A Perspective of Urban High School Teachers on Using System Dynamics Tools

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-Abstract-

Systems thinking tools and system dynamics simulations can provide a valuable means for helping students think their way around complex environmental problems. This study was designed to advance our understanding of teacher adoption of systems thinking and systems dynamic modeling by documenting the perspective of a large group in an urban environment who were tasked with a curriculum that included systems dynamics simulations. This paper reports on the results of a Web-based survey and focus group regarding the use of systems tools in secondary science classrooms and teachers' understanding of the tools already available to them. Teachers identified the barriers to implementing systems simulation activities as both computer access and their own understanding. A test of teachers' understanding of systems principles reveals inconsistencies in the way they interpret models, based on their previous understanding of the system. Strategies for addressing these issues with professional development are provided.

Keywords: teachers, systems dynamic, modeling, implementation, barriers, K-12 education

Introduction

As science, technology, engineering, and mathematics (STEM) education continues as a priority in the United States (U.S.), systems thinking and system dynamics modeling can provide a valuable means for helping students think about complex problems. Jonassen (2007) defines a complex problem as "a function of external factors, such as the number of issues, functions or variables involved in the problem; the number of interactions among those issues, functions or variables; and the predictability or the behavior of those issues, functions or variables" (p. 9). Though complex problems are difficult, students find them motivating (Albanese & Mitchell, 1993) and they are consistent with the authentic problems that are currently being addressed by professionals from across the STEM disciplines (i.e. climate change, energy, food production and supply). For these reasons, recent calls for curriculum reform have included the use complex problems as curriculum. For example, a recent report by the President's Council of Advisors on Science and Technology (2012) recommends the widespread adoption of active learning approaches such as case studies, problem-based learning, peer instruction, and computer simulations as a strategy for improving the retention and recruitment of undergraduate students in the STEM disciplines. Similar calls for reform in engineering education have focused on the need for adaptive expertise, as the intended educational outcome (National Academy of Engineering, 2004, 2005). Pellegrino (2006) defines adaptive expertise as "knowledge and understanding that can support transfer to new problems, creativity and innovation" (pg. 2). Systems thinking and modeling exist as tools of adaptive expertise that afford an interdisciplinary, integrated perspective that accounts for feedback among interdependent parts through dynamic interactions (Jonassen & Strobel, 2006). Thus, requiring learners to organize material more meaningfully, to gauge the potential of a particular solution, and to assess the relevancy of their arguments. However, achieving this grand vision of adaptive expertise requires the explicit inclusion of systems thinking and modeling in K-12, as well as undergraduate education.

Recent policy decisions regarding the pending major revision of the U. S. national K-12 science education standards has made more likely the inclusion of systems thinking and modeling. The purpose of *The Next Generation Science Standards* (NGSS) is described as:

> Science—and therefore science education—is central to the lives of all Americans, preparing them to be informed citizens in a democracy and knowledgeable consumers. It is also the case that if the nation is to compete and lead in the global economy and if American students are to be able to pursue expanding employment opportunities in science-related fields, all students must all have a solid K–12 science education that prepares them for college and careers. (Achieve, 2011)

The theoretical framework for NGSS, *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, published in 2011 as the guiding document for construction of the *Next Generation Science Standards* includes systems and system models as a fundamental scientific and engineering crosscutting concepts for all of the disciplinary core ideas as well as being a component of Scientific and Engineering Practice 5: Using Mathematics and Computational Thinking. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* defines systems and system models as:

> Defining the system under study—specifying its boundaries and making explicit a model of that system—provides tools for understanding and testing ideas that are

applicable throughout science and engineering. (National Research Council, 2011a, p. 84)

From our perspective, we view system dynamics, the language, pedagogy and technology as aligning with all seven of the crosscutting concepts outlined in *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (e.g. patterns; cause and effect: Mechanism and explanation; scale, proportion, and quantity; systems and system models; energy and matter: flows, cycles, and conservation; structure and function; stability and change). Though specifics will not be known until the final version of the Next Generation Science Standards are released, this policy decision is cause for optimism that an explicit focus on systems thinking and modeling in K-12 science education may be imminent. As such, research in this context that involves curriculum, learning environments, professional development and teacher adoption is of increasing importance.

The current study was designed to advance our understanding of teacher adoption of systems thinking and systems dynamic modeling by documenting the perspective of a large group in an urban environment who were tasked with a curriculum that included systems dynamics simulations. Study participants represent a sample of the current population of high school science teachers who were responsible for teaching a 9^{th} grade science course using a curriculum that included two chapters that explicitly used systems models and simulations as content and learning material. The relevant literature for this study involves the potential of system dynamics and systems thinking tools for understanding complex systems, empirical research on the application of system dynamics and systems-based curriculum in a K12 science context and the research on technology adoption for teaching and learning.

Review of Related Literature

System dynamics offers tremendous potential for understanding complex systems. According to Meadows (1991), "system dynamics is a set of techniques for thinking and computer modeling that helps its practitioners begin to understand complex systems"(p.1). In a world where people will increasingly be required to work within complexity to make sustainable decisions, understanding complex systems is a valuable skill. For students, system dynamics and systems thinking tools have the potential for keeping track of the many interconnections within a complex system and to afford visualizing the system as a whole (Meadows, 2009). Basic system thinking skills like identifying interconnections, identifying causal relationships that produce feedback and understanding accumulations within a system will help students understand the problematic trends of sustainability, especially in systems that behave in unexpected ways. Fulfilling this vision implies the use of systems dynamics simulations as central learning elements in a curriculum.

