Supporting education about environmental sustainability: Evaluation of a progressive learning route for qualitative models

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Abstract

Qualitative reasoning (QR) models can encapsulate a lot of expert, conceptual knowledge about interconnections of society, policy, and the environment common to issues concerning environmental sustainability. This paper describes a lesson plan designed to support learner exploration of QR models about sustainability, with the aim of supporting the goal of the European Union's Sustainable Development Strategy to build an active, engaged, and educated society that is prepared to contribute to decision-making about sustainability issues. The lesson plan includes ten questions that follow a QR model's progression from system structure through causality and dynamics to engage learners in application and evaluation of model outputs. We evaluated effectiveness of the lesson plan for supporting learning. Our first evaluation demonstrated that university students could effectively reason from and interpret diagrams produced by the modeling software that corresponded to content addressed in each of the ten questions in the lesson plan. Our second evaluation demonstrated that following the proposed lesson plan, students were able to abstract domain-specific understanding of key concepts from a series of three progressively more complex and realistic models. Furthermore, the proposed lesson format engages students in high levels of cognitive function when examining models and simulations. Hence, the progressive learning route provides a useful structure for designing a model-based curriculum for learning about environmental sustainability.

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1. Introduction

Sustainable development (SD) means improving people's quality of life while preserving the ability of future generations to do the same (Brundtland and World Commission on Environment and Development, 1987). Key to achieving SD overall is environmental sustainability (Lee and Ghanimé 2003). In its SD Strategy, the European Union recognized that environmental sustainability relies on an active, engaged, and informed citizenry (Council of the European Union, 2006). A major challenge, though, to incorporate input from many stakeholders is understanding and communicating the range of possible outcomes that may result from any particular activity, given the multiple interacting social, economic, and environmental factors involved.

To support this, the NaturNet-Redime project was funded in part to develop a curriculum for learning about environmental sustainability using qualitative reasoning (QR) models. Artificial intelligence techniques like QR have important advantages for addressing issues of environmental sustainability because they allow explicit representation of complex conceptual and causal relations between objects, ideas, and quantities even when numerical information is lacking (Rykiel 1989, Struss 1998, Bredeweg and Struss 2003). Furthermore, application to education has been a primary focus of QR research for many years because of its explicit focus on conceptual understanding and causality (Bredeweg and Forbus 2003).

Collaborators in the NatureNet-Redime project encapsulated five case studies involving different sustainability issues in European and Brazilian river catchments into QR models (see Cioaca et al. 2009, Noble et al. 2009, Salles and Bredeweg 2009, Nakova et al. 2009, Zitek et al. 2009), using the Garp3 workbench for qualitative modeling and reasoning (Bredeweg et al. 2006, 2009). These case studies were designed to address a range of biological, social, and economic issues related to environmental sustainability (Nuttle et al. 2006). The goals of this paper are (1) to describe a generalized set of questions and lesson plan we designed to support exploration of QR models for the purpose of learning and (2) to present results from two evaluation studies of the effectiveness of this approach. Though the lesson plan was designed within the framework of the NaturNet-Redime project, the aim was to facilitate easy adaptation to any QR model, to support rapid development of learning materials from models as they become available.

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2. Designing a generalized progressive learning route

Because models investigating environmental sustainability involve many interrelated parts with resulting dynamics, there is too much information for learners to absorb without some guidance in how to explore each model. Salles and Bredeweg (2001) pointed out that when exploring QR models, it is helpful to start with basic concepts and proceed to more advanced concepts that build from these, a curriculum structure they termed a “progressive learning route”. Previous work has evaluated the effectiveness of QR models developed in Garp3 for education about different domains, including ecology and the environment (Salles et al. 2005, Bredeweg et al. 2007). These studies show that within less than 1 or 2 h, undergraduate students learn to use the Garp3 software to navigate the contents of QR models and answer domain-specific questions about system structure, causality, and dynamics, based on what they can see and derive from diagrams that are interactively generated by the software.

Though generally presented in progressive learning format, these studies used multiple-choice and fill-in-the-blank questions specifically tailored to a particular model or scenario. Hence, well-reasoned answers and distractors needed to be developed for each question so that questions could be reasonably closed-ended and non-trivial. For example, students were asked to determine whether a particular value was affected by another value, or which quantities were increasing, decreasing, or stable at a particular instance (Salles et al. 2005, Bredeweg et al. 2007). While these studies demonstrated that QR models and Garp3 platform provided an effective means to educate about domain-specific content, we needed a more streamlined approach to creating lessons due to the large number of models for which we set out to develop learning materials.

