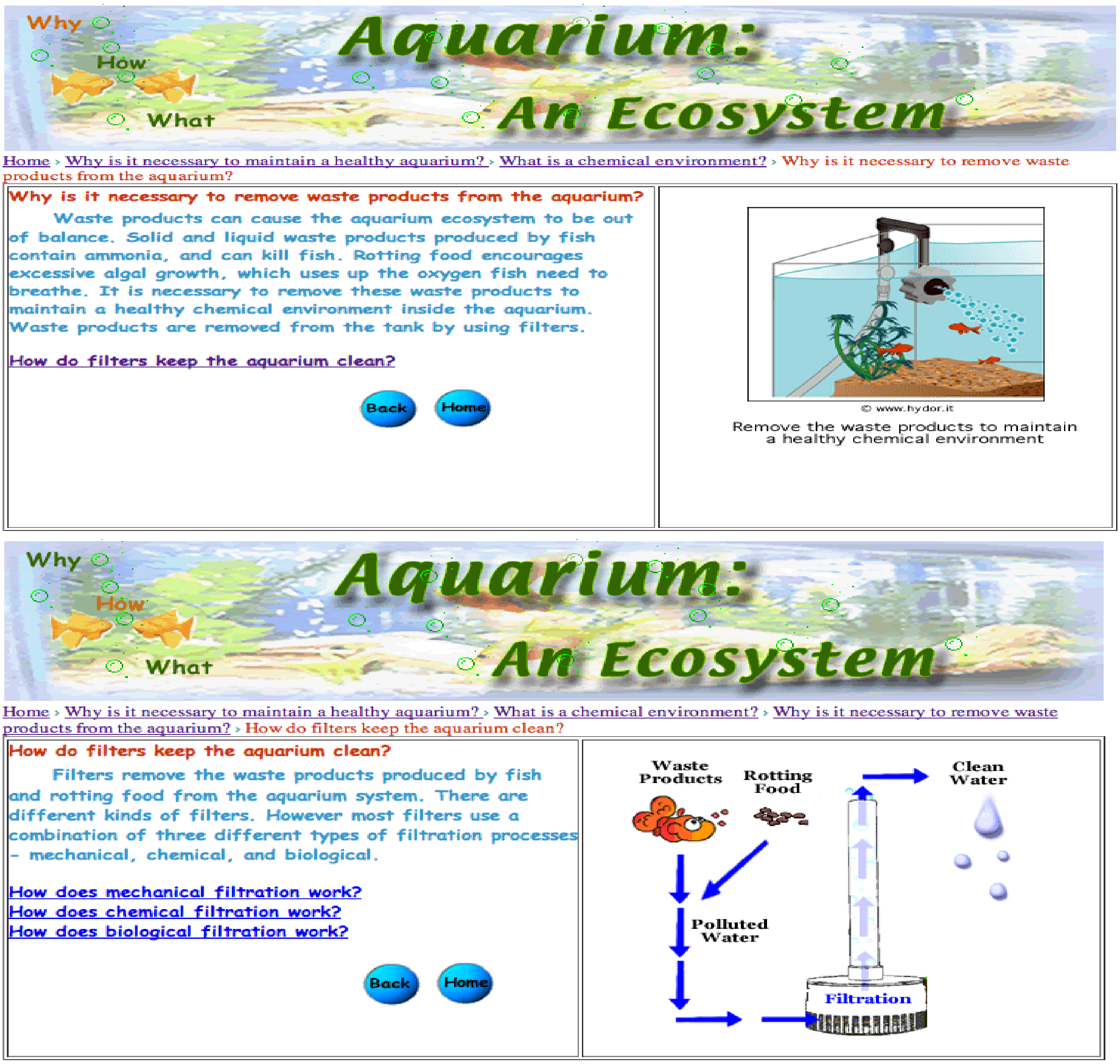
- This study evaluates the use of a technology-rich curriculum unit organized around the structure-behavior-function (SBF) conceptual representation to teach about aquatic ecosystems.
- A pre-post test design with 311 middle school students examined their understanding of how students identified and connected across levels of structure-behavior-and function and macro-micro levels.
- Students demonstrated statistically significant gains in their understanding of SBF and macro-micro relationships.

systems are comprised of multiple interrelated levels that are dynamically related. This makes it difficult even for experts to understand and to predict (Hmelo-Silver & Azevedo, 2006; Jacobson & Wilensky, 2006; Simon, 1996).