A system dynamics simulation is a system dynamics model that has be operationalized so that the user is able to interact with an interface, change the values of variables in the system and simulate the behavior of the system over time. Learning with a simulation is useful for developing student understanding because it allows the student "to simulate the behavior of systems that are too complex to attack with conventional mathematics, verbal descriptions, or graphical methods" (Forrester, 1993, p.185). Teaching the basic principles of complex systems without a simulation might involve lengthy reading assignments, lecture or lessons in the mathematics underlying the system. If the goal of a lesson is understanding an underlying concept, a simulation may benefit the user by demonstrating the concept without the extra work. The simulation reduces the students' extraneous cognitive load by relieving them of the responsibility of remembering equations or principles, while focusing them on the main idea: understanding the relationship between variables in the system (Chandler, 2009; Kalyuga, 2009).

Novice students do not have the requisite knowledge or experience to tackle all of the variables and interconnections of a real-world system. Simulations allow students to work with a less detailed, but also, less complex representation. A good simulation distills the complexity of the, real world to the parts that are crucial to students' understanding of the subject. At the same time, a simulation can link visible or tangible parts of a system, like organisms in an ecosystem, for example, to less tangible parts, such as energy flow through the ecosystem (Committee on Science Learning, 2009). This facilitates a systemic understanding of complex problems without the student being overwhelmed by the complex whole.

Learning with simulations is exploration-based. The student's job is to experiment with the simulation and learn about the underlying system (deJong & Joolingen, 1998). Simulations allow the student to ask a question, generate a hypothesis, and test their hypothesis and form conclusions in an iterative process (Mulder, Lazonder, de Jong, Anjewierden and Bollen, 2011). This changes the student's learning from remembering and reproducing information to a deeper understanding of the principles of causation and feedback (deJong, 1991), facilitating the transfer of this understanding to other domains (Pellegrino, 2006). This type of scientific "messing about" follows closely with the scientific method as it encourages, if only informally, question and hypothesis generation and testing, and interpretation of results, aligning students mental models with the real world systems (Finkelstein, Adams, Keller, Kohl, Perkins, Podolefsky, Reid, & LeMaster, 2005).

Empirical research involving system dynamics and systems-based curriculum in K-12 science education is limited. These studies test the effectiveness of systems tools after they reach the classroom. Much of the support for using systems-based tools in the classroom is anecdotal Lavigne (2009). Most empirical work has focused on the state of student understanding of dynamics systems and their characteristics or on the effect of some systems-based intervention on student understanding. Fisher (2009) conducted a controlled experiment with a group of students that ranged from eighth to twelfth graders that tested the effect on student understanding of Malthusian population dynamics and resource availability when students used two tools to model the problem: Stella modeling software and a graphing calculator. She reported a larger increase in content understanding, from pretest to posttest, for the group using the Stella modeling software than for the group using graphing calculators for the same task. Wheat (2008) conducted a paired experiment in which high school economics students' used either a text description (control group) or a text description paired with a system dynamics causal loop diagram (experimental group) to study macroeconomics principles. He reported that students who used the causal loop diagrams expressed a preference for them and also demonstrated a greater conceptual understanding than the students that read only a text description of the material. Hogan (2000) conducted a study with 11-year-old students to test their systemic understanding of food web interactions in an ecosystem. The intervention did not use conventional system dynamics tools, rather the representation of interconnections of organisms in a food web and asked students to evaluate how a change in the numbers of one organism affect the rest of the food web. Most students used linear rather than cyclic reasoning to relate organisms; that is, they only described relationships as A affecting B, but do not discuss how B, in turn, affects A, as it would in an ecosystem. A larger base of empirical evidence is important to understanding how to best use systems tools so that the most effective interventions are developed. According to Doyle, Radzicki and Trees' (1998), "there is insufficient evidence to convince skeptical, scientifically minded observers, which is crucial if systems thinking ideas and techniques are to become more widely accepted in educational and corporate settings" (p.254).

However useful systems simulations may be for teaching students about complex dynamic phenomena, research on other types of technology adoption shows that teachers perceive several barriers to using technological tools. These barriers fall into two broad categories. First order barriers, such as resource availability, unreliability of equipment and lack of technical support are also called external barriers (Ertmer, 1999). Second order barriers are internal barriers, such as lack of confidence using technology or a disinterest in changing ones teaching practices. External barriers are usually easier to recognize and fix than internal barriers, since the provision of materials and external support is more readily available than changing a well-established teaching paradigm. Addressing internal barriers, such as teachers' beliefs about technology and their attachment to traditional teaching methods requires a change in philosophy, then practice.

Recognizing the challenge in addressing internal barriers requires an understanding that what is really being asked of teachers is for them to change the way that they teach. First, they are asked to teach using a new medium; that is asking them to teach using simulations or interactive materials when they may be accustomed to written notes and lecture. Second, they are asked to change their role in the classroom or perhaps the way the classroom is set up (Keengwe, Onchwari, & Wachira, 2008). New practices require time to achieve proficiency, a concept that that also comes at a premium in the K-12 classroom. The requirement of time to achieve proficiency is an important consideration for both students and teachers.

Bauer and Kenton (2005) describe the result of both types of barriers as the limited adoption of new teaching practices with technology. Teachers never progress past what they call the utilization stage, in which they have a fickle relationship with technology. They are satisfied with their limited adoption, but will revert too more practiced methods at the first sign of trouble, such as lack of administrative support or malfunctioning software. Technology only becomes truly useful in the classroom when teachers reach the integration stage, in which technology adopts some of the responsibility of the lesson, so much so that the lesson would not run the same without it.

Fisher (2011) suggests several strategies that might be useful to decision-makers in integrating systems tools in the classroom for complex and meaningful learning, among which is making systems tools usable for teachers. While classroom studies of system modeling interventions exist, if we wish develop systems tools that are widely implemented in K-12 classrooms there is a need to consider the perspective of teachers as end users. The current study uses phenomenography (Orgill, 2007) as a theoretical framework for interpreting the perspective of a sample of high school science teachers concerning the use of systems thinking and systems dynamic modeling for teaching the issues of sustainability. We achieve this outcome by focusing on how these teachers perceive, interpret and conceptualize the process of using these tools. Our goal is to document and classify their ideas and to explore the relationship among those ideas while limiting our assumptions about them and the context in which they teach. In order to identify and characterize the existing barriers, our research asked teachers about how they teach with these models and probed what they knew about computer modeling and systems thinking as hypothesized internal barriers.