Hence, the progressive learning route we developed is based on a more generalized set of questions and instructions that guide a learner through any QR model and simulation. The questions are embedded within a lesson that begins by providing a textual description (or presentation) of the overall sustainability problem being addressed. Learners are then guided through a series of questions that build progressively to explore the full content of the model. The progression takes advantage of the property of model order, which differentiates between static (zero order) and dynamic (first order) models (Salles and Bredeweg 2001, White and Frederiksen 1990). This approach is a natural fit for QR models because it capitalizes on the way models are built—deriving dynamics from system structure (Bredeweg and Struss 2003, Bredeweg et al. 2008).

Specifically, we developed questions to explore four categories of model content: system structure, causal relationships, dynamic consequences of structure and causality, and application and evaluation to real-life situations (Table 1). In designing specific questions, we focused on areas that helped achieve domain specific (rather than QR methodology) understanding across levels of cognitive ability in Bloom’s Taxonomy, namely knowledge, comprehension, application, analysis, synthesis, and evaluation (Bloom 1956).

3. Evaluation of the progressive learning route

3.1. Evaluation 1: understandability of model diagram representations

We evaluated this progressive learning route (Table 1) with a class of 19 university students, ranging from second- to fourth-year Biology majors at Indiana University of Pennsylvania, USA. None of the

<table>
<thead>
<tr>
<th>Table 1</th>
<th>List of questions and instructions (hints). Specialized terms are linked to an online glossary.</th>
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</thead>
<tbody>
<tr>
<td>1. Explain in your own words the system being modeled by this scenario. (System structure)</td>
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<tr>
<td><strong>Hint</strong>: In the model building environment, open the scenario and arrange the contents if you need to (don’t change anything else!). The scenario describes the system of interest. Try completing this sentence: “The scenario investigates what happens if…” <strong>Hint</strong>: Run the simulation to the initial states. When you do this, the program looks in the digital library for information that matches what is in the scenario and assembles all the pieces of information together to create a more complete model of the system. Next, select one of the initial states and open the Entity Relations view. Arrange the contents so that you can see everything clearly and describe what you see. How is the information described similar/different to that contained in the scenario?</td>
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<tr>
<td>2. Explain in your own words what features and processes are likely to be most important in this system. (System structure)</td>
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<tr>
<td><strong>Hint</strong>: With the initial state still selected, open the model fragments list to see what model fragments fire. Open the model fragment editor for each model fragment to see which one contains causal dependencies (P1). These will describe the main processes. Agents, or external influences, will be evident by their specific agent icons, and also be connected via a causal dependency to other quantities.</td>
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<tr>
<td>3. What are the state variables, the rates, and their starting magnitudes and derivatives for state 1? What entities are the variables (quantities) associated to? (System structure)</td>
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<tr>
<td><strong>Hint</strong>: You can double click the state to display values (magnitudes and derivatives) for all quantities in a state or you can open the dependencies view and choose the button to display values (quantity magnitudes and derivatives). Rates often have the word “rate” in them, or describe some action (generally via direct influences). State variables are the remaining variables, and are generally an amount of something.</td>
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<tr>
<td>4. Explain why the derivative values what they are (NB: The starting derivatives for Rain and Drainage have been pre-set to steady). (Causality)</td>
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<tr>
<td><strong>Hint</strong>: Look at the causal dependencies in the dependencies view. Make sure P1 and P2 are displayed along with the values quantity magnitudes and derivatives.</td>
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<tr>
<td>5. What seems to be the focal quantity or quantities in the system? How can you tell? (Causality)</td>
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<tr>
<td><strong>Hint</strong>: Look at the causal chain (or chains) in the dependencies view. Are there any quantities at the end of a causal chain or that are influenced by several dependencies? Also, what (if any) quantities are influenced by agents?</td>
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<tr>
<td>6. Predict what will happen throughout the system and why. Will the system evolve towards a final end point? What will that end point be? Focus on answer to #5. (Dynamics)</td>
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<tr>
<td><strong>Hint</strong>: Reason through the causal dependencies (including magnitudes and derivatives) to see how they cause and propagate change through the system.</td>
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<tr>
<td>7. Describe what the model predicts to happen in the system over time. How many behaviors are possible? (one, two, three, many…?) Describe/interpret what happens in each (at least three, if present) of these behaviors. (Dynamics)</td>
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<tr>
<td><strong>Hint</strong>: Run the full simulation. You may need to spend some time arranging the state graph to optimise the layout of states and transitions (circles and arrows). Note the general nature of the state graph (cycles, branching paths, etc.). Select a path starting with the initial state. View the value history, focusing on what happens to the state variables. The causes of any changes in quantity values are due to causal dependencies (influences), and the net effect of “competing” influences on any one quantity depends on which influence is larger. To see which influence is larger, view the Equation History for the selected path. Repeat for several paths (if there are more than one).</td>
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<tr>
<td>8. Compare the model predictions (your answer to #7) with your predictions (your answer to #6). Do they match? What in your predictions is missing in the model predictions and vice versa? (Evaluation—application)</td>
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<td>9. Relate your description of the system, starting conditions, and model predictions to a real-life situation. Describe under what circumstances the system being modeled might arise and give examples of the entities, quantities, and agents (as relevant). Evaluate whether this is a realistic situation and what might be done to make the situation more sustainable and improve human wellbeing. What might get in the way of achieving a sustainable condition or reduce human wellbeing? (Evaluation—application)</td>
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<td>10. What do you think the main take home points of this lesson and scenario were? What, if anything, did you learn from this lesson that you didn’t already know (including new facts or ways of thinking about things)? (Evaluation—application)</td>
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students had previously had a course in ecology or SD. Some of the students had worked with concept maps, but none had experience with QR models. Students gave informed, written consent to participate in the study.

