Teaching Sustainability Through System Dynamics: Exploring Stocks and Flows Embedded in Dynamic Computer Models of an Agricultural Land Management System

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ABSTRACT

During the past several decades, there has been a growing awareness of the ways humans affect Earth systems. As global problems emerge, educating the next generation of citizens to be able to make informed choices related to future outcomes is increasingly important. The challenge for educators is figuring out how to prepare students to think about complex systems and sustainability. This article describes a set of design principles used to create online curriculum modules related to Earth's systems and sustainability. The modules include interactive, computer-based, dynamic Earth systems models that enable students to track changes that occur over time. Embedded prompts help students focus on stocks and flows within the system. This approach helps students to identify important resources in the models (stock prompt), to explain the processes that are changing the availability of the stock (process prompt), and to explore real-world examples (application prompts). We report how students learn about the sustainability of soil, a critical resource for growing food, in the module called "Can we feed the growing population?" We give an example of a model-based task, which shows how students identify stocks and flows associated with the model and how they consider human actions in the system. We discuss educational and research implications of using stocks and flows as a framework to structure students' exploration of dynamic models of Earth systems in teaching sustainability. © *2017 National Association of Geoscience Teachers*. [DOI: 10.5408/16-169.1]

Key words: sustainability, system dynamics, computer modeling, online curriculum

INTRODUCTION

Since 1987, when the Brundtland Report *Our Common Future*, was published, issues of sustainability have challenged the world to look toward the future and explore ways to collectively solve very complex problems facing the entire planet. Central to that report was developing a definition for *sustainable development* as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 41). The report focused on issues related to human–environment interactions (Langhelle, 1999), placing an intrinsic value on both natural systems and human well-being (Dryzek, 2005). These considerations remain relevant today as human populations grow and there is greater demand for limited resources. For example, energy consumption continues to rise, competition for land and water resources continues to increase, and ecological degradation has accelerated. In addition, the vast inequality in access to resources both within and across societies presents a huge challenge for sustainability (Sneddon et al., 2006). As new global problems emerge, it is critically important to educate the next generation of citizens to be able to think about sustainability and make choices that consider future outcomes alongside present needs.

Envisioning what it means to educate students to become the scientifically literate citizens of the future, a group of scientists and science education researchers published *A Framework for K–12 Science Education* (National Research Council, 2012). The framework calls for developing an understanding of sustainability by addressing "how humans impact the environment and how scientists and engineers could promote sustainable development through technologies that produce less pollution and waste" (NRC, 2012, p. 165). Similarly, the Next Generation Science Standards (NGSS) (NGSS Lead States, 2013), which grew out of that framework, explicitly included sustainability concepts. After analyzing NGSS, Feinstein and Kirchgasler (2015) found that sustainability was covered primarily under the following disciplinary core ideas: weather and climate, Earth's systems, and engineering design for secondary school students. The NGSS stress that sustainability is necessary to tackle global problems affecting humanity and emphasize the importance of educating students about science- and technology-enabled solutions to address the sustainability of natural resources in the context of Earth's systems (Miller, 2013).

It has been argued that to develop an understanding of sustainability, science education needs to establish a different way to incorporate environmental education concepts (Gough, 2002). In past efforts, concerns about the possible oversimplification of sustainability issues have been raised because, by emphasizing the science of sustainability, the broader social and ethical dimensions were less prominently addressed (Gough, 2002; Feinstein and Kirchgasler, 2015).

Our use of Earth's resources, including soil, water, minerals, and fossil fuels underlie many global environmental issues. It has become evident that we have entered a period when humans have created a noticeable impact on the Earth and its systems from our continued use of those resources. The challenge, therefore, is to figure out how to

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prepare students to think scientifically about complex systems (Mayer, 1995) and sustainability, topics about which students have limited knowledge and experience (Finley et al., 2011). In this article, we describe a curricular approach designed to address Earth's systems and sustainability topics for secondary school students. The curriculum supports students' ability to explore complex interactions between human actions and Earth's systems. The approach focuses on students' analysis of complex systems from a system dynamics perspective (Sterman, 2002) involving stocks and flow. Distinguished from the study of system parts and interactions, system dynamics focuses on describing, understanding, and explaining a system as a whole (Forrester, 1994). Regarding a system as a distinct entity, separate from a mere collection of parts, is necessary because "the properties and behavior of the whole system can be very different from those of any of its parts" (NRC, 2012, p. 92). System dynamics explicitly treats the properties and behavior of the whole system using feedback loops, stocks and flows, and time delays to understand nonlinear causality and emergent behaviors of complex systems (Richmond, 1993). Among these system dynamics concepts, *stock* and *flow* refer to how the quantity in a stock included in a system varies over time given the rates of flow into and out of the system (Sweeney and Sterman, 2000); for example, how the stock of carbon dioxide in the atmosphere varies over time as humans release increasing amounts of carbon dioxide. With the stock and flow concepts, the important variables associated with the system and how and why those variables change can be identified (Ossimitz 2000). Therefore, students' firm grasps of the concepts of stock and flow are necessary (Fisher, 2011) before they begin to use the conventions and rules associated with mathematical, algorithmic, and graphical modeling and testing of complex systems (Richmond, 1993; Brunstein et al., 2010).

We first describe the set of design principles used to create online learning modules related to Earth's systems and sustainability. We then detail how stocks and flows are introduced within one module entitled "Can we feed the growing population?" (hereafter referred to as the *land module*) and how we pair stock and flow concepts with experimentation computer models of dynamic Earth systems and interpretation of the models' outcomes. We also provide an example of the modeling activities and related student responses in the module to show that secondary school students are able to recognize stocks and flows in the models while considering issues of sustainability. This article is intended to illustrate how the High-Adventure Science (HAS) project explores sustainability issues using models and to illustrate those issues by describing our approach and reporting on our preliminary findings.