Context

This study is situated in a large, primarily urban school district in the southwestern U. S. This district serves roughly 300,000 students in Kindergarten through 12th grade and covers approximately 8,000 square miles of territory. For the 2005-2006 school year, following an intensive data-gathering process the district adopted a uniform integrated science curriculum to support a course for ninth-graders. This course was designed to help students make connections between the concepts they had learned in middle school and to provide a global science and sustainability perspective for their ensuing science courses. Since 2005, *Science and Sustainability*, from the Science Education for Public Understanding Program (SEPUP) has been an adopted curriculum for this course. Chapters 7 and 8 of this material include activities that require the use of systems dynamics simulations of deer population change, developed using Stella software. Annually, between three and five teachers at each of the 48-high schools are assigned to teach this course. Virtually all of these teachers are trained in a specific scientific discipline, and prior to the adoption, most of the existing teacher population had taught specific, traditional science discipline focused courses rather than the more general, integrated course. Since 2005, the district has been providing a broad range of professional development activities that target teachers of this course, but none have focused explicitly on systems thinking or systems modeling.

Method

This study takes a step back from evaluating the implementation of modeling tools and leverages a situation where systems simulations have been included as part of an adopted curriculum to investigate potential barriers to their use by examining the knowledge and perspective of teachers who were impacted by the curriculum decision. To serve this goal, a mixed method study was devised in order to answer the following research questions:

1. How are teachers currently using system dynamics and the systems thinking tools that were already a part of their adopted curriculum?
2. For teachers who are not using the systems tools, what barriers persist to their classroom implementation?
3. How do teachers understand system dynamics modeling language and how might that affect the use of systems tools in the classroom?

Our research method took the form of a single group, mixed-method (quantitative-qualitative) design consisting of two-phases. Phase one involved a survey that explicitly addressed each of our research questions. Phase two involved a focus group interview with a purposeful sample of survey respondents that was intended to confirm, reinforce, and add depth to our survey findings. In the following sections, we first describe the survey, including development, analysis of data, and results, then, in a similar fashion, the focus group.

Survey Development

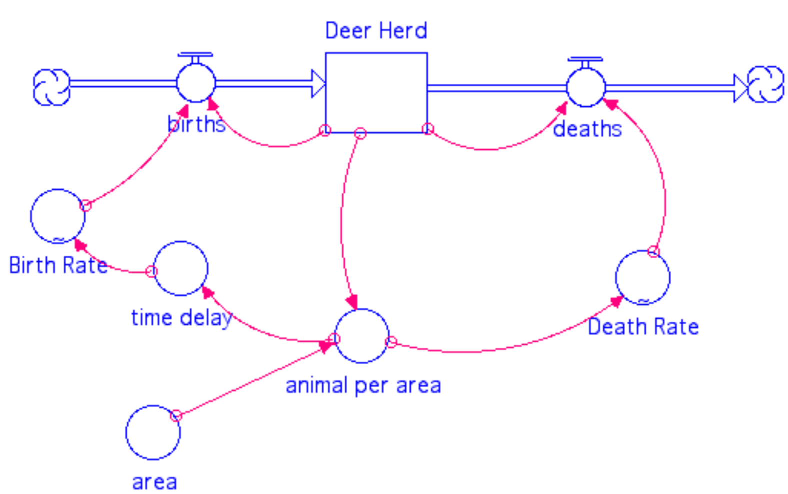
Our review of the literature did not reveal an appropriate instrument; therefore a survey was developed (Appendix). Based upon the research questions, the survey instrument included 17-questions and focused on the following three themes: current perspective on systems thinking and use of modeling tools, understanding and confidence about an adopted model for a familiar system from life science, as well as an unfamiliar system not involving traditional science content.

The first theme, *current perspective on systems thinking and use of modeling tools* included 7-closed response items that asked participants (1) if they taught the lessons from the curriculum that contained the simulations, (2) if they used the simulations to teach the lessons, and (3) the nature of the learning activity that was used to complete the activities. If they indicated that they did not use the recommended simulations, they were also asked to describe the method they used to teach the requisite concepts and to describe these activities in greater detail. Questions 4-6 targeted their perceived barriers to using systems simulations in the classroom. Using a Likert-type scale from not at all confident (0) to highly confident (5), participants responded to two questions indicating their confidence for using the systems models to complete the population dynamics lessons and the general importance of modeling software for learning the material. The remaining item was a short list (e.g. access to computers, instruction on the Stella software) with an additional open-response option for items that were not on the list (i.e. other) and participants were asked to indicate by checking all that applied for additional support or materials that would help implement systems simulations.

The remaining survey items were related to system dynamics content knowledge and understanding of the modeling language and participants were presented with two images of system dynamics models. Addressing the second survey theme of *understanding and confidence about an adopted model for a familiar system from life science*, Model #1 (Figure 1) represented a deer population system and was taken from the population dynamics activities in the curriculum. In the curriculum, this model occurs as the second of four that are presented in order of increasing complexity. Since it is part of the adopted curriculum and because science teachers are typically proficient in content areas dealing with organism population change, the terminology and interconnections represented in the model were assumed to be familiar to the participants. Even if participants were not familiar with the modeling language, we predicted that they would be able to use their previous understanding of how populations change in order to explain the behavior of the system.

Figure 1.

