Published December 19, 2014

A Conceptual Representation to Support Ecological Systems Learning

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ABSTRACT The use of a conceptual representation has been shown to help students orient their thinking about complex systems. We sought to refine and test this idea with ecosystems using the PMC (phenomena-mechanisms-components) conceptual representation. Using pre-post drawing task assessments, we test the hypothesis that after completing a PMC-evidence and explanation-rich ecology curriculum, students would create more mechanistic explanatory models. We found that post-intervention students created more mechanistically oriented models and in our post-hoc analysis found that model sophistication correlated with course achievement, even though models and modeling were not a significant part of the course grade.

Impact Statement This article highlights the use of a conceptual tool (as opposed to physical material) given to students as a resource for systems thinking. As we learn more about how people learn, conceptual tools appear to have the greatest effect in classroom practice. Given the low cost of using such tools, we suggest greater practice and research investment into conceptual/cognitive tools is warranted.

The use of a conceptual representation has been shown to help students orient their thinking about complex ecosystems. A conceptual representation is a framework that aids students in organizing their ideas. Liu and Hmelo-Silver (2009) used the SBF (structure-behavior-function) conceptual representation to help students organize their ideas around functions and mechanisms in aquaria. To further support mechanistic learning, simulations based on micro and macro level processes of aquaria were added (Liu and Hmelo-Silver, 2009).

Using SBF, however, resulted in a few problems. First, teachers were confused about terminology. For example, teachers would tend to conflate the notion of system behavior with the behavior of organisms within the system. They would also get caught up in teleological functional relations (personal observation). Furthermore, SBF encouraged a structure-first notion of complex systems instead of beginning with the phenomenon or outcome of system operation. We argue that focusing on the outcome of system operation encourages a more generic consideration of mechanism. Here we refer to mechanism as being the process by which parts generate an outcome. For example the process of photosynthesis is how the parts within the leaf generate sugar for the plant. When thinking about mechanisms instead of the specific parts of the problem at hand (e.g., why fish may have died in a local pond), learners may be able to think about what they already know vs. finding themselves caught up in the context of the specific system of study (see Jordan et al., 2014).

In response to the issues raised above, we propose the PMC conceptual representation where learners frame and externalize their systems thinking around a particular phenomenon or ecological pattern (P); generate or recall plausible mechanisms (M) that may result in the (P); and explore the parts or components (C) that interact to result in (M and P). This PMC conceptual representation is used in conjunction with a curriculum that provides a platform for finding or generating evidence (E) in support of mechanistic explanations (E). The pairing of our two Es with our conceptual representation (PMC-2E) provides an external language for students to self-direct learning and express their ideas. Below we report on how our intervention, paired with a conceptual representation, aided in students developing and modifying ideas about complex ecosystems.

Complex Ecosystems

The need to be ecologically and environmentally literate is fast becoming a requisite for informed decision-making as citizens (Jordan et al., 2009). The ability to

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Nat. Sci. Educ. 43:141–146 (2014)
doi:10.4195/nse2014.09.0019

Abbreviations: EcoMUVE, multi-user virtual environment; PFL, preparation for future learning; PMC, phenomena-mechanisms-components; PMC-2E, phenomena-mechanisms-components-evidence and explanations; SBF, structure-behavior-function.

reason about complex ecosystems, in particular, has also been suggested to be critical to environmental and scientific literacy (Anderson et al., 2008; Covitt et al., 2009). There is evidence, however, that the public is not particularly knowledgeable about ecology (Magntorn and Helldén, 2005; Stone and Barlow, 2005; Puk and Makin, 2006). In response to these poor reports of performance, increased attention has been placed on modeling complex ecosystems (NGSS, 2013).