THE HIGH-ADVENTURE SCIENCE CURRICULUM

The National Science Foundation–funded HAS project[1] has developed five, online, week-long curriculum modules for middle and high-school students exploring sustainability issues related to freshwater availability, energy choices, climate change, air quality, and land management related to food availability:

- **What is the future of Earth's climate?** The climate module focuses on how much Earth's climate might change in the future. Students use models to learn how greenhouse gas emissions affect some positive and negative feedback loops in Earth's climate system.
- **Will there be enough freshwater?** The water module focuses on freshwater needs as the population grows. Students use models to explore sediment porosity and permeability, rainfall, and human impact on groundwater flow and freshwater supply.
- **Can we feed the growing population?** The land module focuses on whether we can produce enough food for a growing population. Students use models to investigate the effects of different land management strategies, including tilling and crop selection.
- **Will the air be clean enough to breathe?** The air module focuses on whether we can keep air quality high while also producing energy. Students use models and real-world data to explore the relationships among pollution sources, geography, weather, and air quality.
- **What are our choices for supplying energy for the future?** The energy module focuses on costs and benefits of different energy sources for generating electricity. Students use models to explore the process of extracting natural gas via hydraulic fracturing, then make arguments comparing energy sources, including natural gas, coal, nuclear, hydro, solar, and wind.

In these modules, students use dynamic computer models, analyze real-world data, engage in systems thinking, and build scientific arguments for concepts related to Earth's systems and sustainability.

These HAS modules were developed by scientists, educational researchers, and computer programmers working at the Concord Consortium, a nonprofit educational research and development organization specializing in technology-enhanced learning in science, math, and engineering disciplines. The advisory board for the HAS curriculum project consisted of environmental scientists; university-based, science-education researchers; and K–12 science teachers who reviewed each HAS curriculum module as well as each model for scientific accuracy and for pedagogical adequacy for the target student population. Additionally, staff at the National Geographic Society reviewed content and models before posting the HAS modules on their Web site. The HAS modules have been available to the public for 2–5 y through the HAS project Web site at the Concord Consortium as well as through the National Geographic Society Web site. As of August 2016, a total of 409,124 individual page views had been recorded from all 50 states of the United States. Some modules were also translated into Spanish. In the following section, we describe five design principles that guided curriculum development. Table I shows how the design principles are enacted in the HAS modules, with specific examples from the land module.

[1] The High-Adventure Science modules described in this article and other resources, including additional modules and teacher support related to implementing the materials, can be found online at http://has.concord.org or http://nationalgeographic.org/education/high-adventure-science/.

Table I: Design principles for the High-Adventure Science (HAS) modules with a description of how the principles are addressed and examples from the land module.

Design Principle	How HAS Modules Address Each Principle	Examples From the Land Module
Use open-ended, authentic frontier science topics to frame the modules.	Each module has a framing question that expresses both the uncertainty and open-endedness in the current state of the science being explored.	"Can we feed the growing population?" is the framing question for the land module and foreshadows the uncertainty related to humans' ability to feed the world's growing population.
Acquaint students with real-world data.	Students are provided the opportunity to understand research and the nature of science by interpreting real-world data produced by experts in the field.	Students are asked to interpret data representing changes in land use from the U.S. Department of Agriculture and precipitation data from the National Oceanic and Atmospheric Association.
Use model-based experimentation as a means for students to acquire content.	Students can control some parameters, starting conditions, and conditions during a run. In addition, students can conduct multiple experiments and observe changes that occur to the system over time.	Students can change terrain, climate, and precipitation, choose plant types, and observe how changes in each parameter affect topsoil quality, erosion, and plant growth in the model (see Fig. 1).
Engage students with system dynamics reasoning.	Students identify stocks in the model and the mechanisms by which stocks change over time as evidenced in the model.	Students observe how soil (stock) might erode (flow) in different conditions by varying precipitation and slope (mechanism) in the model.
Support evidence-based scientific argumentation.	Embedded argumentation tasks throughout the module require students to make claims based on evidence from data and models and to address the level of certainty about the claim and evidence.	Students use a model to determine what level of precipitation leads to wheat growth. They use evidence from the model to explain their claim, rate their certainty with the claim and evidence, and explain their certainty by describing any sources of uncertainty that might come from the data or model or their own interpretation of each.

Principle 1: Use Open-Ended, Authentic Frontier Science Topics to Frame the Modules

Students need contemporary science injected into their classrooms, engaging them in important, unanswered questions that scientists around the world are actively exploring. Most science teaching is a race to cover as many facts and concepts as possible. By focusing on frontier science, students develop skills and understanding about the content, as well as how science progresses, what is still unknown, and what motivates scientists. One of the goals of *A Framework for K–12 Science Education* (NRC, 2012) was to ensure that, by the end of 12th grade, students would become careful consumers of scientific knowledge, develop scientific reasoning skills, and engage productively in science and engineering practices. To respond, we developed modules that address current issues related to Earth's systems and sustainability (Pallant, 2013) and that are comprehensible to the K–12 audience. (The modules have also been used in undergraduate classes.) Framing the modules in the context of current topics is a powerful way to increase student learning and engagement (Chinn and Malhotra, 2002).

