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Viewpoint

Using research projects and qualitative conceptual modeling to increase novice scientists' understanding of ecological complexity☆

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ABSTRACT

A new program, Teaching Ecological Complexity, is working to develop a heightened capacity for systems thinking among high school biology and environmental sciences teachers. During a 2-week field-based course, the teachers use qualitative conceptual modeling, participate in all stages of field experimentation, and formulate plans to teach field research with their own classes. Qualitative conceptual modeling was found to be useful in revealing the underlying perceptions of ecosystem functioning for these novice scientists. Preliminary results showed improvement in their ability to recognize and apply some of the attributes of complex ecosystem: non-linear feedback loops, hierarchical organization, patterns illustrating the spatial arrangements of species diversity. In addition to using models, teachers used peer-learning techniques. Collegial discussions about what they understood at particular points in time were useful in improving their understanding of ecosystem phenomenon.

1. Introduction

Students typically have difficulty understanding complex ecosystems patterns because they do not reason or structure information the way ecologists can. Ecologists develop particular ways of knowing, such as the ability to perceive underling patterns in structure and function within ecosystems, or the perception that ecosystems are dynamic and complex, having multiple causes and effects (Boero et al., 2001) with time delays in response and effects that are not easy to predict with any accuracy. Scientists develop their perceptions through a combination of first hand experiences, academic training, and conversations with colleagues, and familiarity with the natural world (Hogan and Weathers, 2003). Science teachers participating in the program described in this article are given the opportunity to understand ecological phenomena through immersion in challenging ecology research projects and exposure to systems analysis language and tools (related to qualitative modeling and simulations). In this article, the author will describe how participants in this program were able to replace their older, more simplistic ideas of ecosystem functioning with the more powerful ideas behind ecological complexity. The overall goal of this new program, Teaching Ecosystem Complexity, is to develop a heightened capacity for understanding ecological functioning for high school biology teachers.

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Ecological complexity depends upon species diversity and the structure of species interactions. Complex ecosystems are hierarchically controlled, having subsystems within subsystems. All species assemblages have the same underlying rules regulating their structure (Simon, 1962). Complex ecosystems are not controlled by a central or linear function but are characterized by non-linear feedback loops, demonstrating indirect effects from an action (Li, 2000, 2004). Complex ecosystems exhibit patterns that are bound to each other yet observed over different spatial and time scales (Grimm et al., 2005). Without learning to work with tools such as ecosystems modeling, it is unlikely that students will understand more sophisticated patterns in the natural world.

Ecological complexity is the unifying conceptual theme of this project. The most central component involved science teachers working in partnership with ecologists, conducting field research projects and using conceptual qualitative modeling over an intensive 2-week summer course. Ecological content was provided during a preliminary on-line course containing classic and recent readings and discussion on diversity, complexity, food webs, and disturbance, and practice designing ecological experiments. The field component of the course was conducted with minimal lecture and with a high degree of interaction and ''hands-on'' instruction. This approach was developed over the past 10 years of work with teachers in a program called ''Teachers in the Woods'' and other Schoolyard LTER programs. By placing teachers directly into meaningful ecological field projects that are inquiry-based, teachers had an opportunity to solidify their understanding of ecological concepts and learn the skills that helps them in teaching complex ecological problems During this course, the teachers participated in all stages of one or more field experiments, used qualitative conceptual modeling to illustrate their understanding about interactions, and designed lessons to teach field research the next academic year with their own classes. The program provided them with supporting material to use in the classroom emphasizing the use of ecological models and field research skills.

The two main program components, qualitative conceptual modeling and research experiences, are described below. The third section of this paper includes a demonstration of how teachers showcased their increasing understanding about complex ecosystem functioning using models and essays and summery results from a preliminary group assessment.

2. Qualitative conceptual models

A conceptual model is a visual graphic summary with an accompanying written explanation of the basic features of the system under study that explain a person's thinking about a phenomenon and is drawn from the perspective of the participant. A qualitative model is a visual summary describing the important components of an ecosystem and the linkages between these components. It is a simplification of a complex system. During this project, we combined these two styles of modeling into one: qualitative conceptual modeling. We regard these models as both visualizations of relational networks of factors and as representations of what teachers know about ecosystem structure and functioning.

At the beginning of our course, qualitative ecosystem models were presented as useful teaching tools helpful in conveying ecological concepts such as the hydrological cycle, food webs, and nitrogen cycling. In other instances, qualitative modeling was used in this project to teach how to recognize patterns, developing the skills to perceive underlying structure within overall ecosystem complexity. As participating scientists gave presentations to the group, they also illustrated their own conceptual approaches towards field experiments using qualitative models.