It is not surprising that students have difficulty learning about ecological systems (e.g., Hmelo-Silver et al., 2007; Jordan et al., 2009). Students tend to have difficulty thinking beyond single causes, structures they can see, and linear flow of ideas (e.g., energy flow: Leach et al. 1996; food webs/nutrient cycles: Hogan and Fisherkeller, 1996, Hogan, 2000; food chains: Reiner and Eilam, 2001; Eilam, 2002; energy flow: Ozkan et al., 2004; aquaria: Hmelo-Silver et al., 2007; water cycle: Covitt et al., 2009). Because of these difficulties, educators are encouraged to help students participate in deep consideration of the interactions within ecosystems (e.g., Enger and Smith, 2006).

Means to support these interactions, however, are not always clear. For example, middle school students who participated in an ecology systems intervention where they were asked to draw system models, tended to link all parts together in a circular fashion or indicate that end nodes need linking (Jordan et al., 2009). These authors found that student efforts to link all ecosystem parts in a somewhat circular fashion resulted in spurious connection of ideas. Students often tried to find connections, even when they did not exist, so they could close the system. This disconnect suggests that students have a naïve view of how ecosystem parts are linked. Students tended not to be consistent with how they used arrows in their models and they tended to draw lines with unidirectional flow. As previously mentioned, students may be limited by linear ecosystem thinking, thus making dynamic system modeling difficult (Grotzer and Bell Basca, 2003; Reiner and Eilam, 2001). The results of the Jordan et al. (2009) study underscores the need not only for explicit systems instruction but also an opportunity to make reasoning clear and feedback more dynamic in a manner to allow individuals to integrate their ideas (DiSessa, 1993; Linn and Hsi, 2000).

Another investigation into students' learning about complex ecosystems found that understanding of ecological concepts was limited and learners often failed to grasp the basic processes that occur (Covitt et al., 2009). This work focused on the water cycle and suggested a particular problem encountered was making the invisible system processes visible and open for manipulation. Further, Jordan et al. (2014) found that while explicit instruction about ecosystem processes improved student accuracy on ecological assessments, students failed to discuss these processes in a dynamic and interrelated way.

Interactive computer-supported learning environments have been used successfully to support dynamic and interrelated ecological system learning. At the very basic level, the use of external, visual representations in virtual environments have served well as learning scaffolds (e.g., Hmelo-Silver et al., 2007). Furthermore, Gobert and Buckley (2000) raised the notion of dynamic models as being necessary supports for multiple levels of organization in complex systems. Certainly tools such as Betty's Brain (focusing on rivers systems; Blair et al., 2006) and VModel (domain independent; Forbus et al., 2001) are examples of interactive modeling environments that help learners to successfully address system-level problems. Additionally, Grotzer et al. (2011) have approached ecosystem-related problems by engaging students in creating causal explanations. Through EcoMUVE (multi-user virtual environments), learners encounter a three-dimensional simulated ecosystem to test causal relations (Metcalf et al., 2011). This world can be enhanced through "augmented reality" where students can use live environment probe ware to further create and test explanations (Kamarainen et al., 2013).

In our work, we use similar principles of visual representation, graphical images, simulations, and mapping causal relations (see systemsandcycles.weebly.com; accessed 19 Nov. 2014). With our use of a conceptual representation, however, we wanted to further allow students to grasp emergent phenomena that may arise from system interactions. What is also distinct from the work above is our use of a conceptual representation that is explicitly embedded into our interactive environment. In this article we measure the extent to which students, using the PMC-2E conceptual representation and modeling tools, create models that feature causal explanations of discrete phenomena, both individually and in groups. Using pre-post drawing task assessments, we test the hypothesis that—after completing a PMC-2E rich curriculum—students would create more mechanistic explanatory models. Because we are working with a small data set, we use visual inspection and simple correlation to draw conclusions.

MATERIALS AND METHODS

The students in this study were enrolled in a semester-long course, Environmental Education, as a part of their undergraduate curriculum. All of the students were upper-level undergraduates, at similar levels of achievement, and were 55% female and 45% male. As a part of the coursework, students were administered several thought and modeling tasks connected to course content. Students were asked for consent at the beginning of the semester for their completed tasks to be used as data in this study. Only those students who gave consent ($n = 13$) are reflected in this study. This research took place from January to May 2014. All research was approved by the University Institutional Review Board in August 2013.