Principle 2: Acquaint Students With Real-World Scientific Data

One dimension of *A Framework for K–12 Science Education* (NRC, 2012) was engaging students in eight science and engineering practices, including developing students' ability to analyze and interpret data and to construct explanations from the analysis of the data. Students who analyze authentic data collected by scientists have an opportunity to evaluate the sources from which the data were generated from both theoretical and empirical perspectives (Allchin, 2012). Deep learning can result when students work actively with data and concepts situated within the original contexts of scientific investigations (Buck et al., 2014).

Principle 3: Use Model-Based Experimentation as a Means for Students to Acquire Content

A substantial body of research shows that exploration of models and simulations allows students to understand the behavior of systems that are difficult to fathom by other means (Horwitz, 1996; Feurtzeig and Roberts, 1999; Horwitz, 1999; Horwitz and Christie, 1999). Virtual environments that students can actively explore are valuable for both motivation and content acquisition (Dede et al., 2005). It is also important that students take an active role in trying different initial conditions and parameters to run experiments and see the results of their selections (Krajcik et al., 2000; Tinker, 2003; Slotta, 2004; Tinker, 2004).

Principle 4: Engage Students in System Dynamics Reasoning

To understand sustainability issues, students should be able to recognize and analyze complex systems (Feinstein and Kirchgasler, 2015). Students need to understand the structure of the system under study and the interactions of factors within the system by tracking changes over time (Fisher, 2011). The science of changes in complex systems is called *system dynamics*. For professionals, system dynamics usually involves computational modeling and testing (Ossimitz, 2000). However, secondary school students cannot engage in computational modeling without proper training, which may take a long time (Hogan et al., 2000). A reasonable, intermediate step is for secondary school students to learn how to (1) convert descriptions of system structures and interactions captured in conceptual diagrams into quantitative relationships, and (2) assign appropriate quantities to system parts and track changes at the system level (Forrester, 1994).

Principle 5: Support Evidence-Based Scientific Argumentation

Engaging students in scientific argumentation deepens science concept learning, altering students' views of science and supporting student decision-making (Duschl and Osborne, 2002; Lawson, 2003; Jiménez-Aleixandre and Erduran, 2008; Kuhn, 2010). Through scientific argumentation practice, students are encouraged to use data to support their claim about a scientific question (McNeill et al., 2006).

A CURRICULUM MODULE EXAMPLE: LAND MODULE

To illustrate how a HAS module incorporates the design principles and highlights how students use system dynamics thinking to learn about the sustainability of Earth's resources, we describe the land module "Can we feed the growing population?"[2] in greater detail. The land module is similar to the other four HAS modules because it was developed to use all five design principles. However, it is also unique because, as part of our design research, we incorporated system dynamics thinking more thoroughly throughout the module and implemented a specific set of prompts to elicit students' systems thinking based on stocks and flows when they use the computer-based models.

The land module explores the topic of meeting the needs of feeding a growing population by examining the resources that make up an agricultural system. Food producers are faced with a growing number of challenges, including the availability of resources, such as arable land, sunlight, rain, and high-quality topsoil. Throughout the module, students investigate how land use and soil quality are related to crop production by analyzing real-world data, graphs, and maps. Students run experiments with models to compare the effects of different landforms, climates, and land management strategies on the amount and quality of topsoil and plant growth, and to consider ways that humans can maintain and even replenish important resources such that food production is sustainable now and in the future.

The land module consists of five activities. Each multipage, online activity is designed to fit into one typical class period of 45 min. Students work independently or in groups, and their answers are saved automatically, if they are registered online in a class (a free service). Teachers can see student progress and have access to student answers through a teacher report. Students also have access to their own answers.[3]

In activity 1, students explore data showing how humans have modified and managed the natural environment. Students explore why agricultural land is a limited resource and ways in which human development and other factors affect this resource.

In activity 2, students investigate the distribution of cropland around the world and the role of nutrient-rich soil in crop growth. Using computer models, students begin to explore how erosion depletes the resources necessary for plant growth. Through this model, students identify soil as an important stock and erosion as a process that creates a flow such as depletion of the soil (stock).

In activity 3, students explore climate graphs and use models to discover how temperature and precipitation affect plant growth. Students investigate how climate changes can alter the availability of resources and use maps of average precipitation and temperature to predict the suitability of an area for agricultural production.

In activity 4, students explore factors necessary to create and maintain high-quality soils. Students use real-world data from scientists' field research to discover that high-quality soils have more nutrients and retain more water than lower-quality soils, resulting in greater plant growth. They use models to determine how farming practices affect soil quality and erosion rates. Finally, they analyze data to discover how fertilizers can be used to replenish the nutrients needed for plant growth and use data about the nutrient needs of different crops to consider a crop-rotation plan.

In activity 5, students evaluate different factors that can increase the productivity of agricultural systems. They explore data on the yields of cereal grains around the world, learn about research attempting to replenish resources necessary for increased plant yield without chemical or biological intervention, and learn how genetically modifying crops can help with pest resistance or make plants more nutritious. Ultimately, students are asked to apply what they learned about effective practices for preserving and replenishing the resources necessary for plant growth to propose land management strategies for different fields.

SCAFFOLDING SYSTEM DYNAMICS THINKING THROUGH MODEL-BASED ACTIVITIES

General Guidelines

Every HAS module includes a set of increasingly complex, dynamic computer models that represent the Earth system under study (Table II). The models in the land module, for example, allow students to change the slope of the land, farming strategies, climate, and precipitation and to investigate the effects of those changes on the amount and quality of topsoil and crop production. Student learning is based on guided experimentation with these models (Fig. 1).

The land module scaffolds students' system dynamics thinking in several ways. First, we introduce important

[2] This module can be found at http://authoring.concord.org/sequences/50.