Many studies have demonstrated that it is particularly challenging for learners to grasp relationships within systems (Ben-Zvi Assaraf & Orion, 2005; Gallegos, Jerezano, & Flores, 1994; Penner, 2000). Often, learners focus on simple linear relationships and visible components of an ecosystem (e.g., Hmelo-Silver, 2007; Eilam, 2012; Hogan, 2000; Hogan & Fisherkeller, 1996; Leach, Driver, Scott, & Wood-Robinson, 1996; Reiner & Eilam, 2001). In clinical interviews, when novices were asked to identify features of an aquarium system, they were likely to emphasize visible components, such as fish and rocks, and rarely mentioned invisible components, such as oxygen, nitrogen, and bacteria (Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver et al., 2007). Other research has found that student explanations favor single causal and linear connections between system components (Grotzer & Basca, 2003). Moreover, learners tend to think about ecosystem dynamics as a series of discrete events rather than continuous processes (Ben-Zvi Assaraf & Orion, 2005, Grotzer, Kamarainen, Tutwiler, Metcalf, & Dede, 2013). A promising approach for promoting systems thinking in a way that can enable students to think about multiple interacting components and their fates is encouraging Structure-Behavior-Function (SBF) thinking (Vattam, Goel, Rugaber, Hmelo-Silver, Jordan, Gray, & Sinha, 2011). An SBF model of a system explicitly represents its structure ("S"; i.e., the configuration of components and connections), its behaviors ("B"; i.e., the internal causal processes that enable the functions of the components into the functions of the system), and its functions ("F"; i.e., the output of the system or system components).

Empirical research has demonstrated that experts represent complex systems in terms of interrelated structures, behaviors, and functions, whereas novice understanding is characterized primarily by identifying isolated structures, demonstrating minimal understanding of functions, and largely missing system behaviors (e.g., Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver et al., 2007). Based on this research, we hypothesize that embedding the SBF conceptual representation in a suite of technology tools including a function-oriented hypermedia (Liu & Hmelo-Silver, 2009), simulations of macro- and micro-level processes (Eberbach & Hmelo-Silver, 2010; Liu & Hmelo-Silver, 2008), and the Aquarium Construction Toolkit; (Vattam et al., 2011), should improve students understanding of complex systems. Recent research supports this notion that learning through the use of models and simulations supports the development of knowledge about complex systems (e.g., Buckley & Quellmalz, 2013; van Borkulo, van Joolingen, Savelsbergh & de Jong, 2012). Moreover, there have been numerous studies that demonstrate that agent-based modeling can support helping learners make connections across different systems levels (e.g., Dickes & Sengupta, 2013; Levy & Wilensky; 2008; Wilensky & Reisman, 2006). However, much of the research with agent-based models has been based on case studies or research with relatively small numbers of students (but see Levy and Wilensky, 2009 for an exception with high school chemistry students).

In this research, we present both the design and initial testing of an innovative and technology-intensive classroom intervention in the form of a two-week aquarium focused unit designed to support middle schools students' understanding of an aquatic ecosystem. The goals of our SBF 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.



Home › Why is it necessary to maintain a healthy aquarium? › What is a chemical environment? › Why is it necessary to remove waste products from the aquarium?

Why is it necessary to remove waste products from the aquarium?

Waste products can cause the aquarium ecosystem to be out of balance. Solid and liquid waste products produced by fish contain ammonia, and can kill fish. Rotting food encourages excessive algal growth, which uses up the oxygen fish need to breathe. It is necessary to remove these waste products to maintain a healthy chemical environment inside the aquarium. Waste products are removed from the tank by using filters.