An aquarium was setup in the classroom 1 month before the study began. The systems and cycles toolkit (see examples at systemsandcycles.weebly.com) was installed on classroom computers prior to the study for students to use in small groups of two to four students. This toolkit was used to teach students about aquatic environments without instructor guidance. Group exploration of aquatic environments through the toolkit was supplemented with only brief class-wide discussions about systems modeling. When system modeling, students were taught to connect major ecosystem processes (e.g., cellular respiration, photosynthesis, and carbon cycling) to emphasize ecosystem complexity.

The curriculum was divided into three units and each unit followed the same pattern. The three units focused on an aquarium, a pond, and an estuarine system. The pattern of the curriculum for each unit was: introduction to the basic problem, then students were asked to model the problem, interact with hypermedia that feature aquaria,

Table 1. Non-model based course tasks completed in the course involved writing arguments, supporting claims with data, and presentation. Certainly one can imagine a link between these tasks and PMC-2E, but no explicit instruction linking the two was made. The major focus of this course was to teach students how to teach/communicate the practice of socio-environmental research to others. Only the underlined models were used as data described in this article. Drawings turned in were each 2.5% of the total course grade. These models were returned immediately and were graded on accuracy alone.

Week	Assignment	Activity	Model collection
1	None	Introduction	Pre individual, Pre Collaborative Models
2	Reading paper	Identify key environmental issues	None
3	Reading paper	Outdoors and science	None, created paper models
4	Field trip	Field Trip: outdoors	None
5	Quiz 1	Issue investigation	None, but 1 question on modeling was included.
6	Reading paper	Eutrophication	Ecomodel Eutrophication
7	Reading paper	Eutrophication	Drawings turned in
8	Teaching	Teaching presentation	None
9	Reading paper	Carbon Mitigation	Ecomodel Carbon Mitigation
10	Reading paper	Carbon Mitigation	Drawings turned in
11	Teaching	Unit presentation	None
12	Quiz 2	Environmental communication	None, but 1 question on modeling was included.
13	Reading paper	Bringing themes together	Post individual models, Post Collaborative Models
14	Final xxam	Final exam	None

Table 2. Coding scheme for PMC. All P, M, and C elements were taken as counts per model. Explanations and supporting evidence was measured by simple presence and absence. See Fig. 1 for examples.

System element	Description	Examples
P = Phenomena	Overall pattern or outcome that is explicitly being explained in the model	Dead fish, global temperature rise, anoxic conditions
M = Mechanism	Processes that are generic (i.e., happen in other systems) and specific to the phenomena being represented. (Note if students did not explicitly represent a phenomena their model received a P = 0, but for mechanism the phenomena was inferred based on the curriculum)	Nutrient runoff, greenhouse effect, photosynthesis, decomposition
C = Components	Physical parts that exist in the system	Fish, plants, carbon dioxide, cars

ponds, and oceans (Liu and Hmelo-Silver, 2009), and interact with simulations on NetLogo (Wilensky and Reisman, 2006) (see systemsandcycles.weebly.com for description of curriculum and to access the computer modeling tool).

We used several measures to collect data. These measures were embedded in the classroom experience (Table 1). First, students completed a pre- and post- course drawing task on paper that focused on what happens in the aquarium system. This task was not subsequently discussed at any point during classroom instruction. Additionally, a single collaborative model was generated after the pre-drawing task again with no further discussion. This model was completed using the ecomodeler computer-based modeling tool (systemsandcycles.weebly.com). In addition, students completed individual PMC-2E models with ecomodeler for both eutrophication and carbon mitigation as homework. These models were the only two models that were graded and comprised 5% of the course grade. Students were made aware of the study and what comprises their grades during the first class period.