[3] To register for a free teacher account that provides access to pretest and posttest scores, teacher guides, student reports, and the ability to assign materials to students, go to https://has.portal.concord.org/

Table II: Learning goals for the land module, description of the computer models embedded in each activity, and stocks, flows, and factors affecting the stocks and flows incorporated in each model.

Learning Goals—Students Will Be Able to:	Dynamic Earth Systems Computer Models	Stocks, Flows, and Factors
Activity 1: Using the land		
• Describe how humans have changed the landscape. • Describe consequences for using land for alternative purposes.	*Activity does not include a computer model.*	
Activity 2: Preserving soils		
• Explore the relationship between slope and erosion. • Describe how plants prevent or minimize erosion. • Explain how a plant's growth could be affected by erosion.	Model 1: Slope. Erosion is visualized at the land-air boundary and students can see soil moving along the surface. Model 2: Plants. Students plant annuals and perennials to see how plants change erosion rates.	Model 1 Stock: soil Flow: erosion Factor: slope Model 2 Stock: soil Flow: erosion Factors: slope, plant growth
Activity 3: Climate and crop growth		
• Explore the role of precipitation for plant growth. • Describe the role of temperature on plant growth.	Model 3: Climate—students change climates and plants to explore crop growth in different environments. Model 4: Droughts and floods—students explore extreme climate effects on plant growth.	Model 3 Stocks: soil, plants Flows: erosion, runoff Factors: slope, plant growth, precipitation, temperature Model 4 Stocks: soil, plants Flows: erosion, runoff Factors: slope, plant growth, precipitation, temperature
Activity 4: Soil quality		
• Describe the role of nutrients in plant growth. • Explore how farming practices affect soil quality and erosion rates.	Model 5: Soil quality—students determine what factors increase soil quality. Model 6: Tillage—students compare farming practices and investigate what different tillage practices mean for soil quality.	Model 5 Stocks: soil, plants Flows: erosion, nutrient depletion Factors: slope, plant growth, precipitation, tillage strategy Model 6 Stocks: soil, plants Flows: erosion, nutrient depletion Factors: slope, plant growth, precipitation, tillage strategy
Activity 5: Best practices		
• Describe how genetic modifications can increase crop yields. • Explain why different landscapes require different land management plans.	*Activity does not include a computer model*	

systems thinking vocabulary related to stocks and flows—we refer to stocks as *resources* in the module—for the land system to maintain and *flows* as changes in stocks, i.e., depletion or replenishment of the stock resulting from processes such as erosion or precipitation. In particular, the land module explores soil, water, nutrients, and plants as the stocks. Second, we focus students on the analysis of model outputs related to soil and plant stocks in particular. This means considering that the stocks are influenced by various factors, such as erosion, changes in precipitation, slope of the land, and human actions, including tillage methods and use of fertilizer. These factors create a complex web of interactions that change topsoil and plant stocks as shown in Fig. 2. Students are encouraged to experiment with the model and to discover the interactions among parts of the system. Third, we embed structured prompts to help students articulate their system dynamics thinking and to apply their understanding to real-world examples. The prompts are designed around the following structure:

- **Open-ended stock prompt (general for all models):** What do you think is the most important resource in this model?
- **Open-ended process (flow) prompt (general for all models):** What processes are changing the availability of this resource in the model? This prompt focuses students on the sets of interactions that can be discovered when they use the model and asks