How do filters keep the aquarium clean?

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Remove the waste products to maintain a healthy chemical environment

Home › Why is it necessary to maintain a healthy aquarium? › What is a chemical environment? › Why is it necessary to remove waste products from the aquarium? › How do filters keep the aquarium clean?

How do filters keep the aquarium clean?

Filters remove the waste products produced by fish and rotting food from the aquarium system. There are different kinds of filters. However most filters use a combination of three different types of filtration processes - mechanical, chemical, and biological.

How does mechanical filtration work?
How does chemical filtration work?
How does biological filtration work?

Figure 1. Function-centered hypermedia

Tools to Support Learning about Complex Systems

An important goal of our instructional approach is to provide learners with opportunities to engage with ecosystems phenomena, particularly those that are not available to their unaided perception. Learners find many ecosystem phenomena hard to understand because they have not had experiences thinking about those processes that are dynamic and outside their perceptual range (Jacobson & Wilensky, 2006). The SBF conceptual 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 (see Figure 1), through NetLogo simulations that make behaviors visible (see Figure 2) and through the ACT tool (see Figure 3), which makes SBF explicit as students build models using the language of the SBF conceptual representation. The function-centered hypermedia organizes learning and orients students to thinking about how a system works and what its functions are rather than thinking largely about components. Learners drill from why questions about function to how questions about behaviors.

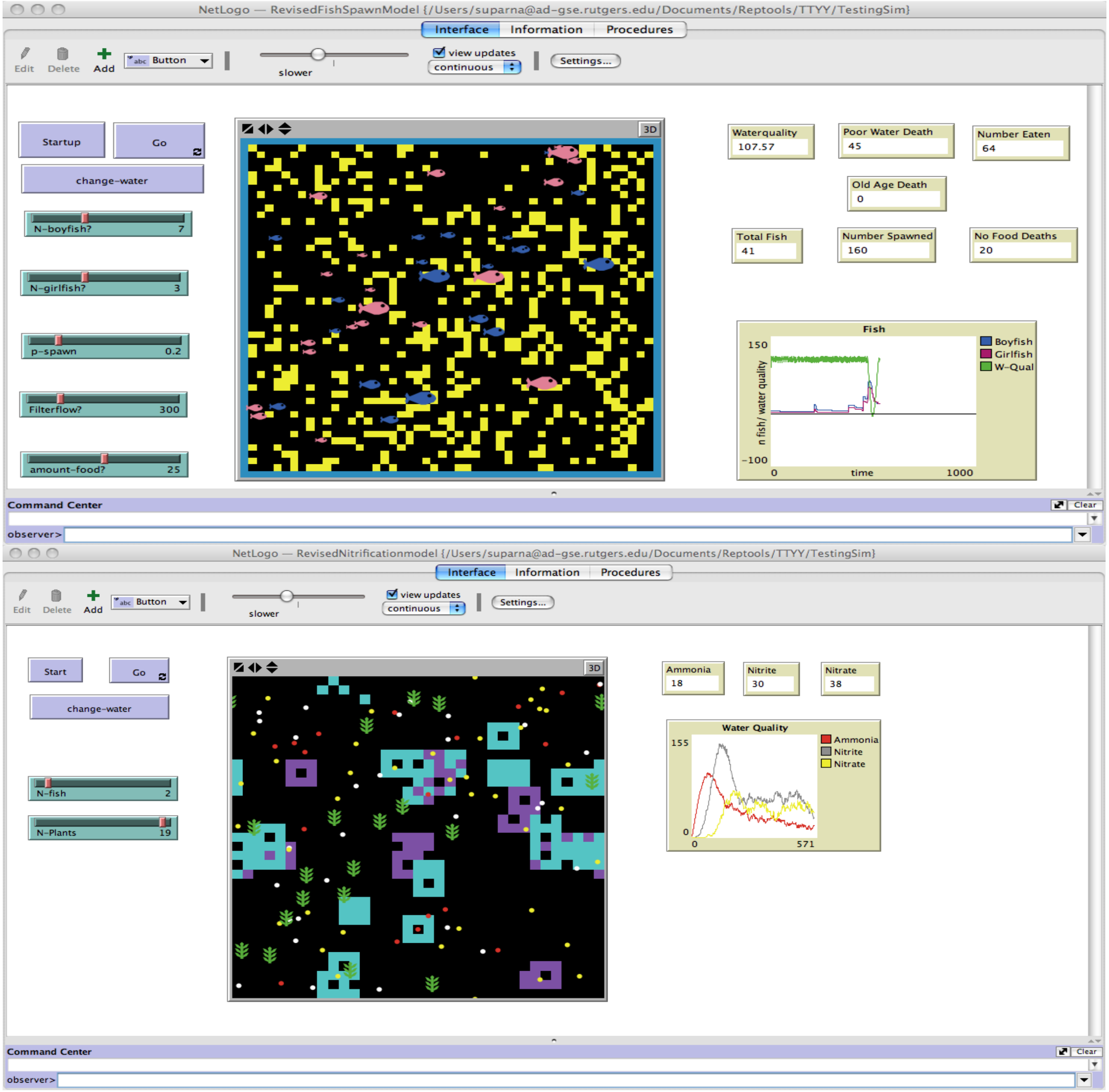
Along with the hypermedia and ACT tools, students also used NetLogo simulations to learn about the behaviors and functions in an ecosystem (Hmelo-Silver et al., 2007; Wilensky & Reisman, 2006). Using these simulations, students have opportunities to explore factors that affect the dynamic balance in the aquarium.