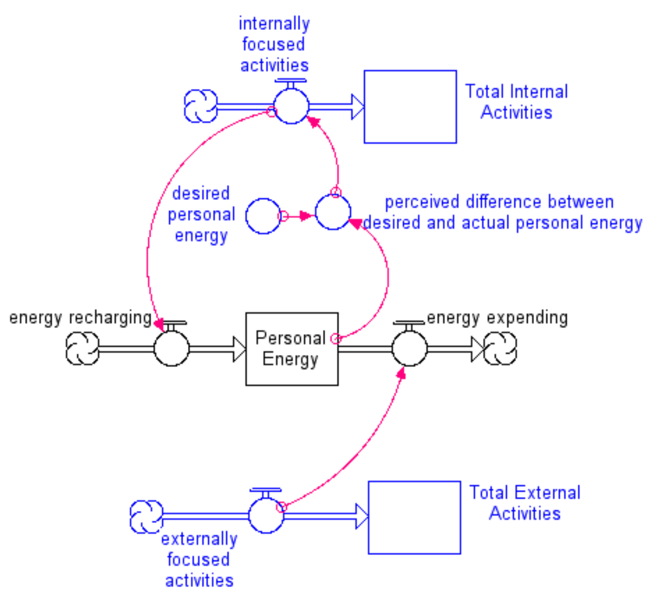
Survey model #1, a system dynamic model of a deer population.



For the final survey theme of *an unfamiliar system not involving traditional science content*, participants were asked to interpret Model #2 (Figure 2) that represented personal energy as a system. Since it was removed from their area of expertise, we assumed that this model was unfamiliar and that interpreting it would require a deeper focus on the representation itself, rather than simply using prior knowledge. In essence, our intent was to require participants to reason with an unfamiliar representation in order to assess the degree to which their model interpretation could be inferred or transferred. Though the content was different, Model #2 was constructed to be as parallel as possible in complexity and structure to Model #1.

Figure 2.

Survey model #2, a system dynamics model of personal energy.



Three parallel, closed-response items were posed, asking participants to: a) identify a direct causal relationship within each model, b) identify the relationship between the inflow (births or energy recharging) and outflow (deaths or energy expending) in the system that would produce an increase in the system's accumulation variable (deer herd or personal energy level) and c) identify their level of confidence for interpreting each model's representation. Follow-up, open-ended items asked participants to use each model to describe what might produce an increase or decrease in the system's stock, using as many of the system's variables as possible. These questions, applied to each of the two different models, were intended to afford an analysis that separated participants' science content knowledge from understanding of the model representation and modeling knowledge.

Content validity of the items was established through expert review and a piloting session using a think-aloud protocol. Two-university faculty with content expertise reviewed and commented on the items during two rounds of revision. A science teacher from a local high school who had extensive experience teaching the 9th grade course with the systems tools and simulations agreed to take the survey online while sitting with the first author and describing her thoughts and explaining her responses. Field notes were recorded and revisions were completed to ensure that items were understood and interpreted in a consistent manner.

Participants

This study focused on secondary science teachers who were responsible for teaching the integrated science course that included the systems models as part of the adopted curriculum. Criterion sampling was used to select the names and email addresses of teachers from across the district that met these conditions. Using Dillman's (2007) Tailored Design methodology, the Web-based survey was deployed to 160-teachers and resulted in 81-responses from 48-different high schools for a response rate of 51%. Though inclusive of a large number of schools, it is important to note that this sample is limited and may not be representative of all science teachers in the district. Following analysis of the survey data, a non-random purposeful sampling technique (Creswell, 2008) was used to select four respondents as information-rich cases for a focus group. Based upon the student population they served as well as their prior involvement with professional development, these participants were distinguished as unique and mutually exclusive.

Table 1

Attributes of teacher participants as members of the focus group.

Teacher Participant	School & Student Population	Prior Professional Development	Personal	Reason for Inclusion
#1 (TP1)	A low socioeconomic status high school with historically high student transiency and a large population of English Language Learners (ELL).	No	Bilingual, has taught classes specifically for ELL students, and was able to speak to specific issues for these students.	To explore the issue of teaching ELL's and our belief in the potential of system dynamics modeling as a communication tool for complex concepts.
#2 (TP2)	The only virtual high school in the district and has no face-to-face interaction with students.	No	None	To explore any unanticipated barriers unique to the delivery medium.
#3 (TP3)	A low socioeconomic status high school with historically high student transiency and a large population of English Language Learners (ELL).	Yes	None	To explore professional development needs related to the student population.
#4 (TP4)	A high socioeconomic status high school, with relatively low student transiency and a small population of English Language Learners (ELL).	Yes	None	To explore professional development needs related to the student population.

Analysis of Survey Data

The first two research questions were addressed with descriptive statistics for survey responses to the 7-items that composed the theme, current perspective on systems thinking and use of modeling tools. The third research question was addressed with descriptive statistics for survey responses for the collection of parallel items that asked participants to interpret figures 1&2 and composed the themes, understanding and confidence about an adopted model for a familiar system from life science and an unfamiliar system not involving traditional science content. A response pattern was created for each closed response item by normalizing by percentage the count of individual responses. Responses to open-ended items were analyzed using a content analysis with a constant comparative method (Creswell, 2008). Responses were open-coded, and then these themes were discussed and clarified among the researchers and finally re-coded to consensus.

Survey Results

Forty-three participants (55%) reported completing the activities from the textbook that include system dynamics simulations, however, only two (3%) reported that they do so with the systems simulations. One selected response item asked participants to identify as many completion alternatives as applied to them, if they did not complete the activity using the Stella interactive software. The list of options included pencil and paper activity, other types of modeling software, group discussion, lab activity and "other." Participants were asked to elaborate if they chose the "other" option. The most common method of completion was a combination of a pencil and paper activity and class discussion (30%). Another 17% reported that they used pencil and paper, combined with class discussion in a lab. 10% used discussion only and 8% used only a pencil and paper activity. Another 5% used discussion paired with a lab activity. Although no participants identified other modeling software as their method of completion, of the 5% that chose "other," some elaborated stating that they did in fact use modeling software or other simulations. In some cases this was Microsoft Excel, to graph predator prey dynamics and in some cases other simulations demonstrating the same principles were used. Several described physical demonstration as their method of completion, in which some students assumed the role of predator and some the role of prey and they acted out predator prey dynamics.