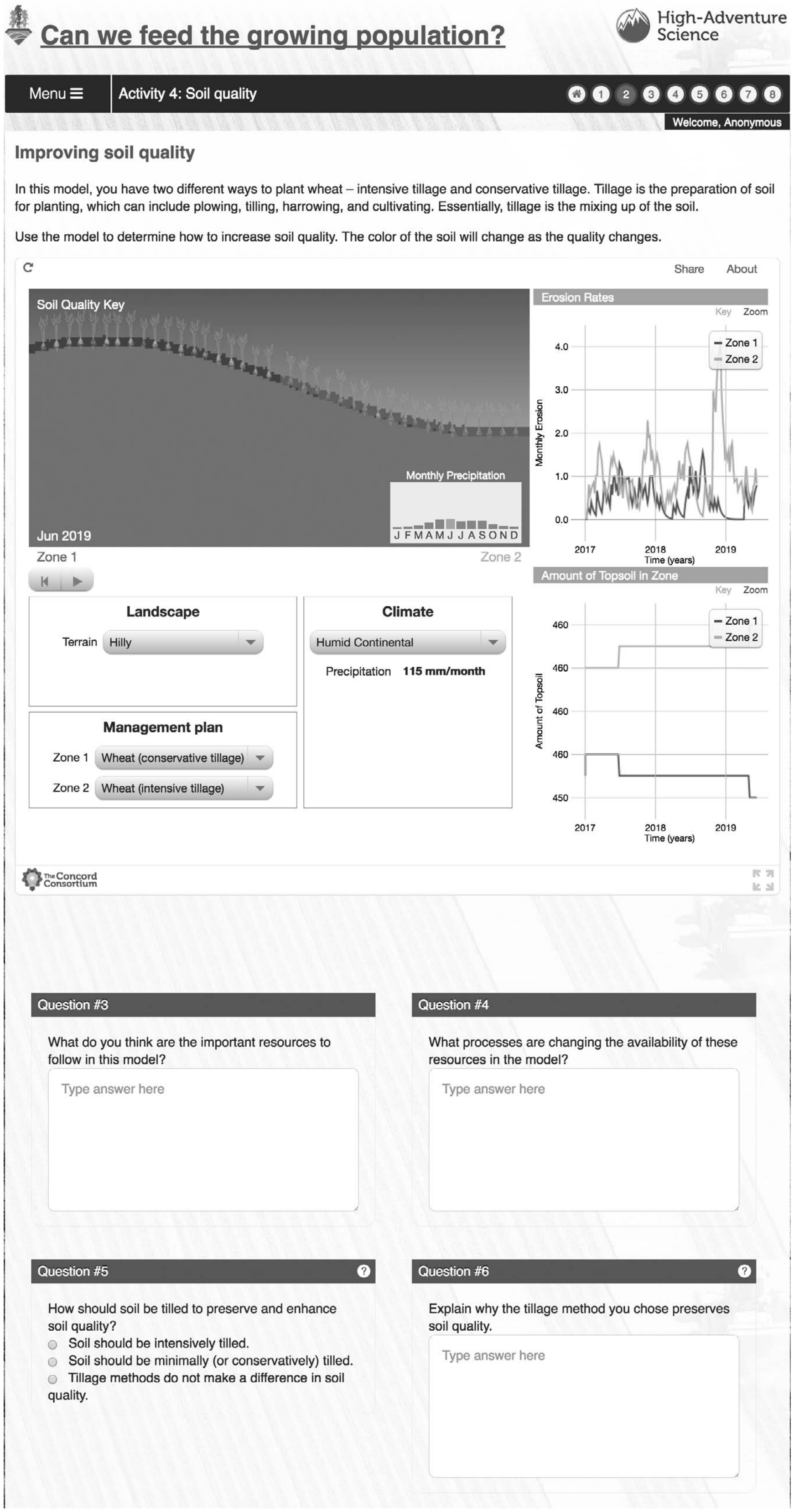

FIGURE 1: Screenshot of the sixth model used in Activity 4 of the land module. Students can change landscape, choose plant type and farming method for each zone, and select the climate for the region represented in the model. As students run the model, they can observe seasonal plant growth, changes in topsoil quality (represented by changing colors) and erosion, and see output graphs of erosion rates and amount of topsoil for each zone. Embedded argumentation tasks prompt system dynamics thinking related to stock, process, and application.

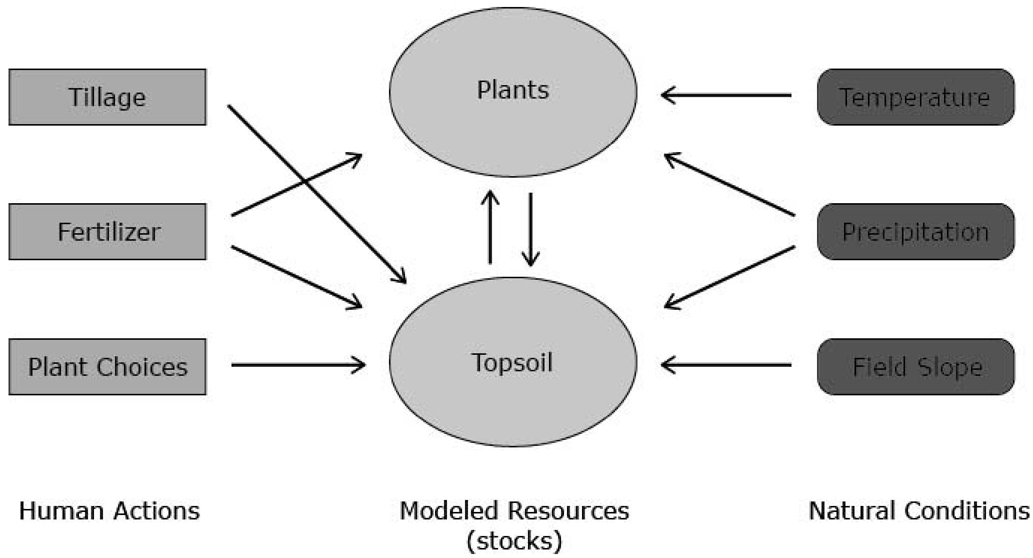

FIGURE 2: How human actions and natural processes affect the resources (stocks) modeled. The choice in tillage practice affects the quality and quantity of soil. With conservative tillage, e.g., the soil is minimally disrupted, leaving a lot of organic matter and preventing erosion (decreasing a flow). Models are designed to become increasingly complex as students proceed through the module. The models start by allowing students to observe erosion under different natural conditions and then introduce human actions, including different plant choices and farming practices (tillage and fertilizer).

students to elaborate on the mechanisms revealed by the model that caused the change in the stock of their choice.

- **Application prompts (consist of two prompts specific to each model):** A real-world, multiple-choice question and an accompanying explanation prompt, which are intended to solidify students' knowledge by having them apply the information to a real-world situation. Students choose an answer to the first multiple-choice prompt and provide an open-ended explanation for their choice in the second open-ended prompt.

These prompts are designed to help students make sense of potential causal mechanisms that underlie the changes in stocks and flows in the system. According to Fisher (2011), several instructional strategies are necessary to orient precollege students toward system dynamics thinking. To introduce system dynamics thinking, Fisher suggested using the change-over-time graph in which an important variable for the system can be tracked over time. The change-over-time graphs can be used to ask students questions about what is changing (stock prompt) and how it is changing (process prompt). These questions can provide an opportunity for students to express causal accounts among system variables to answer why it is changing. Students' understanding of causal mechanisms can be elicited when they are asked about real-world problems in which their hypotheses about the system are tested with the simulation model provided to students (application prompts). The primary purpose of embedding these system dynamics prompts after the model is to allow students to express the ideas they gain from interacting with the model. Based on students' responses, teachers and curriculum developers can examine to what extent students are able to make sense of the system relationships from the model, which can further inform changes in instruction, curriculum design, and model design.