The above models were coded using a PMC scheme (Table 2) and explanations and evidence were used to support these (e.g., Fig. 1). The PMC scores are comprised of counts. Simple correlation analysis and presentation of means was used to inspect for differences pre- and post-treatment. We rated sophisticated models as those that included mechanistic (or process-based) explanations and were supported by data. See Table 3 for a summary of all data sources.

Table 3. Data sources are listed in sequence with location and whether or not the task was graded. All data sources were first coded using the PMC-2E scheme (see Fig. 1). After this, sophistication of models was assessed for each student in sequence and trends were noted. Sophistication was assessed as increased identification of mechanisms and using data to support ideas.

Data source	Location
Drawing task-pre-post	Classroom
Ecomodeler-collaborative model	Classroom
Ecomodeler-eutrophication	Homework
Ecomodeler-carbon mitigation	Homework
Drawing task-terrestrial model	Classroom
Drawing task-microbial model	Classroom
Drawing task-pre-post	Classroom
Ecomodeler-collaborative model	Classroom

RESULTS

Pre–Post Comparisons of Individual Aquarium Models

Inspecting by student, pre- to post-instruction models contained an increase in accounting for phenomena using causal explanations. Recall that this task simply had students observe aquaria and provide a model that describes what happens in the aquarium system. The number of individuals who represented phenomena increased (5 out of 13 students represented 0 phenomena pre-instruction to 1 phenomenon post-instruction, 1 out of 13 students remained with 1 phenomenon from pre- to post-instruction, and 7 out of 13 students remained with 0 phenomenon from pre- to post-instruction). The phenomena that were represented tended to be life support for fish and aesthetically pleasing for the classroom. Additionally, mechanisms