One selected response item asked participants to identify as many barriers to using the Stella interactive software as applied to them. The list of options included the school's lack of access to software, their own ability to use the software, their implementation of a more effective alternative, their own belief that the activities referenced were not important to cover and "other." Participants were asked to elaborate if they chose the "other" option. A majority of participants identified only a lack of access to software as a barrier to implementation of the Stella-enabled activity (64%). An additional 21% stated that their own understanding of the software and lack of software access were both barriers. 6% said that lack of access to software and that they complete their own activity were both barriers to their implementation. 16% chose "other." Some teachers that chose this option stated that the lesson does not fit with what students are required to know for the science proficiency exam and so they do not wish to spent time on it. Some cite difficulty in reserving time in the schools computer lab. Some say that it is not their own understanding that is a barrier, but that they do not wan to spent additional time teaching students to use the software.

One selected response item asked participants to identify as many items that would help them implement the Stella interactive software as applied to them. The list of options included additional computer access, instruction on how to use the simulation associated with the activity, instruction on how to operate the Stella interactive software, instruction on the system dynamics and systems thinking theory behind the simulation, and “other.” Participants were asked to elaborate if they chose the “other” option. 19% of the participants identified all four options (excluding “other”) as support they would find useful. 16% identified only computer access, while another 16% identified computer access, instruction on the simulation operation and instruction on the Stella software. 10% chose other. These participants elaborated saying that using computers creates several issues, but most of them are related to the amount of time it takes to book computers labs, get students to computer labs, and teach students to use the computers. Other participants stated that the software was simply not available at there school, which means that the teachers are not aware that, in fact, the software is available online and for free.

The majority of participants (77%) felt modeling software was important to teaching population dynamics and most of those (73%) reported some degree of confidence in teaching the course using the systems simulations. When asked about their confidence in their own content knowledge, most participants (68%) reported that they felt they understood, to some degree Model #1 (Deer Population Dynamics). Testing this, when asked about the direct causal connection that accounted for death rate changing, twenty-four (35%) chose only the correct answer. Another eighteen (26%) chose some combination of variables represented in the system that included the correct answer. When asked about the relationships that cause deer population to increase, twenty-two (34%) chose only the correct answer, while twenty-seven participants (37%) chose a combination that included the correct answer. Finally, in describing how the size of a deer population might increase or decrease, using as many of the model's variables as possible, seventeen (43%) responses included correct concepts. Only three participants (7%) answered the question fully by describing how each of the variables represented in the model were related to each other.

When asked about their content knowledge in relation to Model #2 (Personal Energy Level), more than half of the participants (55%) responded that they understood the model to some degree. Testing this, when asked what direct causal connection caused an introvert's recharging rate to change, thirty-three participants (56%) responded correctly. This figure is much higher than those responding correctly to the parallel question in the deer population example. When asked about the relationship that causes personal energy level to increase, nineteen (36%) chose only the correct answer, while fifteen (29%) chose a combination of answers that included the correct answer. Finally, in describing how personal energy level might increase or decrease using as many of the model's variables as possible, only nine (26%) answered with a response which included correct concepts. None of the respondents described the system completely in their answer.

The following themes were identified from the survey results and were used to frame the follow-up focus group interview:

- Simulation use and barriers to use
- Understanding of system dynamics modeling language
- Need for professional development

To validate the identified barriers from the survey and to facilitate a deeper discussion of those themes, a focus group was conducted within 6-months of the initial survey.

Focus Group

The focus group interview protocol was guided by the themes that emerged from the survey results: simulation use and barriers to use, system dynamics content understanding, and the utility of professional development in the implementation of system dynamics simulations in the classroom. Following the guidelines of Krueger & Casey (2009), discussion prompts were developed to address each of the themes that emerged from the survey and served the following three purposes: (a) to support or refute information discovered in the survey data, (b) to ask more specific questions that would not have yielded information if asked to the general teacher population, and (c) to discover any new and unanticipated themes.

The focus group met for one and a half hours with two of the three authors moderating. The group met away from teachers' school sites at the district office. The focus group was recorded on video and field notes were recorded. An abridged transcript was prepared from the video recording and the moderators' field notes. The transcripts were abridged in that they recorded only participant responses that addressed the research questions and emergent topics deemed relevant to answering those questions. Off topic conversation was not recorded. Abridged transcripts were then coded by theme and each theme was organized by purpose (i.e. support of previous findings, more specific questions, discovery of new and unanticipated themes). The following sections describe the themes identified prior to focus group meeting: use of simulations and barriers to use, system dynamics content knowledge and recommendations for professional development. Subsequent themes were not directly related to survey themes, but emerged through discussion: recommendations for model use and simulation use with English Language Learners.

Focus Group Results

Analysis of the focus group data supported the survey finding that the system dynamics simulations are not being used. Teacher Participant 3 (TP3) reported having used the simulations as prescribed by the text during the first year that the curriculum was implemented, but changed her strategy in subsequent years. She deemed the cost of time required to use the Stella software to not be commensurate with any benefit that students might have from completing the activity. The simulation of predator-prey dynamics was noted as a valuable element. When asked about how they completed the activity, all of the teachers responsible for face-to-face instruction (TP1, TP3, and TP4) used either the computer simulation, a live simulation, like a board game, or both.

The focus group also supported computer access as a primary barrier to completing the curriculum with the system dynamics simulations. Specifically, access to the Stella simulation software was noted as the primary, technology-related barrier. Participants commented that a free version of the software package had to be downloaded in order to complete the activity, and while this eliminates the cost associated with completing the activity, it represents an added step that teachers perceived as a barrier.