Model-Based System Dynamics Task Example

The system dynamics thinking guidelines above are implemented in six model-based tasks in the land module. In one model-based system dynamics task, shown in Fig. 1, students explore the way two different tillage practices affect soil quality and soil availability. In the model developed for this task, topsoil is represented by the colored layer between the surface of the land and the air. Dark brown represents topsoil with many nutrients and light brown represents topsoil that is depleted of nutrients. Students experiment with the landscape, land management plans (types of crops, farming practices), and climate settings. For example, Fig. 1 shows a hilly terrain in which Zone 2 is downhill from Zone 1. In Zone 1 (on the left of the model) the crop is wheat, and the tillage method is conservative (soil is minimally disrupted by plowing, tilling, harrowing, and cultivating); for Zone 2, the crop is also wheat, whereas the tillage is intensive (soil is completely tilled between each crop planting). The climate is humid continental. The inset graph shows how precipitation varies over the year. Students use the model and graphs to compare erosion rates and topsoil amounts and quality over time. The graphs show that Zone 2 seems to have a higher erosion rate than Zone 1 has. Zone 2 appears to be gaining topsoil in the winter months (seen both in the lower graph and in the topsoil layer Zone 2 getting thicker). Additionally, the topsoil color is darker for Zone 1 than it is for Zone 2, indicating higher-quality soil in Zone 1. After students experiment with the model, they respond to system dynamics prompts related to the stock (Question 3 in Fig. 1), process (Question 4), and application (Questions 5 and 6).

To illustrate how these prompts elicit student ideas, we use student responses to the systems thinking prompts for

Table III: Rubric for scoring students' explanations related to mechanisms.

Score	Explanation Status	Criteria	Examples
0	Off task	No information or off task	I don't know.
			I had a garden.
1	Incorrect	Incorrect statements	The more you till, the better.
			It keeps the ground out of the air.
2	Restatement	Restated the relationship	Soil should be minimally tilled.
3	Relevant, unelaborated	Correct with additional information, but not fully elaborated	It doesn't damage the nutrients.
4	Relevant, elaborated	Relevant, correct, and elaborated explanations about the relationship between stocks and flows (the factors that change the stocks)	Tilling the soil conservatively preserves the soil by preventing erosion, leaving more nutrients and organic matter in the soil, which plants need to grow.

this model. Student responses were collected from classes taught by six teachers in five states, including Kentucky, Indiana, Minnesota, Montana, and North Carolina. These teachers implemented the land module as part of their Earth Science or Environmental Science courses. One teacher taught 8th-grade students, whereas two teachers taught 9th-grade students. The other three teachers taught mixed-grade classes consisting of 11th- and 12th-grade students. Among the students ($N = 242$), 52% were female, 12% spoke English as a second language, and 55% used computers for science learning according to self-reported demographic surveys. All six teachers had prior experience teaching HAS modules and were familiar with the general pedagogical approaches associated with the modules. Teachers received professional development during the summer before the implementation.

Students' Responses to the Stock Prompt: What Do You Think Are the Most Important Resources to Follow in This Model?

Fifty-two percent of the students mentioned soil as the most important resource to follow, whereas 62% mentioned *factors* influencing resources, such as precipitation and tillage methods, as the most important resource. Among the factors mentioned, 20% of the students referenced the tillage choice as the main factor causing changes in stock. Twenty-four percent of the students described the link between a factor and its influence on topsoil (stock). These results show that, when asked to identify an important stock, (1) more students paid attention to a factor that might change a stock rather than the stock itself, and (2) more students mentioned either a stock or a factor (65%), whereas 24% linked them to each other, even though they were not prompted to do so.

Students' Responses to the Process Prompt: What Processes Are Changing the Availability of These Resources in the Model?

This prompt is designed to elicit how well students can recognize how important factors or mechanisms influence changes in stocks—in other words, the flow. Among the 239 students who answered this prompt, 63% mentioned factors such as slope or rain influencing the process. Twenty-eight percent indicated processes, including 13% who described a simple process, such as erosion, without explaining how erosion leads to a change in the stock, whereas 15% fully described how the process was changing the availability of the soil. For example, one student said,

> *"The types of tillage help determine the growth of the crops. Precipitation and the slope of the land help us know how much the soil is going to erode. The type and color of the soil lets us know how nutrient filled the soil is."*

Students' Responses to the Application Prompts.

The multiple-choice question asked: How should soil be tilled to preserve or enhance soil quality? The response choices were

(a) Soil should be intensively tilled.
(b) Soil should be minimally (or conservatively) tilled.
(c) Tillage methods do not make a difference in soil quality.

The related, open-ended prompt was "Explain why the tillage method you chose preserved soil quality." The students' explanations were scored using the rubric in Table III.

Figure 3 shows the distribution of students' responses to the multiple-choice question and compares the distribution of explanations for each choice. Students who chose an incorrect answer to the multiple-choice part of the application prompt (i.e., [a] intensive tillage or [c] tillage does not matter) wrote incorrect explanations most of the time. On the other hand, students who chose the correct answer ([b] soil should be conservatively tilled) wrote a range of explanations with scores from 0 to 4. Among the 168 students who chose the correct answer, more than 75% of the students recognized that conservative tillage led to better-quality soil and scored between 2 and 4. Of those students, more than two-thirds were able to provide additional details about the processes changing the resource beyond restating the relationship between tillage method (conservative tillage) and the soil quality. We can thus infer that (1) most students were able to recognize the influence of tillage practice on the soil quality, and (2) many students still need to develop detailed mechanisms that are robust enough to use in the real-world application.