Before being asked to design their own conceptual models, participants learned the symbolic language of qualitative models (for example, predator–prey interactions are represented using −/+). Using the variables involved in their research, they were asked to focus on particular components and interactions, sub-components, and climate, and then designed their models. Using these models, they responded to guided questions, including questions about ecosystem complexity, conducted discussion about their models with peers, and then each teacher developed a narration to accompany their model.

Throughout the process, teachers were asked to continually reflect upon, discuss, and create new models and accompanying essay narrations. The acts of construction and subsequent narration about one's own conceptual qualitative models are meta-cognitive processes. Teachers had to reflect about what they understand.

Their awareness of their own degree of knowledge about ecosystems and their understanding about the behavior of the system improved. Over the course, teachers revised their original model, or constructed new ones. As they gained experience in field experimentation, and gained knowledge about ecosystems, their models and essays reflected their increasing understanding.

During this program, qualitative conceptual modeling was also used a means of authentic, reflective assessment. Processing and synthesis are important stages of learning. These conceptual models are ways of organizing one's thinking, and bring hidden assumptions to light. Participants followed a series of steps in choosing the particular variables and interactions to be depicted that are deemed important to them. The teachers compared their earliest conceptual models with their latest ones to understand how the prior knowledge was either de-constructed or enhanced through the course of their experiences. As teachers learned how to perceive patterns via conceptual qualitative modeling, they were asked to generate explanations of what they understand along the way. The teachers' models were scored for scientific accuracy of the depictions; their essays were scored for the degree of understanding of aspects of complexity expressed in their essays. Their explanations were used as evidence showing whether their understanding had increased.

According to Zelmer et al. (2006), the point of studying complexity is to ''turn it into something simple''. At first, a novice modeler might depict a welter of details or, a simple model using very broad, general concepts, such as ''diversity''. As teachers are guided through the steps of a simple field experiment, and as they read more of the scientific literature, they appeared to pay more attention to particular ecological patterns. Their models started to include some of the specific variables under study. We used a variety of tools to develop their ability to recognize patterns and build the skills to be able to perceive trends. For example, a reference library of qualitative models used during the course includes a variety of food web models from different participating ecosystems.

These are used to portray how some patterns among ecosystems may be similar, although the individual species are different. As they continued to work with participating scientists, teachers began to become more discriminative in their choice of elements used in models. Teachers' final models and essays provided evidence that they had learned to distinguish background noise from possible meaningful change in ecosystems.

There are other notable educational software and other programs that highlight particular aspects of ecological interactions. The ''Understanding of Consequences'' project provided pre-college students with lessons about more complex models of causality (Groetzer and Perkins, 2000). Systems analysis tools such as Stella have been used with pre-college audiences to learn about ecological interactions (Hogan and Thomas, 2001) Other simulations can be useful in illustrating particular ideas about ecosystems, including the Daisyworld model a simulation game that illustrates non-linear feedback (included in SimEarth: The Living Planet). Tools like these can bring about an awareness of more complex ecological attributes to the user. In the program described in this paper, some of the attributes of complex ecosystems, for example, indirect causality, were recognized by all of the participants in our program by the end of the course.

3. Research experiences

The central element of the course was emersion in field research, from design of the research question through discussion of implications of the results. Teams of teachers worked on different research topics, such as plant community composition, rates of decomposition, and invertebrate predator diversity. Teachers' assumptions about the key variables, and interactions among them, were eventually articulated into research hypotheses. They were asked to identify what they think were the key elements in their system, and to point out the ''lynchpins''. The factors and relationships in their models were tested. Meanwhile, teachers worked on their field research projects, which included an experiment comparing terrestrial arthropod species diversity, and continually observed and discussed patterns in their data under the guidance of the scientists. Each teacher wrote a research paper or poster. The construction of qualitative conceptual models complemented their study along the way.

4. Demonstrations of teachers' understanding of complexity

Teachers' understanding of complexity was documented by their models, their essays, and through interviews with program staff. The essay questions inquired into specific aspects of ecosystem complexity and the experimental process. An analysis of both the elements used in their qualitative models and of their written and spoken responses to particular questions concerning their models was conducted. The scored elements of the models included use of feedback loops and hierarchical organization. The scored essay and interview questions were about non-linear feedback loops, hierarchical organization, how multiple factors interact and change over time and ecosystem functioning. As shown in Table 1, scores for each item were based upon a scale ranging from 0 (no response) to 4 (mastery). Scores for each aspect of understanding complexity were tallied. Teachers were also given a content test before and after their course. The scores for the four questions applicable to ecological complexity were tallied; these two scores were combined into one composite score (ecosystem complexity).

We then compared their ''pre-research experience'' composite scores with ''post research experience'' composite scores for a group of 10 teachers, as is shown in Table 2. A Wilcoxin matched pairs signed ranks test that was run on this paired set of scores showed significant improvement ($W+ = 0$, $W- = 45$, $N = 9$, $p \leq 0.003906$).