Though the lesson plan was designed with computer-based, individual instruction in mind, for the purpose of this study, the lesson was presented in a classroom setting using a video projector. This is not considered a problem, because the current study focuses on the content and structure of the educational materials rather than the usability of the Garp3 software, which has been investigated in previous studies (Bouwer 2005, Bredeweg et al. 2007). Students viewed a slide presentation providing basic background on QR, including some example diagrams from an unrelated QR model, as well as an overview of the case studies developed in the NaturNet-Redime project. The lesson evaluated involved a model from the River Kamp, Austria, case study (Zitek et al, 2009). To introduce the model, students were shown a photo of a catastrophic flood in the River Kamp and read some brief accompanying text (Fig. 1). Students were then shown diagrams (Fig. 2) prepared from Garp3 based on the River Kamp model with corresponding questions following the template from Table 1. Because students did not have the opportunity to interact with the model individually, some questions were modified or elaborated to provide additional guidance (see Fig. 2). Students were allowed to view each diagram and write down their responses until it looked like most had finished writing. Then, the facilitator solicited student responses to the question. If it looked like students didn’t understand how to answer the question, the presenter showed the corresponding hint (Table 1). After a few students had responded, the facilitator presented a prepared “correct” answer before moving on to the next question (see Appendix). This allowed students the chance to catch up if they didn’t understand how to answer earlier questions.

Handwritten responses to each question were collected and analyzed. Each response was given a score from 0 to 3 based on the degree to which the response matched our predefined learning objective for each question (Appendix). A score of 3 was assigned to questions that matched all learning objectives for a question, 2 was assigned to responses that got many of the main points but not all, 1 to responses that made an effort but were mostly wrong, and 0 to responses that were left blank or lacked a substantive response. Scores were averaged among students and categories of questions to provide a measure of the effectiveness of the QR representations and models for facilitating learning about the subject covered in the model.

3.1.1. Results: questions exploring system structure

Some students at first had difficulty grasping the meaning of some of the model diagrams during the first few questions. For example, instead of basing their answers solely on the diagram for question #1 (average score 2.37±0.14 (1 SE), Fig. 3), several students included additional information from their background knowledge that could not be derived directly from the diagram. For question #2 (average score 2.32±0.18), which asked which processes were active, many responses focused on the causal aspects related to each quantity rather than simply naming what processes were evident from the diagram. The high score on this question may be attributed to the high number of processes in the diagram: students could just list all quantities because they were all involved in a process. Question #3 received a much lower average score (1.69±0.16); no student answered this question completely, and several left it blank or were way off base. Most students were able to identify magnitudes and derivatives of each quantity, but most did not identify which quantities were rates or states, or which quantities belonged to which entities. It seems students did not understand the concept of state vs. rate or the association of quantities to specific entities.

Overall, student responses to questions in this category received an average score of 2.14±0.10, meaning that students understood most of the content related to system structure. Most errors were due to incompleteness or over-completeness (including extraneous information), rather than complete misunderstanding. Some students commented that they did not understand some of the symbols in the diagrams; however, once they had the opportunity to hear responses...
1. Explain in your own words the system being modeled.

2. Explain in your own words what processes and external influences are likely to be important in this system.

3. What are the state variables, the rates, and their starting magnitudes and derivatives for the initial state? What entities are the variables (quantities) associated to?