In particular, system processes, such as nitrification and population growth can be made visible. For example, the macro fish spawn simulation allowed students to manipulate different aspects of the system such as initial population, spawning, filtration level, and amount of food. Thus, if the students overfeed the fish, the increasing ammonia as a result of increasing fish excretion in the water would affect water quality and have toxic effects on the fish, leading to mortality. This helps problematize water quality, which is a black box in the macro simulation. This creates the need for students to identify some of the invisible components within an ecosystem. For example, using the micro-level simulation, students can 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 like ammonia into less toxic forms of nitrogen such as nitrate.

METHODS

The research reported here comes from data in three public middle schools in suburban school districts in the Northeastern United States. Four teachers used the instructional intervention, which was conducted during regular science classes. All students in these classes participated in our adapted curriculum, but only those students who returned consents were included in this study. A total of 311 students completed both the pre- and post-tests that were analyzed here.

Although there was some minor variation among the



NetLogo — RevisedFishSpawnModel {/Users/suparna@ad-gse.rutgers.edu/Documents/Reptools/TTYY/TestingSim}

☑ view updates: continuous

N-boyfish? 7

N-girlfish? 3

p-spawn 0.2

Filterflow? 300

amount-food? 25

Waterquality 107.57

Poor Water Death 45

Number Eaten 64

Old Age Death 0

Total Fish 41

Number Spawned 160

No Food Deaths 20

NetLogo — RevisedNitrificationmodel {/Users/suparna@ad-gse.rutgers.edu/Documents/Reptools/TTYY/TestingSim}

☑ view updates: continuous

N-fish 2

N-Plants 19

Ammonia 18

Nitrite 30

Nitrate 38

Figure 2. NetLogo Fish Spawn and Nitrification simulations

four participating teachers, they followed the same general sequence. The science teachers introduced the unit by asking students to articulate their ideas about ecosystem functions, activating their prior knowledge and providing formative assessment for the teachers. The teachers 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 (see Figure 4). The teachers also encouraged the students to use the hypermedia to build on their ideas about the ecosystems. The teachers then had 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