These results indicate that participating teachers understood complexity to a greater extent as a result of the course. A specific case study is presented below to illustrate the development of one participant's understanding of ecosystem functioning at two points during the program. Asking teachers to develop a series of qualitative conceptual models gave them an opportunity to view the development of their own ecological understanding. Rob, for example drew the first model (see Fig. 1) early on during the course. He explained in his first essay, that

> ''I expect to find greater abundance and diversity in forest arthropods compared with arthropods in the clearing...''

He reasoned that variation in moisture and aspect were important phenomenon in his experiment and would explain the difference in terrestrial invertebrate species richness in a meadow as compared with the forested site.

After having collected the data, reading particular journal articles about ecological diversity, calculating species diversity for his experiment, and having had numerous collegial discussions, he then wrote that he understood that species richness was important in functional groups, but was not found to be different between the two sites.

As he designed his next qualitative conceptual model that included hierarchical properties, feedback and indirect effects, he explained that his understanding had shifted.

> ''In the future, I would expect that there would be higher abundance and diversity of arthropods in the meadow due to an increase in sun at soil levels. (I know now that) there would be a greater concentration of primary producers in the meadow... comparing the consumers targeted by traps may narrow the practical differences.''

He also wrote that he used to view soil in its component parts, and he had taught it to his students that way, but now saw that these parts worked together. In his final model, he

Table 1 – Example of how essays and models are scored for understanding complexity

Score	Examples in essay
(1) Does essay discuss and illustrate feedback, any indirect effects, and change over short and long timescales	
0: Not score-able; no response	"I don't know."
1 point: Poor understanding of feedback and indirect effects	One example of feedback is the vegetation in the meadow
2 points: Shows minimal understanding of and application of feedback, minimal ability to describe indirect effects	A change in arthropods would ricochet up the food web and the entire ecosystem
3 points: Shows good understanding of and application of feedback, but less proficient describing indirect effects. Only describes one plausible pattern of change (short term)	Ecosystems function through varied array of relationships that are usually nonlinear and include many complex feedback loops...
4 points each: Expertly understands and applies both feedback and indirect effects (4 points). Describes plausible patterns of changes over short and long time spans (4 points)	Feedback loops may have negative impacts (competition) placing limits on growth of herbivores... it may accelerate the rate of growth of plants over the short term, but due to feedback, not in the long term
(2) Does model show and explain the connections between variables	
0: Not score-able; no response	"I don't know."
1 point: One or two linear connections, errors	Hare → Willow
2 points: Either few or many (spaghetti strings) incorrect connections, some correct, all have one or two steps (linear)	Willow → Hare
3 points: Many connections, all are purposeful and correct, some complex with at least two steps, some simple linear	Willow o→ Hare o→ Lynx
4 points: Many connections, mostly complex and multi-stepped with three or more steps, shows two-way interactions or even cyclical interactions	Nutrients→Willow o→ Hare o→ Lynx Aquatic grass o→Moose o→ Wolf

illustrated an appropriate hierarchical scheme, illustrated non-lineal relationships and vast and varied feedback loops in the system he modeled. He wrote that by the end of the process, he had a new realm of questions about soil and abiotic factors in the ecosystem that he had not considered before. Further, he described an emergent behavior of the ecosystem, namely forest succession, through a description of how the meadow would change over time to a forest. His final model is presented in Fig. 2.

Table 2 – Results of Wilcoxin matched pairs signed ranks test run on participants' composite ecological complexity scores

Participant number	Post-test score (Xa)	Pre-test score (Xb)
1	12	17
2	11	17
3	12	15
4	9	18
5	10	18
6	14	14
7	8	19
8	9	18
9	10	18
10	11	17

One explanation for the overall shift in teachers' expression of their thinking about complexity is derived from how qualitative conceptual modeling was used as a metacognitive tool. Each participant was asked to describe to a colleague how they thought the system, depicted in their initial qualitative conceptual models, functioned. During this process, participants began to understand some of the weaknesses in their initial explanations; they were forced to confront early on what they know and what they do not yet understand. They knew they would be asked to redraw their models later on in the course. During the interim, they appeared to pay particular attention to alternative explanations in presentations, the scientific literature, and in their observations of patterns in their data and about the ecological processes they were studying. Every participant's final qualitative conceptual models and essays contained richer and more scientifically accurate explanations about ecological complexity.