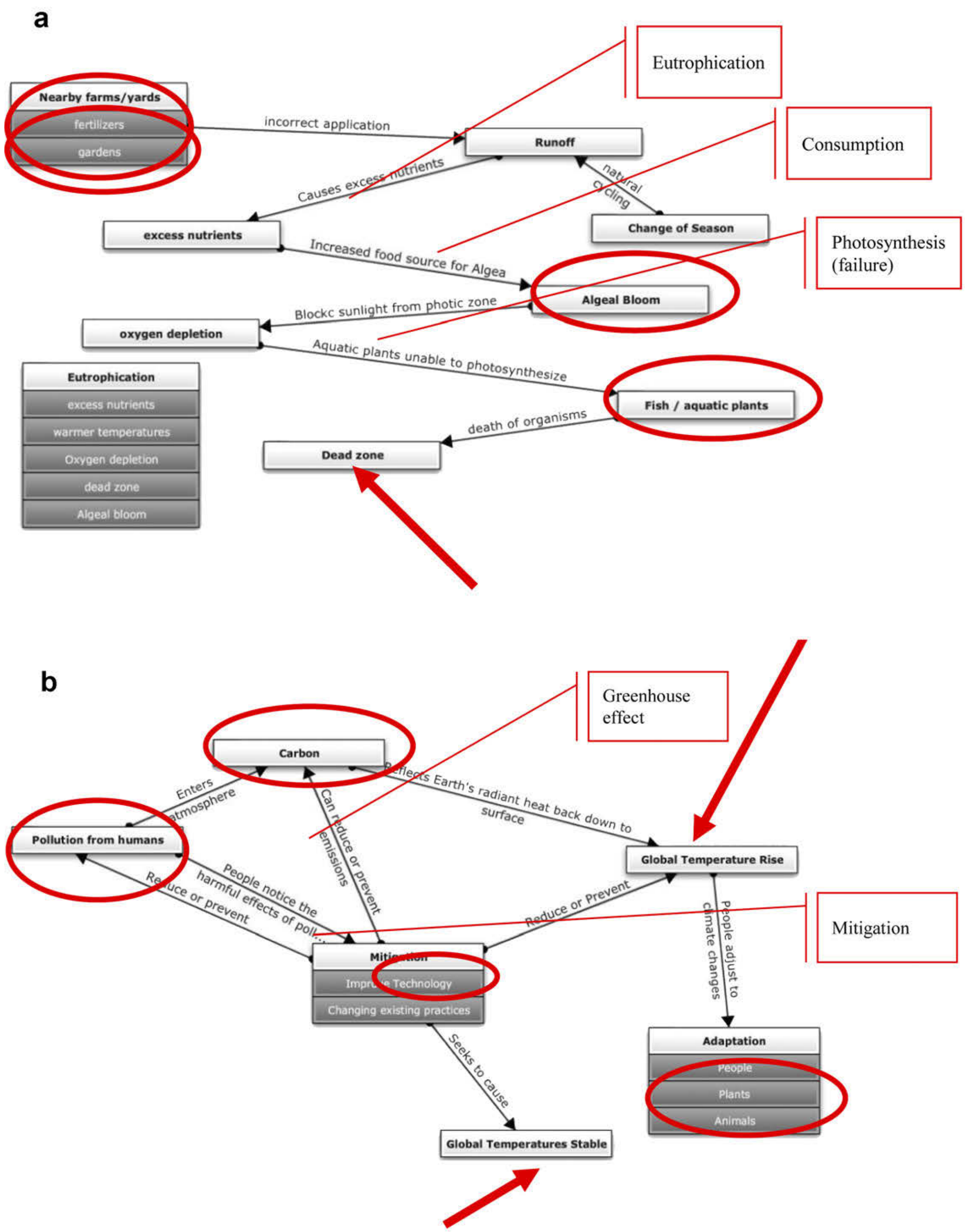

Fig. 1. Two examples of PMC-2E coding.

increased (8 out of 13 added mechanisms, 2 already had mechanisms, 3 no mechanisms pre to post). Lastly, mechanisms and phenomena were significantly correlated (r = 0.625, p = 0.020, n = 13), such that the more phenomena represented was associated with more mechanisms. Components did not show a trend of increase or decrease.

Pre–Post Comparison of Group Aquarium Models

When students worked collaboratively, there tended to be on average more phenomena and components but not mechanisms. More specifically, on average, the individual model drawing tasks contained 0.6 phenomena, 1.4 mechanisms, and 7.2 components, whereas the group (~3 students per group) model drawing tasks contained on average 1.4 phenomena, 1.3 mechanisms, and 10.1 components. These models were naïve and followed only the pre-instruction model task drawing.

In Class Model Analysis

Progressing from their initial models, students provided more sophisticated (i.e., mechanistic and data driven) models with time. That is to say, that only 2 out of 13 students had mechanism and data in their pre-instruction models. At the end of the course 10 out of 13 had increased mechanisms and evidence in their models. This was evident through the "notes" prompts where students were asked to provide evidence. For the purposes of this study, we simply counted instances where evidence was paired with mechanism. If this number increased, then we noted that sophistication increased. While the "notes" prompts for evidence and explanation were available, students did not use this feature during initial model development. All, however, use the "notes" section without being told to do so, post PMC-2E instruction.

The models, accounting for eutrophication, developed by students earlier in the instruction tended to feature a 1-to-1 or linear narrative to support explanations for the phenomena, which was most often articulated as dead fish (see example in Fig. 1a; for this, 11 out of 13 students presented a narrative whereas 2 out of 13 failed to account for a phenomena). The models, accounting for planetary warming mitigation, tended to be either linear as described above or more dynamic to support explanations for phenomena. This was evidenced by embedded cycles and feedback loops (see example in Fig. 1b; for this, 8 out of 13 students represented cycles and feedback loops, whereas 5 out of 13 remained in narrative form).

Post-Hoc Analysis

Finally, while not part of our original research question, we noted a high correlation between students' sophistication (i.e., included mechanistic explanations supported by data) during the last aquatic system modeling task and students' overall course grade ($r = 0.854$, $p < 0.000$, $n = 13$). Recall that only 5% of the students' course grades were based on direct PMC-2E modeling. This suggests that students' achievement in creating PMC-2E models (based solely on our coding scheme) is related to achievement in creating and supporting clear arguments (as these skills comprised much of the course grade). It is unclear, however, the extent to which there is a causal relationship between the two.