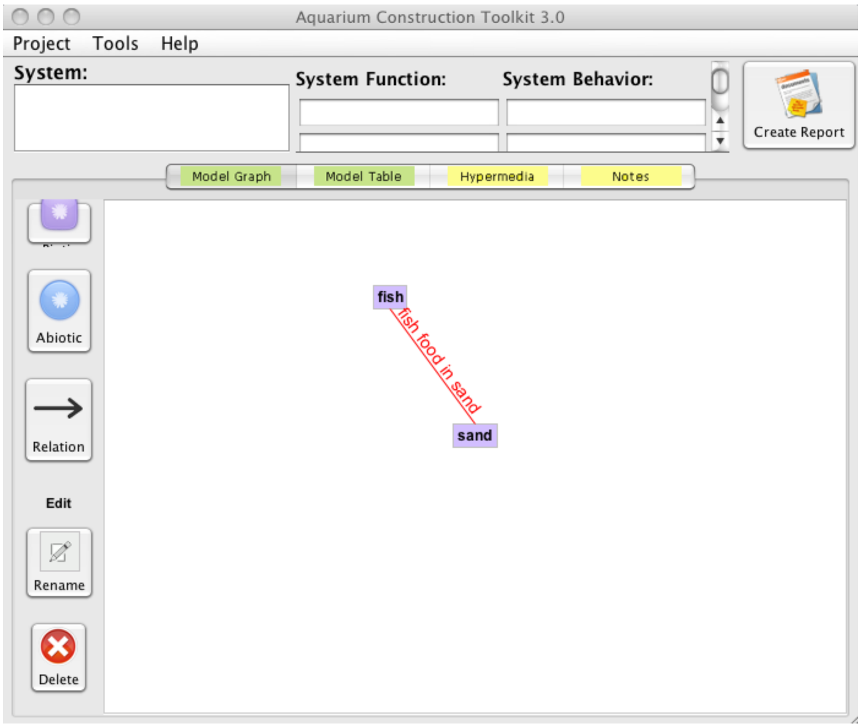


Figure 3a. ACT: A space to create models

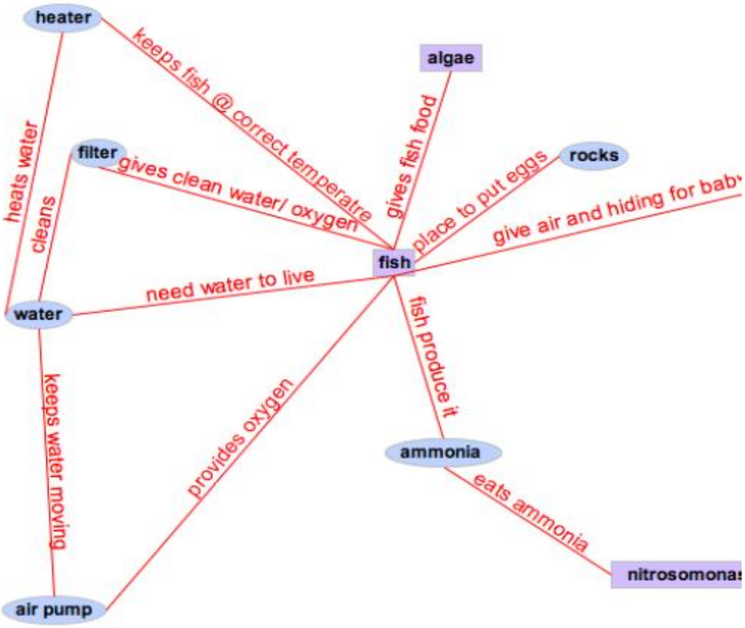


Figure 3b. ACT: Example of model created by a student.

refine their models. At the completion of the two-week period, students presented their models to the rest of the class.