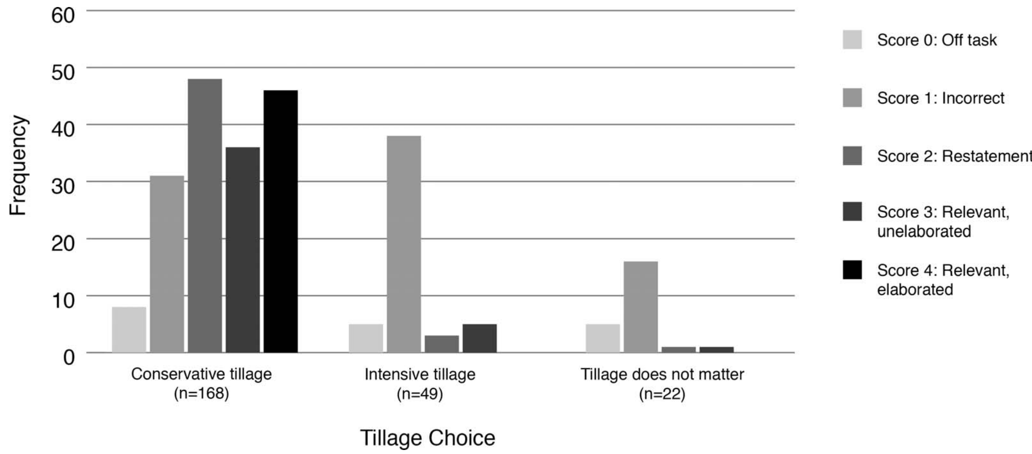

FIGURE 3: Distribution of student responses to the multiple-choice question and the open-ended application prompt following experimentation with the model.

Students' Progression Across Process Prompts Throughout the Module. Stock, process, and application prompts can be analyzed for each model-based task, as well as across multiple tasks. For example, if we want to see how students in this sample progressed in terms of recognizing how the important resource embodied in the system is changing in response to factors (the process prompt), we can apply the same scoring rubric to these prompts and compare across tasks (See Fig. 4). We applied rubrics to their open-ended responses to identify whether students mentioned only the stock, flow, or factor, or a combination of stock, flow, and factor. Overall, there was an increase in listing of factors affecting the availability of stocks over time as students engaged with model tasks throughout the module. The increase in the inclusion of factors in students' responses corresponded to more factors becoming available for students to manipulate in the model. There was also a steep increase in linking factors to changes in stocks between Task 2 and Task 3. After Task 3, linking factors to changes in stocks remained steady. These two results indicate that the linking between the factor and the resource change became more robust later in the module for some students. These results also indicate that more students later in the module were able to elaborate on mechanisms salient to the system by making scientifically valid connections between a factor and a change in stock and articulating what made these connections possible. However, results in Fig. 4 also indicate that students need support to link a factor and a resource change because only about 20% to 30% of the students were able to do so in their explanations. As the complexity of the models increased, students' focus on flow related to erosion rates diminished, indicating that it was difficult to incorporate flow mechanisms as a way to further elaborate changes in stock.

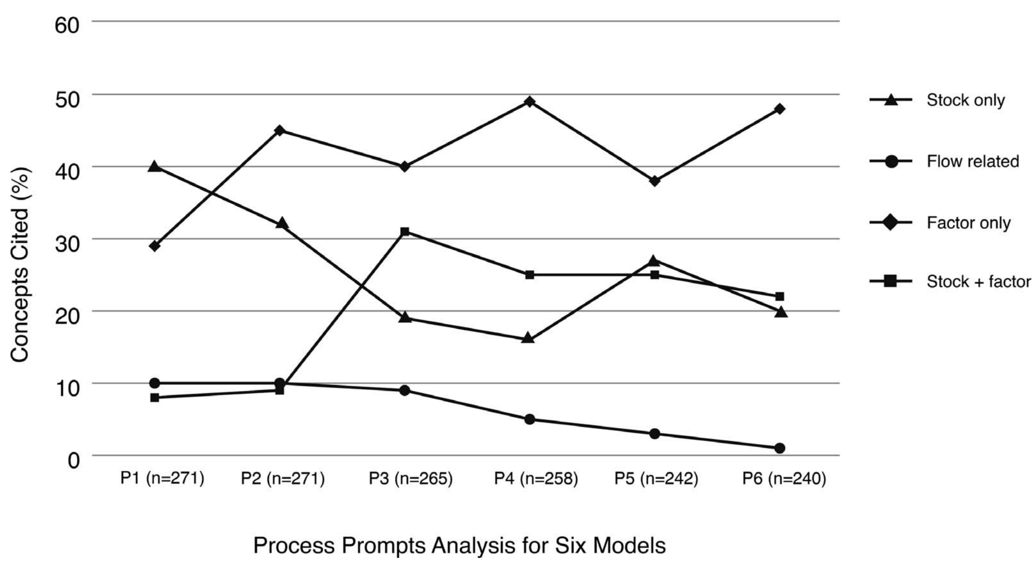

FIGURE 4: Analysis of process prompts (second item of the system dynamics tasks) for all six models in the land module. Identifying only stocks was highest in the first model and then decreased (see the stock-only line), which was accompanied by a subsequent increase in mentioning both stock and factor (see the stock + factor line). Mentioning the process that creates flows decreased as students progressed through the module (see the flow related line).