The participant from the virtual high school (TP2) was able to provide information about barriers specific to students who complete their work in an online environment. She indicated that the added step of downloading the Stella simulation software becomes an even larger barrier for online students. While students in a blended learning environment have real-time teacher support for technical problems, as well as content-related issues, online students do not have this benefit and are less likely to persist should they encounter difficulty. TP2 also stated that any additional software or technical requirements for an online simulated environment should be compatible with Smartphone and iPad technology, as this is how many students are completing their work. From her experience, if the software is not compatible with these technologies, students are not likely to request assistance from the instructor and instead, will not complete the assignment. TP3 added that learning a new modeling language would be a more difficult task for online students, as it typically requires immediate instructor feedback, followed by immediate student revision, in an iterative process. Using their model of online learning, this type of support is difficult to accomplish.

The focus group interview resulted in two unexpected findings. While the survey results found that a lack of access to computers was the most significant barrier to implementation, the focus group did not entirely support this conclusion. When asked how much of a barrier computer access created in activity completion, TP3 and TP4 both stated that computer access was not a prohibitive barrier and that if any assignment was "worth it" in terms of how useful it was to student understanding, they would take the time to go to the computer lab. Their interpretation of a teachers' unwillingness to complete these activities as designed was not necessarily an issue of access, but an issue related to classroom management in a computer-mediated learning environment.

A second unexpected finding from the focus group involved their citation of student mathematics ability as an additional barrier to understanding the models on which the simulations are based. The simulations are intended for ninth grade students and participants indicated that these students have not formally been introduced to algebra. They indicated that while the mathematics used to describe the relationships among the variables in the simulation are not complex, the ability to relate phenomena in the natural world to numerical representations, is still above many students' understanding.

Focus group participants were generally reluctant to answer questions related to the content of the systems models (Figures 1&2). We deemed this as confirmation of the finding that teachers' lack an understanding of the system dynamics modeling language used to create the simulations. TP3 was the only focus group participant who attempted to answer a content-related question. When asked to indicate the variables from Model #1 that directly caused birth rate to change, she noted that there were two arrows pointing to birth rate and that the variables connected to those arrows were probably the ones that affected birth rate. Her response was correct, but no other participants attempted an answer. Participants indicated that there was some confusion over whether this question was addressed to them or if they were being asked to respond as they thought the students' would respond. When the participants perceived that they could answer for their students and not for themselves, they deflected the question from a test of their personal understanding, to that of their students. This line of discussion evolved into the next theme, which was unplanned in the protocol: recommendations for model use.

TP3 recommended that use of system dynamics simulations would be most effective if paired with a physical simulation. In her opinion, if students were able to play out the scenario physically, and then use the systems simulation, they might be able to make connections between the numbers of organisms and the graphical representations used in the simulations. She indicated that this would also assist students in their mathematical understanding of the predator-prey dynamic, so that they could understand that the simulation involves, not just numbers, but amounts. TP1 suggested further that first the words used to label the variables and then what they mean to the system as a whole were details that could be used to direct a class discussion about the system's variables and how they are interconnected. In his opinion, this discussion should preclude any discussion or simulation of how variables in the system increases or decrease over time. TP1 also agreed that the models might help students' mathematical understanding of dynamic systems. For example, he described, "there are ratios there (represented in the model) and we can describe the meaning of those words (in the ratios) to improve their numeracy." After students understand the meaning of variable labels, teachers can guide them through looking at the model as a whole, and then discuss the interconnections. The discussion of using the model to convey meaning to students led to a more specific discussion of the utility of system dynamics simulations for English Language Learner (ELL) students.

Due to the large number of first-generation English Language Learners in the schools of the participating teachers, the issue of using systems dynamics simulations with these students was addressed explicitly with the focus group. By including two participants from schools with a relatively high proportion of ELL students, we purposefully intended to capture their experience and expertise. These teachers (TP1 and TP3) each provided input on how systems simulations might benefit instruction for the ELL students. In their combined opinion, the biggest benefit they recognized was that these representations allowed complex ideas to be conveyed without using text-heavy explanations that might be difficult for ELL students to understand. Both teachers cautioned that, because the number of words included in the models is limited, they have to be the right words. Any words that are used within the model and simulation should be basic and commonly used; jargon should be avoided. For example, the teachers noted that the words “delay” and “herd” would be difficult words for ELL students.

Discussion

Both survey and focus group data show that teachers are not currently using the system dynamics and systems thinking tools that were part of the adopted curriculum. Teachers are instructing students on the curriculum’s content, that is, students are learning about population dynamics and predator-prey relationships, but are doing so through other activities. Many of these activities are also simulation-based. In cases where computer simulations are used, the simulations are freely available online. In some cases, teachers physically simulated population dynamics with either board game pieces or with students representing the organisms.

In general, participants indicated that systems simulations are valuable classroom tools and they have confidence that they are able to teach using them. Almost without exception, participants reported not using the systems tools because of restricted access to computers and the software used to run the simulations. Focus group participants stated that computer access was not as much of a barrier as software access. If given proper access, participants responded that the simulations would be useful. However, most did not think instruction in systems thinking or system dynamics was necessary. The most common reason teachers cited for not using systems tools was a lack of access to technology, including computers to run the simulations as well as the modeling software. This is an external barrier, as described by Ertmer (1999).

Focus group participants also noted that many teachers who perceive computer access as a barrier do so because they are challenged when helping students access and complete a technology-enabled activity. This highlights in to integrating technology in the classroom. Martinez and Burton (2011) name the affordances of cyberlearning environments in math and science. They can provide immediate data, access to experts, analytical and visualization tools, retrieval of source documents, a forum for public discourse, and opportunities for meta-cognitive structuring of ill-defined problems. One of the presumed benefits to using cyberlearning materials, such as the simulations provided for this activity, is that technology can provide affordances like the ones named above, if attempted another way, might create more difficult management issues (Bauer and Kenton, 2005). The use of technology should shift the role of the teacher to guide, rather than manager, but higher levels of management may be required until students become proficient using the tools for their intended purposes. This can be a prohibitive factor to moving teachers past the utilization phase of technology adoption, where they will use technology until a there is a problem and then will revert back to more traditional teaching practices (Bauer and Kenton, 2005). Also, if the barrier is not computer access, but student management, it is internal, not external. Internal barriers involving a teacher's self-efficacy and belief systems are more difficult to address, as they require a change in deeply-engrained thinking, rather than the provision of materials (Ertmer, 1999).