5. Inspect each of the focal quantities’ derivatives (in state 1) and explain why it is increasing, decreasing or stable.

6. Predict what will happen to the focal quantities (your answer to question #5) and why. Will they stay the same, or will they reach another value, e.g., a maximum/minimum? Will a new equilibrium be reached, or might the system keep changing? Are multiple outcomes possible?

4. What seems to be the focal quantity or quantities in the system? How can you tell?

7. Describe what the model predicts to happen.
   - In the state-transition graph, select state 1 and press the button ‘Select a path’.
   - Does the behaviour end at a certain state?
   - Describe what happens to the focal quantities during this behavior path.
   - Now look at the state-transition graph again. Are alternative behavior paths possible? Pick one of these alternative paths and describe how the behavior differs from the first one.

8. Compare the model predictions (your answer to #7) with your predictions (your answer to #6). Do they match? What in your predictions is missing in the model predictions and vice versa?

9. Consider how this relates to a real-life situation.
   - Now that you have inspected the simulation, consider how this relates to the real-life situation as described in the introduction. More specifically, Where in the cycle do you think the system was prior to the flood that happened in 2002, in terms of values for Fear and Government action rate? Where is it now?
   - Can you give some examples of sustainable actions and non-sustainable actions?
   - Can you think of ways to maintain a high level of sustainable actions and a low level of non-sustainable actions even when fear of catastrophes is low?

10. What do you think people can learn from studying this lesson and scenario (including new facts, ideas, or ways of thinking about things)?

Fig. 2. Questions presented to students and associated diagrams (arrows point to relevant diagrams) from the River Kamp QR model.
of other students and the prepared answer, most seemed able to catch up and better understand and more appropriately respond to later questions.

3.1.2. Results: questions exploring causality in the system

For the most part, students were able to understand the nature and direction of causality in the model. Though question #4 had a rather low average score (1.79 ± 0.21), there was a wide spread in the scores. While all students provided a response, many (10) were completely wrong because they assumed symbols meant something they didn’t (e.g., many students incorrectly assumed Qs in the diagram indicated focal quantities) or because they confused entities with quantities. Six students received perfect scores because they not only identified one to several important quantities but also attributed their importance to the correct causal dependencies. For question #5, 10 students received perfect scores because they identified each of the correct magnitude and derivative values and attributed these derivatives to the correct cause. However, the average score (2.11 ± 0.24) was reduced because other students (6) provided only information on quantity values without attributing a cause (these scored 1 point) and one student left the question blank (score 0). The two students scoring 2 points seemed to get the point of the question, but omitted some important information.

Overall, student responses to questions in this category received an average score of 1.95 ± 0.16, indicating that there was some confusion about causal representation in the model. However, about half the students understood the causal representations completely (scoring 3 points for each question). These students successfully used the diagrams to reason about a complex system involving causal feedback loops. Low scores were mainly attributable to students leaving out important information, rather than obvious misunderstanding of concepts.

3.1.3. Results: questions exploring dynamics of the system

Question #6 was conceived to provide a chance for the students to think about how causality in the model would create change in the system. Having a chance to think about what will happen engages students in the material and piques their interest to see if their understanding is correct. Four students correctly predicted that the system would create a never-ending cycle where values continually fluctuate and no equilibrium would be reached. However, two factors contributed to the somewhat low average score (1.74 ± 0.23) for this question. First, several (6) students provided trivial answers (scoring 0 or 1) that indicated an unwillingness to devote much thought to the question. The remaining students predicted that the system would reach a new equilibrium value; though incorrect, these students did refer to the model to support their answer. This was a challenging question because it asks students to follow the model several steps into the future for quantities that have oscillating behavior.

Students scored well (average score of 2.67 ± 0.14) on question #7, which asked them to describe dynamics of the system as predicted by the model. Students were able to interpret the state graph and value histories correctly: they noted the multiple possible outcomes all involving a cyclic system where all quantities oscillate. During class discussion, one student pointed out that there was a lag in response of variables, specifically that the government responds only after a catastrophe occurs, which is a subtle but important point of the model. This comment sparked some fruitful classroom discussion. The five responses that didn’t score 3 points on this question correctly interpreted the state graph but didn’t discuss fluctuating values from the value history diagram, and thus were incomplete.

Overall, student responses to questions in this category received an average score of 2.19 ± 0.15, indicating that students mostly understood the intended content. Students seemed to have difficulty predicting model dynamics on their own (question #6) but were able to understand quite well the diagrams presenting the simulation’s predictions (question #7).