EDUCATIONAL IMPLICATIONS

Thinking about sustainability involves exploring and tracking multiple resources and interacting processes that affect the availability of those resources. Research suggests that learning about systems concepts is difficult and involves extended exposure to the concepts (Stillings, 2012) because Earth's systems do not necessarily behave in a linear or predictable fashion. The complexity associated with Earth's systems cannot be simulated through simple experiments in laboratories. This barrier can be addressed by engaging students in computer-based modeling, so they can practice model-based reasoning around underlying complex causal relationships and related emergent phenomena (Nersessian, 2002). Although models are common across the sciences, the challenge for model developers and curriculum designers is how to address increasing complexity in Earth and Environmental Science. This article illustrates how a curriculum based on design principles that include dynamic computational models can promote system dynamics thinking when secondary-school students interpret evidence generated from the models. In teaching and learning about Earth's systems and sustainability in secondary school classrooms, our experience with the HAS curriculum modules indicates that system dynamics thinking can be fostered by focusing students' attention on identifying important stocks in a system and monitoring changes associated with the stocks. When students recognize changes, they can be primed to further think about what causes changes and why and how those changes occur. This type of thinking can serve as a prerequisite for students to develop computational and mathematical models of a system. Our study indicates that stocks and flows can be naturally introduced to students as part of a regular science class without painstaking introduction of mathematical and quantitative formalism related to stocks and flows. We acknowledge there are limitations to this study. We have not done a large-scale study on the effectiveness of this approach nor have we compared this approach to other approaches. Instead, this article is intended to illustrate one possible approach to introducing system dynamics thinking to secondary Science, Earth Science, and Environmental Science students. We encourage others to consider how to incorporate the language of system dynamics, such as stocks and flows, into Earth's systems and sustainability topics so students can become familiar with systems thinking as early as possible. We believe this is an important endeavor considering the national push to develop students' ideas across school years through crosscutting concepts, including systems and system models.

We learned several lessons from the land module implementation that could inform curriculum design and teacher instruction about Earth's systems and sustainability. First, student investigations with the models are possible even though students are not trained in system dynamics thinking. Students improved their abilities to identify resources (stocks) and changes in resources (flows) without explicit focus on mathematical relationships in stocks and flows. Second, we noticed student growth as they engaged repeatedly with the models and the system dynamics prompts. At first, students had difficulty identifying stocks and flows, but they improved as they repeatedly encountered the embedded prompts over the course of the land module. *A Framework for K–12 Science Education* (NRC, 2012) is explicit about the development of students' learning progression of important ideas. Although the literature on systems thinking (Gonzales and Wong, 2011) identifies the difficulty of teaching and learning stock and flow concepts, modeling has been proposed as a tool that can provide opportunities to help students clarify ideas and articulate explanations related to systems (NRC, 2012). Thus, embedding a system dynamics approach in a sustainability curriculum represents an opportunity to challenge students to think critically about the system under study, about how human actions affect that system, how resources are used and replenished, and how certain factors do not change outcomes.

RESEARCH IMPLICATIONS

Research has shown that grasping stock and flow concepts is challenging (Sweeney and Sterman, 2000; Cronin et al., 2009). Even simple problems have proven to be perplexing for many students, including those who are mathematically inclined (Cronin and Gonzalez, 2007). It has been suggested that representations can be problematic or that analogies may not be easily correlated to the topic being studied (Holyoak and Koh, 1987; Cronin et al., 2009). Gonzalez and Wong (2011) indicated that instruction related to stocks and flows needs concrete interventions that highlight the relationship between stocks and flows and how flows affect stocks over time. The design of the dynamic models in the HAS land module that represent changes in stocks and flows over time, both visually and graphically, and the system dynamics thinking prompts that scaffold students' stock and flow thinking may be just such an intervention. The models were intended to simplify a complex system to focus students' attention on salient aspects of the agricultural stocks and flows and human impacts on the system. The goal of the scaffolds was to elicit system dynamics thinking and to encourage students to specifically address the resources and factors affecting the change in resources when interpreting the models and responding to the prompts. Further research is necessary to design instructional materials, activities, and strategies that can prudently scaffold students' development of system dynamics thinking appropriate to students with different knowledge, experience, and abilities.

Because this article analyzed student responses to a selected set of system dynamics models and prompts, we did not account for teacher influence on student learning of system dynamics with the curriculum module. Future research should address teacher professional development and implementation. This descriptive article highlighted one approach to marrying systems modeling with system dynamics scaffolding. The land module focuses on ways in which human actions, such as tillage, fertilizer use, and irrigation practices, can affect an agricultural system. We are exploring this curriculum design approach in other modules. Given the difficulty of teaching and learning about systems concepts, careful research combined with assessment of student learning about Earth's systems and sustainability with a focus on stocks and flows could be a valuable approach to improving Earth and Environmental Science education.

CONCLUSION

Because system dynamics is central to understanding sustainability issues, we designed curriculum modules in which students learn about Earth's systems and sustainability topics through formulating system dynamics ideas informed by experimentation with computer-based models. We focused on helping students track stocks and flows over time in an agricultural system in our land module. This article shows that, by engaging in experimentation with models and observing changes in the simulated land environment, students were successfully able to articulate and produce evidenced-based responses to the system dynamics prompts and to consider how human actions were responsible for sustainable and unsustainable changes to the system. This approach provides one example of how a curriculum module used complex models as a way to teach about complicated system dynamics in the context of sustainability. This treatment showed positive outcomes and has great potential. The lessons learned will help in planning for additional system dynamics curricula and complex sustainability models. Additionally, the approach provides a valuable framework for teachers to use when teaching other topics. Finally, once students begin to understand that humans are not separate from natural systems but are an integrated part of Earth's systems, a new appreciation for sustainability and a thriving planet could emerge.

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