The added step of downloading the free software was perceived as a prohibitive barrier for live classroom teachers, and was perceived as an even greater barrier for the virtual high school teacher focus group participant. Virtual high school students do not have instantaneous teacher feedback to guide them, so the more technological challenges there are, the more likely it is that they will not complete an assignment. In this case, the curriculum is most meaningful if students are familiar with the system dynamics modeling language, are able to interact with the systems simulation and are able to answer formative assessment questions that are intended to scaffold their use of the simulation. Each part of this puzzle might require its own software, website, document, etc. In a blended environment, teacher feedback would ensure that students are on task and interacting correctly with the materials. In the virtual-only environment, it is less likely they will receive the same guidance. Again, where cyberlearning tools were thought to streamline instruction, focus group discussion made clear the need to assess each chosen technologies to ensure that their affordances are maximized and barriers minimized for a specific learning environment.

For example, systems simulations were regarded by both ELL classroom teacher focus group participants as beneficial for teaching ELL students about complex environmental phenomenon without having to use lengthy verbal descriptions. They noted that the modeling language would accurately convey the interconnections and the interactivity of the simulation would allow them to guide their own understanding. Lee (2005) supports this, citing a study in which Mexican American students were better able to construct biology understanding by using diagrams and other semiotic tools. However, word choice is very important when only a few are used, so when designing the simulation activity, special attention should be paid so that the simulations are as useful as they have the potential to be for those students. In this instance, the barrier of having to learn a modeling language is less of a barrier than learning a verbal language, so the affordances outweigh the barriers.

Although only 21% of the survey participants cited their own understanding as a barrier to implementation, most had trouble correctly identifying and describing variable dynamics and interconnections. Many survey participants were not only unable to identify the correct variable relationships in closed item format, but also expressed frustration at the line of questioning. This sentiment was mirrored in the focus group discussion, where participants quickly translated questions about their own understanding to questions about student understanding. It may be secondary to technology access in implementing systems tools in the classroom, but if the right access were provided, teacher understanding may still be prohibitive. This follows with Goddard, Hoy, and Hoy's (2004) description of behavior related to ones perceptions of their own efficacy. A teacher's sense of self-efficacy in a particular content area or practice is a significant predictor of whether or not they will employ that content area or practice in their classroom.

Goddard, Hoy and Hoy go further to describe the four categories of efficacy-shaping information first postulated by Bandura (1986, 1997). They are mastery experience, vicarious experience, social persuasion and affective states. A mastery experience is one in which performance has been effective and promotes the belief that performance will be effective in the future. A vicarious experience increases self-efficacy through having a practice modeled by an expert. Social persuasion occurs when peers, leaders, students, etc. promote self-efficacy through feedback that informs the teacher of their effectiveness. Finally, affective state is related to an individual or group's reaction to feedback, whether it be encouraging or discouraging. Stress related to performance and perception of efficacy. It can promote behaviors that lead to increased efficacy or it can lead to more dysfunctional behaviors if a support systems (such as school administration or teacher peers) do not provide avenues for behavior corrections. These information sources are important to describe, because one of the proposed action items to increase the use of systems tools in the classroom is teacher professional development on system dynamics modeling and systems thinking tools, Professional development opportunities have the potential to impact in all of the described information sources that promote self-efficacy in teachers, making it more likely that they would use systems tools in their classroom. Further, Guzey and Roehrig (2009) speak directly to the utility of professional communities in promoting the use of new technologies, saying that teachers need ongoing support in the form of teacher-to-teacher communication about problems and solutions associated with integrating technology in the classroom. Focus group participants supported the idea of professional development that addressed teachers' systems thinking skills and understanding of the modeling language as long as it provided them with concrete tools they were able to bring back to the classroom. Fisher (2011) makes a similar recommendation, saying that "it will be important to have a set of simulations that are out-of-the-box ready for…teachers to use, in a variety of disciplines. A simulation with (ideally) formal curriculum, or with possible leading questions that could be used with students, could provide satisfactory experiences" (p. 400).

Unexpectedly, more survey respondents were able to answer multiple-choice items correctly that were related to an assumed unfamiliar model (Figure 2). Yet, our coding of responses to open-ended items about these models revealed the opposite, that participants could better explain the relationships of the familiar model. Glazer (2011), discussing the literature related to the challenges associated with graph interpretation, describes a model of the factors affecting it. These factors include difficulties with graphing, prior theories/beliefs about the conventions associated with graphical representations, prior content knowledge associated with the displayed information, and mastery of graphing and explanatory skills. We see all of these factors in the teacher participants' ability to interpret the system dynamics representations. We speculate that, because the participants were fluent in the language of population change, they relied on prior knowledge to describe the system, without referring to the model. When examining an unfamiliar system, like Figure 2, we infer that they would be more likely to refer to the representation, where they could, to some degree, rely on their prior knowledge of graphing conventions, like arrows indicating an interconnection and possibly indicate causality. None the less, can be considered a complex graph (Glazer, 2011), as it contains several variables, connections between those variables and requires a certain amount of domain knowledge (system dynamics) to comprehend that graph. As such, it requires instruction to be optimally understood and applied.