A pre-post test single-group design was used for this study in which students completed tests before and after the classroom intervention. In completing this assessment instrument, 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. They also solved problems related to ecosystems. The scoring criteria for the pre- and post-tests are summarized in Table 1. These scoring criteria build on research on expertise and student understanding of ecosystems (Eilam, 2012; Hmelo-Silver et al., 2007) All 17 of the questions 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 responses on a four-point scale, shown in the upper part of Table 1. We also coded for whether the students were able to identify and explain relationships between macro and micro elements within an ecosystem. Only the eight questions that afforded opportunities to explain both macro and micro level connections were coded for Macro-Micro (M-M) level. The other nine 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 M-M level as it reflects connecting macro (waste) and micro (ammonia, nitrogen cycle) level structures and processes. Interrater reliability was calculated by having two independent raters code 20% of the sample. The overall reliability was 87% agreement.

RESULTS

The results, shown in Table 2 demonstrate moderate to large effects of our technology-rich SBF intervention. These results demonstrated significant improvement in understanding SBF relationships over time ($F_{(1,\ 310)}= 69.58$, $p < 0.001$), with a moderate effect size. In addition to the SBF relationships, we also measured the relationships between macro and micro elements of the system. Descriptive statistics are shown in Table 2. The

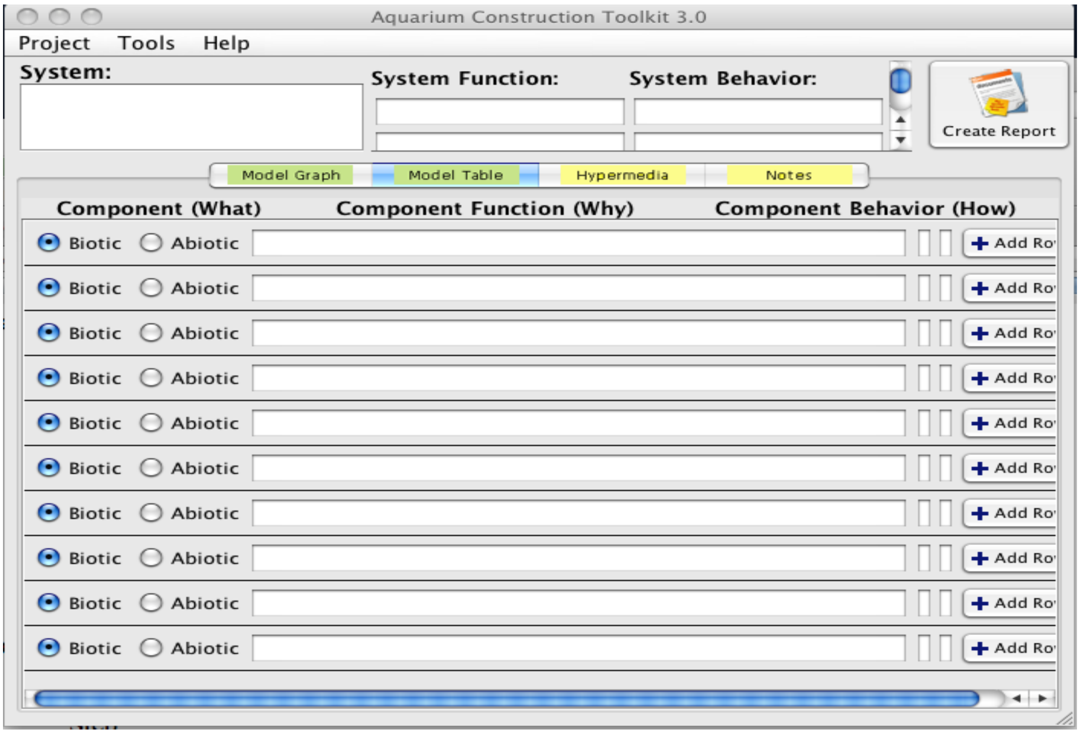


Figure 4. ACT table where students record ideas as structure, behavior, and function

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: -Children 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
Macro-Micro 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

Table 2. Descriptive statistics for pre- and post-tests (all n=311).