When asked to explain what had best helped them to learn during the course, half of the group of teachers credited their use of conceptual modeling as the most important element in the development of their own understanding of ecosystem complexity. Four of these teachers stated they had directly used the insights gained while developing their final qualitative conceptual models to develop research papers. Other teachers in the group

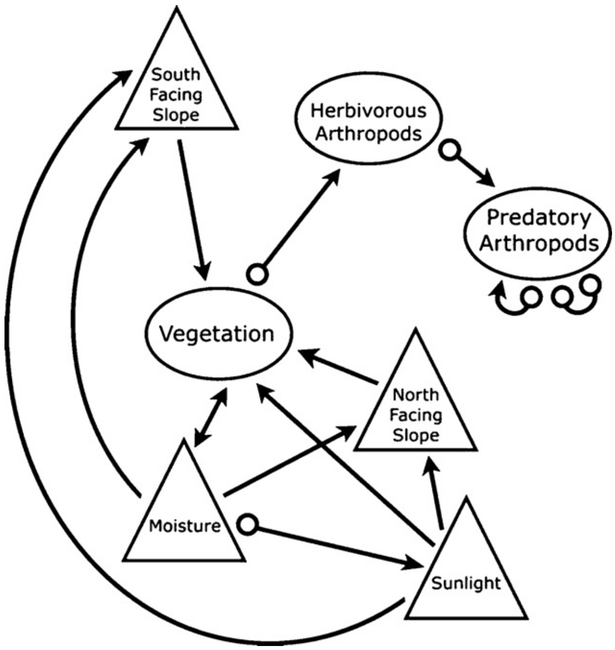

Fig. 1 – First conceptual model illustrating causes of expected differences in diversity.

attributed the class readings and discussions on classic scientific papers to their increased understanding, while others attributed discussions with colleagues as the most important factor.

5. Students and complexity

Successful incorporation of the concepts and skills into teaching strategies is a good indicator that teachers have

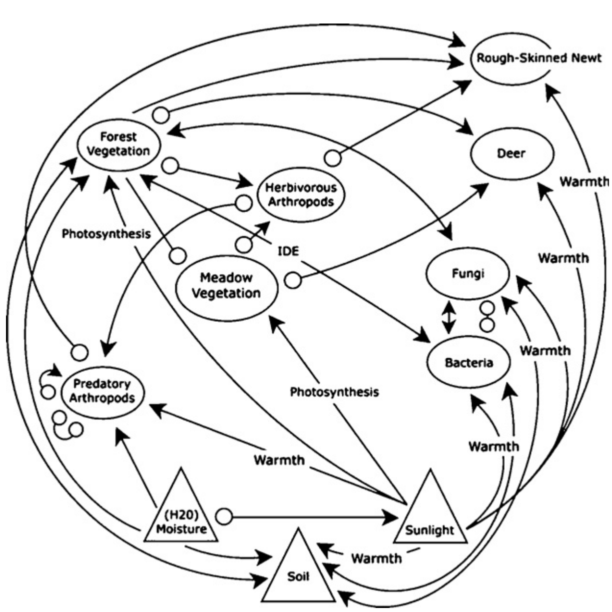

Fig. 2 – Final conceptual model illustrating factors influencing differences in species diversity between sites.

thoroughly understood the materials. Being able to articulate for themselves what they know, considering it important enough to take the time to teach this material at the expense of other topics, and knowing the material so well they can teach it to others, are all landmarks of success. During the summer course, teachers exchanged ideas about particular classroom strategies for teaching research skills, conceptual modeling, understanding of ecological patterns, etc. Over the ensuing school year, teachers proceed to implement a ''rich'' and ''extensive'' ecology research unit with at least one of their classes over the school year. Ultimately, we hope to find evidence that teachers have changed their teaching practices in ways that reflect the understanding and skills they developed during the course.

Although we do not yet have any student data, preliminary results from a graduate student's work with high school life science classes (Steiner, 2007) point to the value of qualitative conceptual modeling as knowledge representations. Steiner found that the use of qualitative conceptual models forced the students to articulate their own understanding of the ecological processes they studied. Further, it showed the teacher where the gaps and misunderstandings in the students' understanding were.

6. Conclusion

Participants' models and narrations illustrated they had learned to recognize and apply some of the attributes of complex ecosystem they had learned during the 2-week course: non-linear feedback loops, hierarchical organization, and patterns illustrating the spatial arrangements of species diversity. Their models became more sophisticated as they became more discriminative in their choice of elements to use. Qualitative conceptual models were useful in exposing the underlying perceptions of ecosystem functioning for novice scientists. Further, using conceptual modeling along with research experiences was useful in helping participants let go of their older, inaccurate understandings about ecological functioning and developing newer, more accurate views. Participating teachers subsequently conduct field research with their students, and test these modeling and research experience evaluation tools with their own classes.

For additional information about this project, please see the program web page at http://ecoplexity.org/. Suggestions for teaching materials, additional approaches, modeling tools, etc. from the Ecological Complexity community are welcome. Please contact the author at dresnem@pdx.edu.

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