This study identified several barriers, all of which can be categorized as either first order (external) barriers or second order (internal) barriers, as described by Ertmer (1999). Even more helpful is that they all are related to teachers' time constraint issues: not enough time to increase their own understanding, not enough time to manage students through technology instruction, etc. Bauer and Kenton (2005) discuss time as a major barrier to the adoption of new teaching practices. This may provide insight on how to best support teacher's needs or at least inform their perception of the usefulness of new tools. For example, focus group participants expressed confusion that there was so much focus on one activity, demonstrating a viewpoint that the system dynamics language used in the activity is specific to this one lesson only. If professional development communicated the utility of the system dynamics modeling practices and systems thinking tools in most of the course work in the year's curriculum, they may perceive it as worth their time to participate and change their teaching practices. It the tools were understood to be useful across curricula, it is more likely that teachers would see them as "worth their time."

Conclusion

This study focuses one of the first steps to adopting systems simulations and system dynamics as a technology and framework that has the potential to be effective across disciplines in helping students and teachers communicate with each other about complex global problems. System dynamicists seek to understand the behavior of a system by recognizing the complex causal relationships between the variables within it and to become better decision-makers through their understanding. Providing students and teachers with systems tools will facilitate a similar understanding.

The results of this study have important implications for the field of science education because understanding the barriers to using systems tools is the first step toward their wide implementation. As a crosscutting theme, systems thinking skills are critical to fully enacting the pending Next Generation Science Standards and educating students literate in STEM content, who are able to understand the complex problems of sustainability and make responsible decisions. It is an important first step to understand the needs of teachers who could use systems tools, in order to put them in practice.

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Appendix

Chapters 7 and 8 of the Science and Sustainability textbook for the Principles of Science course include activities designed to help students think about interconnections between organisms and their environment. Activity 7.2, 'Deer Me!' and Activity 8.3, 'Deer Me! Deer Me!' use Stella modeling software that allows students to manipulate habitat conditions for a deer and wolf population in a simulated environment and observe the effects.

We are interested in how these simulations are used and if they are beneficial in helping students understand systems. Please answer the following questions so that we may better understand how these simulations are being used. First, take a look at the activities by clicking on the link below. Please answer a few questions about how you complete the assignment

1. In Principles of Science, do you teach the content of Activities 7.2 'Deer Me!' and 8.3 'Deer Me! Deer Me!'?
    a. Yes (go to #2)
    b. No (go to #5)
2. Do you complete Activities 7.2 'Deer Me!' and 8.3 'Deer Me! Deer Me!' as described in the textbook, with the Stella interactive simulations?
    a. Yes (go to #5)
    b. No (go to #3)
3. What do you use to complete the activities? Check all that apply:
    a. Pencil and paper activity
    b. Other modeling software
    c. Class discussion
    d. Lab activity
    e. Other
    f. Please explain your answer:
4. If you don't use the Stella interactive software to complete Activities 7.2 and 8.3, what is the reason? Check all that apply:
    a. My school doesn't have access to the software.
    b. I don't know how to use the software.
    c. I have my own way of completing the activity that is more effective.
    d. I didn't think those activities were very important.
    e. Other (Please explain):
    f. Please explain you answer:

Please answer a few questions about the Stella modeling software:

5. How confident are you in your ability to teach Activities 7.2 'Deer Me!' and 8.3 'Deer Me! Deer Me!' exactly as described in the Science and Sustainability text?
    a. Very confident
    b. Pretty confident
    c. Somewhat confident

   d. Not very confident
   e. Not confident at all
6. Is the modeling software an important tool when teaching population growth and organism interactions?
   a. I think it is extremely useful.
   b. I think it is pretty useful.
   c. I think it is useful.
   d. I don't think it is very useful.
   e. I don't think it is useful at all.
   f. How is it useful to you?
7. Is there additional support or additional materials that would make the Stella simulations more useful in your classroom? Check all that apply:
   a. Access to computers
   b. Instruction on the operation of the simulation
   c. Instruction on the Stella software
   d. Instruction on system dynamics and systems thinking (the theory behind the model used in the activities).
   e. Other (please explain):

Please answer these questions about the system dynamics modeling language that the Stella modeling software uses: The model below is used to describe the effect of the carrying capacity of an environment on the size of a deer population (Figure 1). Please use it to answer the following questions:

8. How well do you feel you understand this representation of the way deer populations change?
   a. Extremely well.
   b. Pretty well.
   c. I understand it
   d. Not very well.
   e. I don't understand it at all.
9. Using this representation, what variable(s) directly cause the deer death rate to increase and decrease? Choose all that apply:
   a. Deaths
   b. Deer Herd
   c. Animals per area
   d. Births
   e. None of them
10. Using this representation, what relationship between variables might cause the deer population to increase? Choose all that apply:
    a. A difference between birth rate and death rate.
    b. If the number of animals per area are greater than the area available can support
    c. If the number of births is greater than the number of deaths.
    d. If the number of births and the number of deaths are equal.
    e. If birth rate and death rate are equal.

11. To the best of your ability, please describe how the size of a deer population might increase or decrease? Use as many of the model's variables in your description as you can, describing how they relate to each other to produce a change.
12. Do you have questions about this model or method of representing change in deer population?

The model below shows how personal energy level can change for an introverted person (Figure 2). Please use it to answer the following questions:

13. How well do you feel you understand this representation of the way an introvert's energy level changes?
    a. Extremely well.
    b. Pretty well.
    c. I understand it
    d. Not very well.
    e. I don't understand it at all.
14. Using this representation, what variable(s) directly causes the introvert's recharging rate to increase and decrease? Choose all that apply:
    a. Personal Energy
    b. Expending
    c. Desired personal energy
    d. Internally focused activities
    e. None of them
15. Using this representation, what relationship between variables might cause the personal to increase? Choose all that apply:
    a. A difference between total internal activities and total external activities.
    b. If the desired personal energy is greater than the actual personal energy
    c. If the total internal activities are less than the total external activities.
    d. If expended energy and recharged energy are equal.
    e. If the recharged energy is greater than the expended energy.
16. To the best of your ability, please describe how an introvert's personal energy level might increase or decrease? Use as many of the model's variables in your description as you can, describing how they relate to each other to produce a change.
17. Do you have questions about this model or method of representing an introvert's energy level?