Measure	Pretest	Posttest	d	Range
SBF relationships	44. 64 (16.17)	54.06 (21.40)	0.58	0-98
Macro-Micro Level	13.87 (5.12)	19.70 (8.11)	1.13	0-44

results from a repeated measure ANOVA found a significant gain in M-M level maximum scores from pre- to post-test ($F_{(1,\ 310)}$= 193.30, $p < 0.001$) with a large effect size.

DISCUSSION

In summary, following our innovative and technology-rich classroom intervention, students significantly improved their understanding of the aquarium ecosystem in terms of the relationships between structures, behaviors, and functions (SBF). In addition, students increased their identification of micro level structures and there was a significant trend toward students' articulating relationships between macro and micro (M-M) level structures. We argue that the increased discussion of relationships among students and with their teachers derived from our SBF intervention is necessary for a more sophisticated understanding of ecosystems in middle school science classrooms.

From an ecosystem perspective, the interrelationships between structural and behavioral/functional levels represent mechanistic explanations of ecological phenomena. A critical aspect of these mechanistic explanations is encouraging students to draw links that are not solely one-to-one, linear connections, as students have a tendency to do when representing ecosystems (e.g., Hogan, 2000; Hogan & Fisherkeller, 1996; Leach et al., 1996; Reiner & Eilam, 2001). We suggest that the SBF conceptual tool may have enabled students to conceptualize at a more general level, thereby enabling more links to be made among structures.

Additionally, relating the invisible components in complex systems is something that middle school students often find difficult (Liu & Hmelo-Silver, 2009). By thinking about elements within a system using the SBF framework, micro-level phenomena might be made more salient for young learners. It is important to note that SBF thinking also provides a language by which students can both think about and describe the levels within the complex ecosystem.

We acknowledge that our study is limited by lacking a comparison group within our pre-post design. This study represents the results of a first step during iterative program development and design research. Additional analyses are being conducted to better understand achievement among different subgroups. In addition, we are in the process of qualitative analysis of both written and video data to further explore how students develop their understanding of complex systems and how the technology utilized serves to mediate student inquiry. Nonetheless, we have demonstrated that embedding a conceptual representation in a technology-rich learning environment can be used by teachers in multiple schools with a relatively large number of students.

Both the technology and social structures provided important support for the conceptual tools. The simulations provided opportunities for learners to test their ideas at multiple levels. They can discuss effects at the macro level in one simulation and at the micro level in another simulation. Because the computers are shared, learners must make their thinking visible as they negotiate meaning with their group members and construct representations in ACT. As students worked with the ACT modeling tool, they needed to integrate and synthesize across the system levels from the two simulations. Together, this set of conceptual representations, technological tools and social activity structures provides a learning environment that allows learners to tackle complex phenomena.

Given the cross-cutting nature of systems ideas, it is important to think about how activity systems support learning about the complexity within systems (Danish, 2014). The results presented here suggest that an activity system that incorporates conceptual representations, technological tools for thinking, and a mix of small group and whole class discussions is effective in promoting student learning. We posit that that there was a synergy among these different components of the learning environment.

The findings from our SBF intervention have important implications for instruction. The innovative use of a distinctive conceptual representation embedded within the intervention clearly resulted in more complex ideas being highlighted by students. Students were able to adopt the SBF conceptual framework as a language to express complex notions about ecosystems. We hypothesize that given the difficulty that students have in transferring ideas between one ecosystem to another, this framework might serve to broaden the scope of ideas a student has, potentially promoting abstraction of ecosystem concepts. We have elsewhere demonstrated that teachers can appropriate these ideas and transfer them to other curricular units (Sinha et al., 2013). Future directions should include a focus on the development of the SBF language outside of our technology tool suite and understanding the mechanism by which students transfer ecosystems principles across different systems. Given the value of systems understanding to ecological literacy as well as science literacy at large, we contend that such investigations will be important in furthering our knowledge of how to improve teaching and learning of complex scientific phenomena.

Author Notes

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