DISCUSSION

Engaging in scientific practices is essential for science learning (NGSS, 2013). With PMC-2E, we are focusing on the specific practices of modeling and using evidence to support explanations. Our work encourages students to develop a conceptual representation by which they can reason about complex systems. Students' models, which tended to be more mechanistic, helped make ideas visible and open for constructive discourse and class discussion. Clement (2000) has gone as far as to argue that model construction and revision is at the heart of science, which requires a top-down disciplinary perspective, bottom-up raw observations and data, and a dialectic process that encourages meaning-making. These features were integrated into course instruction.

Constructing and appropriately utilizing representations can prove difficult for novices who tend to use representations in fundamentally different ways than scientists (Kindfield, 1994). Kindfeld found that while reasoning about subcellular processes, geneticists spontaneously used diagrams as flexible tools for reasoning and that these diagrams cued relevant knowledge, whereas students used models in a rigid manner. Similar results have been observed in chemistry (Kozma et al., 2000). Chemists use representations in their reasoning to mediate between physical phenomena and the structures, functions, and mechanisms that are not perceptually accessible. Kozma et al. (2000) demonstrated that chemists used representations to express and refine their understanding of invisible phenomena by providing features that can be manipulated and socially negotiated. Nersessian (1995) also discusses the manner in which scientists are generative in their construction of models. Certainly in our study, students used their models to support explanations, which is one of the practices used by scientists. We found that most students who initially had static models, through time and practice, tended to create more dynamic models.

We hypothesize that PMC-2E can serve as a scaffold for students organizing their ideas while taking in the dynamics and levels of organization of systems. Although we had a small data set, there was enough of a trend to suggest that using modeling tools allow students to integrate elements as they understand them and to refine their ideas. Using relatively simple language and practice, students can build their understanding and communicate ideas, especially by moving from more generic mechanisms to specific explanations. Further, the PMC-2E organization can help in the physical representation of evidence-supported explanations that enable teachers, peers, and the students themselves to communicate ideas. Also, the PMC cognitive support may allow cognition to be distributed by offloading difficult and elaborate reasoning tasks into the physical modeling environment.

Remember that many of our tools were designed using the SBF conceptual representation. We were easily able to transition to PMC because it, like SBF, is intended to capture system-level phenomena and because the conceptual representation, although embedded in the language of our tools, is most related to how the system-level problems are framed for the students. Metaphorically, rather than provide students with instructions to file each piece of paper, we are providing them with a filing scheme allowing them to take ownership over each piece of paper filed. This allows our tools to be more open-ended and multi-purpose compared with many of the interactive environments discussed in the introduction.

Finally, we suggest that cognitive tools like PMC may enable students to transfer ideas. Because individuals using PMC create generic mechanisms to explain ideas, learning transfer to novel ecosystems can occur. In addition, we may also see transfer of the conceptual representation. Viewing transfer as a system where students are prepared, based on previous experiences, to re-learn necessary elements to aid in understanding novel experiences, PMC-2E can serve as a thinking tool that enables this relearning (similar to Bransford and Schwartz 1999, preparation for future learning, PFL). These latter ideas warrant further investigation.

Implications

Although our data are preliminary, there is sufficient supporting evidence to suggest that using conceptual representations when teaching about complex natural systems can help students manage the multiple and dynamic layers of these systems. By remembering the conceptual representation, students were able to ask themselves questions directed at the salient system elements. With the software support, they had a place to record this information and access it when necessary. In the design of new instruction and even in the absence of supporting technology, one can use PMC-2E or other representations as a means to guide the classroom conversation. Notebooks, worksheets, or journals could be used as a place for students to record and later access ideas.

It is this supporting of students in the development of ideas (i.e., before and during learning) that can help them to focus on relevant information and to abstract ideas that enable integration and retrieval of information on subsequent tasks.

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