3.1.4. Results: questions evaluating and applying concepts in the model

Question #8 asked students to compare their own predictions with those from the simulation. We didn’t score this question because there was no “correct” answer. Many students identified outcomes from the model that they didn’t expect in their own predictions (such as lag times or cycles). Overall, however, students often responded that their predictions matched those of the model even though their written responses to question #7 included things that were not included in their responses to question #6. This may indicate that students had difficulty determining the level of detail to include in their responses to question #6, or did not know how to express certain ideas in words until they saw them in the diagrams provided for question #7.

Question #9 was aimed at students applying the concepts from the model to the actual situation being faced by the residents of the Kamp Valley. Responses scored reasonably high (2.21 ± 0.18), indicating that students were able to successfully apply the concepts from the model and synthesize these with their knowledge of the situation in the Kamp Valley and background knowledge about environmental sustainability. Students named several types of sustainable actions (e.g., maintaining natural ecosystems in the watershed to reduce flood levels) and unsustainable actions (e.g., building too close to the river or in low-lying areas).

Question #10 asked students what the “take home message” from this lesson is. Most students responded that people could learn that the government should institute policies that maintain sustainable actions even when community fear level is low. Responses averaged 2.26 ± 0.15, indicating good overall understanding of the main learning objectives. The main reason for lower scores was incompleteness or vagueness in the responses.

Overall, students did a good job at applying concepts from the model to real-life sustainability situations (average 2.24 ± 0.16 points). None of the responses in this category indicated misunderstanding of concepts, though many answers were incomplete.

3.1.5. Student impressions and overall learning progression

Students were also asked about their impressions of the lesson format and using QR models to learn about sustainability. Many students responded that they thought the simulation model provided useful support for learning about the behavior of complex systems. Some students commented that they had difficulty understanding the various symbols contained in the diagrams. This may also have been due to their inability to access the help tips that would ordinarily be

![Fig. 3. Mean scores per question. Error bars represent 1 standard error about the mean. Question 8 (evaluation/application) was too open-ended to score. See Table 1 and Fig. 2 for questions and diagrams viewed.](image-url)
available if they were working on their own computers as well as limited prior exposure.

Based on the written responses to questions in the lesson, students mostly made a good effort to answer the questions to the best of their ability. Students successfully used the diagrams to reason about a complex system involving causal feedback loops and multiple possible outcomes, including cyclic behavior. Over all questions, responses scored on average 2.13 ± 0.06, indicating students were able to understand most of the domain-specific content contained in the model. Students had the most difficulty answering questions about causality in the system (Fig. 3), perhaps related to inexperience with how causal dependencies are represented in Garp3. Additionally, response scores would have been higher for many questions if students had provided more complete responses. Breaking questions up into parts that must be answered separately may help ensure more complete answers.

3.2. Evaluation 2: student interaction with models and modeling software

Having established that students could, with minimal instructor support, understand and reason from model diagrams relevant to steps along the progressive learning route, we next designed an experiment to provide a more quantitative assessment of student learning outcomes, again following the progressive learning route but this time with students interacting with dynamic QR models in the QR modeling software Garp3. This assessment also allowed us to determine whether students could abstract from specific questions in the learning route (Table 1) and specific model representations to learn key principles relating to causal theory in a domain.

We applied the lesson plan to exploration of a model depicting interaction of a plant population and resources in the environment, based on the model presented in Nuttle et al. (2009). Briefly, the model describes how plant growth is affected by resource concentration and vice versa. The lesson was evaluated with a class of undergraduate students similar to the one described above. Twenty-four students were randomly assigned to two groups for a cross-over experiment: Group A completed the lesson on the first day and an unrelated alternative activity (watching the film An Inconvenient Truth) five days later whereas Group B did the reverse. To assess prior understanding, all students completed a pre-test consisting of three questions (Table 2) before engaging in either activity. As background, all students had investigated for ca. 40 days population dynamics of duckweed (Lemma minor) in small culture dishes with different nutrient concentrations (one culture per student).

During the QR-based lesson, students worked in pairs to investigate progressively more complex and realistic models of population and resource dynamics. Consistent with the concept of model progression, experience has shown that learning is better achieved when students start with simple models and move gradually to more complex models. First, students investigated a simplified version of the model with no mortality in the duckweed population. This simplified model served to familiarize students with the modeling software—students were provided a detailed handout with screen shots pointing to which icons to click to generate desired diagrams that should be viewed to answer each of the ten questions in the progressive learning route (Table 1). The outcome of this scenario is that the duckweed population grows to a high biomass and remains there even though they have used up all the resources in the environment. Next, students modified the model by changing the mortality rate from zero to med (a positive value). This model still failed to capture realistic duckweed dynamics, as once the duckweed used up all resources in the culture dish, the population died out. Finally, students made the model even more realistic by adding a (pre-defined) process wherein nutrients from dead duckweed leached back into the resource pool, replenishing resources available for duckweed growth. This model produced oscillating population behavior consistent with results from most students’ real duckweed cultures. For each model version, students investigated the model using the same set of ten questions in the progressive learning route, focusing their free-form, written responses on how model representations or outcome changed since the previous version. During the lesson, the instructor was available to answer questions posed by students; answers were provided for questions related to how to operate the software but not about model content or simulation results (these questions were re-directed to the students).

After completing the lesson or alternative activity, students took a post-test consisting of the same set of questions as the pre-test. Five days later, groups were reversed: Group B completed the QR-based lesson and Group A completed the alternative activity, with the same post-test administered at completion of the activity. The alternative activity served as a control to the experimental treatment of working with models. Differences in number of correct responses between the pre-test and first post-test and between first and second post-tests were used to assess overall learning about the plant–resource system, which was evaluated for significance using one-tailed, paired t-tests.

3.2.1. Results: student interaction with models and modeling software

Results from the cross-over experiment support the hypothesis that interaction with QR models following the progressive learning

Table 2
Pre- and post-test questions for the experiment evaluating ability to learn domain theory related to plant-resource interactions.*

<table>
<thead>
<tr>
<th>For the following questions, consider a plant population that uses a resource, e.g., nitrogen, phosphorous, or water. To the best of your ability, pick the most appropriate answer to each question.</th>
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<tbody>
<tr>
<td>1. How is the growth of the plant population affected by the amount of resource available in the environment?</td>
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<tr>
<td>a. Population growth is not affected by resource availability</td>
</tr>
<tr>
<td>b. As long as there is some resource available, net population growth will be positive.</td>
</tr>
<tr>
<td>c. The more resource available, the more plant production, so the higher net population growth will be.</td>
</tr>
<tr>
<td>d. Mortality increases just as much as production, so net growth rate remains constant despite any change in resource availability.</td>
</tr>
<tr>
<td>2. What happens to a resource when a plant population uses it?</td>
</tr>
<tr>
<td>a. There is no change since there is too much resource in the environment for the plant to have any effect on it.</td>
</tr>
<tr>
<td>b. The plant removes resources from the environment, reducing the amount that would otherwise be available.</td>
</tr>
<tr>
<td>c. Plants don't affect the amount of resources available, but resource can affect the ability of plants to grow in certain areas by making the environment unsuitable.</td>
</tr>
<tr>
<td>d. Plants increase the amount of resources available so that they can grow better.</td>
</tr>
<tr>
<td>3. What would happen to the plant population if the resource runs out?</td>
</tr>
<tr>
<td>a. Nothing—the plant consumes the resource, not the other way around.</td>
</tr>
<tr>
<td>b. The plant population would increase so it can find more resource.</td>
</tr>
<tr>
<td>c. The plant population would decrease and eventually die out unless more resource becomes available.</td>
</tr>
<tr>
<td>d. The population would stop growing and remain stable, neither increasing nor decreasing.</td>
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*Correct answers are c, b, c, respectively.
route described here supports learning: test scores improved after completing the QR-based lesson (Group A: $P = 0.018, n = 9$; Group B: $P = 0.017, n = 8$) but not after completing the alternative activity (Group A: $P = 0.500, n = 7$; Group B: $P = 0.297, n = 9$; see Fig. 4).

Furthermore, rather than asking students questions about specific values and relationships in the QR models, the pre-/post-test (Table 2) asked more general questions about the interaction of plants and resources in the environment. Hence, results from this experiment indicate that students can abstract from specific questions and model content targeted in the progressive learning route to understanding more general concepts related to a domain theory.

4. Discussion

This evaluation indicates that students are able to understand QR model representations of system structure, causality, and dynamics; apply this understanding to real-world situations; and evaluate model content compared to real-life experiences or outside knowledge (Fig. 3). Furthermore, after following a set of models using the progressive learning route, students can abstract model content to general principles in a domain (Fig. 4). This demonstrates engagement at a high level of cognitive ability according to Bloom's Taxonomy (application through evaluation; Bloom 1956). Overall, students responded positively to the experience of viewing and working with QR models and several expressed interest (orally or in their written evaluations) in participating in future activities using QR models. We are currently integrating additional lessons based on QR models in two undergraduate science courses (botany and introductory geology). We anticipate that as students become more familiar with QR representations, they will be able to provide more correct and detailed responses to each question. Indeed, a study focusing on the learnability of the graphical QR representations in Garp3 indicates that working with the software for 6–8 h led to significant improvements in users’ correct interpretation of diagrams, and that much of this knowledge was retained after six months during which time the software had not been used (Bredeweg et al. 2007). This holds promise for using this approach for multiple courses in a curriculum because students would not have to relearn the software or modeling ontology each time.

We applied the lesson format and progressive learning route to two completely different models, with positive results for learning. The open-ended question and answer format allows students to provide in-depth responses but students may not take advantage of this opportunity. In their work on educational conversational agents, Graesser et al. (2008) explored dialogue mechanisms that stimulate students to give more lengthy responses to open-ended questions. However, more detailed responses also require more intensive interpretation from human or machine evaluators. Though we did not score student responses to open-ended questions in the investigation involving the plant–resource model, we noted that students frequently simply jotted down a few comments or phrases, or drew annotated sketches of model output. Nevertheless, our results from comparing pre- and post-tests indicate that working with models following the progressive learning route facilitated learning of key domain concepts even when provision of detailed answers to each question along the route was not enforced. Hence, in a curriculum involving learner interaction with many QR models, the instructor may wish to begin by checking student responses to each question in the progressive learning route followed by a closed-ended quiz at the end of the lesson. Once it is clear students are able to follow the progressive learning route and provide sufficiently correct and detailed answers, the instructor can then scale back to using only closed-ended quizzes for assessment.

4.1. Implementation in a curriculum for learning about sustainability

Though the evaluations presented here took place with university students, the goal of the NaturNet-Redime project was to develop learning materials that make expert knowledge about sustainability more accessible to decision makers and stakeholders. Because the EU’s SD Strategy calls for more involvement of the public in decision making, this means everyone. Only a small proportion of these potential learners are enrolled in or in close proximity to formal educational institutions. Hence, a curriculum to support objectives of the SDS must be open, rather than formal. Whereas formal curricula are generally linear in their presentation of content, open curricula should be organized more like a web, where alternative ways to explore the content reflect the diverse interests and learning needs of our diverse target groups. Nuttle et al. (2006) presented a plan for organizing and optimizing QR models developed in the NaturNet-Redime project into a structure that guides learners through a “landscape of sustainability concepts”. An open curriculum that follows this plan and includes lessons for the River Kamp model described here as well as material for other models has been implemented in Moodle, an online course management system (http://www.moodle.org) and can be viewed at http://portal.natur-net.org. Taking advantage of the hierarchical and compositional nature of our QR modeling approach, the aim is to support development of a deeper understanding of causal linkages between environmental, social, economic, and institutional aspects of sustainability. Future work includes applying methods that exploit QR’s explicit representations to automatically generate interactive explanations in natural language (Bouwer 2005). This can be an important feature to provide feedback when learners are widely distributed geographically and distant from an actual ‘teacher’ (Bredeweg and Forbus 2003). In the meantime, the high level of cognitive engagement, from application through evaluation (Bloom 1956), demonstrated in our evaluations of the progressive learning route holds promise that a curriculum based on learner interaction with QR models may indeed help build a society equipped to meet the challenges of environmental sustainability.

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Appendix A

Prepared answers to questions presented to students during Evaluation 1 (see Fig. 2 for questions and diagrams viewed by students).

**Answer to question 1.** The system that is modelled in this scenario includes three entities, which are related in the following way. There is a community living in the Kamp valley. According to this scenario, the community influences the government, and the government affects the Kamp valley.

**Answer to question 2.** The Government action rate influences Sustainable actions (I+) and Non-sustainable actions (I−). The net effect of sustainable and non-sustainable actions determines the Change of risk (notice the P+ and P− dependencies and the calculation in the model fragment view or the dependencies view). The Change of risk influences the Magnitude of catastrophic effects (I+). The Magnitude of catastrophic effects propagates to Fear of the community (P+). Fear of the community propagates back to Government action rate (P−). The other information in the model fragment (the Q- and V-correspondences) helps to reduce the complexity of the resulting simulation.

**Answer to question 3.** In the dependencies view for state 1, we see:

- **Government action rate**: Zero, increasing
- **Change of risk**: Plus, steady

State variables with initial magnitudes and derivatives:

- **Fear**: Low, increasing
- **Sustainable actions**: Zero, steady
- **Non-sustainable actions**: Max, steady
- **Magnitude of catastrophic effects**: Low, increasing

Which quantities belong to which entities?

- **Fear** belongs to the entity Community.
- **Government action rate**, Sustainable actions and Non-sustainable actions belong to the entity Government.
- **Change of risk** and **Magnitude of catastrophic effects** belong to the entity Kamp valley.

**Answer to question 4.** Inspecting the Dependencies view in state 1, we see:

- **Fear** is increasing because **Magnitude of catastrophic effects** is increasing (P+).
- **Government action rate** as response to fear is increasing because fear is increasing (P+).
- **Non-sustainable actions** is currently steady because Government action rate is zero; therefore the negative influence (I−) currently does not have an effect.

**Answer to question 5.** In this scenario, we see a feedback loop which results in cyclic behavior. Therefore, all of the quantities can be considered important. Specifically, **Government action rate** and **Change of risk** are the quantities which directly influence the Sustainable actions, Non-sustainable actions, and the Magnitude of catastrophic effects, respectively. Although its behavior directly corresponds to the Magnitude of catastrophic effects, the quantity Fear of the community is also important because it provides a causal feedback loop to the Government action rate.

Sustainable actions is also currently steady because Government action rate is zero; therefore the positive influence (I+) currently does not have an effect. Change of risk is currently steady because both quantities affecting it are also steady (P+P−). Magnitude of catastrophic effects is increasing because the quantity influencing it (I+) has a positive value.

**Answer to question 6.** The quantity **Change of risk** is calculated as Non-sustainable actions (current value: Max) minus Sustainable actions (value: Zero). This difference is positive (value: Plus), which causes the Magnitude of catastrophic effects to increase (via the positive influence 1+). This propagates to an increase of Government action rate. This value of Government action rate will therefore become positive, which will positively influence Sustainable actions (I+), and negatively influence Non-sustainable actions (I−). Therefore, in the following states, Sustainable actions will increase and Non-sustainable actions will decrease. Change of risk will decrease and Magnitude of catastrophic effects will stabilize, and then start to decrease. This will in turn propagate further, so that Government action rate will decrease again, in which case the whole cycle starts again.

**Answer to question 7.** When selecting state 1 and pressing the button ‘Select a path’, a cyclic path is selected: [1, 2, 3, 4, 5, 6, 8, 13, 16, 22, 1]. In this cyclic path, the value of Fear and Magnitude of catastrophic effects goes up to high first, and down again to low. These values lag behind a few states after the actions of the government, which also go up and down (or vice versa, for the sustainable actions). This lag can be interpreted as the time that it takes for government actions to have an effect on the environment.

Note that the actual maximum or minimum value reached by the various quantities differs for the various paths that are possible. For example, in the cyclic path [1, 2, 3, 4, 5, 6, 8, 13, 15, 23, 22, 1] (which you get when selecting state 23 in path selection mode), you’ll see that both the fear and magnitude of catastrophic effects reach zero for a moment. In the path [1, 2, 3, 4, 5, 6, 10, 11, 19, 20, 26, 3] (which you get when you select state 20 in path selection mode), you’ll see that from state 3 onwards, the turning point occurs within the interval high, so that both the Fear and Magnitude of catastrophic effects are high all the time — not a very positive prediction!

If you chose to describe a different path, that’s OK.

**Answer to question 8.** Probably, your predictions were not as complete as those produced by running the full simulation. Perhaps you found some surprising results. Here is a checklist of things to consider when comparing your own predictions with the model’s predictions:

- Did you predict that Fear and Magnitude of catastrophic effects would go up at first?
- Did you also predict that Fear and Magnitude of catastrophic effects would go down again later?
- Did you consider that cyclic behavior was possible?
- Did you predict the time lag between Government action and Magnitude of catastrophic effects (and Fear)?
- Did you consider that different values could be reached as a maximum/minimum by the various quantities?

**Answer to question 9.** Where in the cycle do you think the system was prior to the flood that happened in 2002, in terms of values for Fear and Government action rate? Answer: Fear: low, Action rate: zero/minus

Where is it now? Answer: Fear: high, Action rate: plus

Can you give some examples of sustainable actions and non-sustainable actions? Possible answers:

- **Sustainable actions**: planting forested buffer areas, building only on high ground, removing unnecessary dams
- **Non-sustainable actions**: cutting forest in buffer areas, building on low ground, channelizing the river

Can you think of ways to maintain a high level of sustainable actions and a low level of non-sustainable actions even when fear of catastrophes is low? Possible answer: This requires continuous lobbying and public support to attract the attention of decision makers for the importance of sustainable actions.

**Answers to question 10** were open-ended.

References

