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Environmental Systems Simulations for Carbon, Energy, Nitrogen, Water, and Watersheds: Design Principles and Pilot Testing

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ABSTRACT

Guided by the Next Generation Science Standards and elements of problem-based learning, four human–environment systems simulations are described in brief—carbon, energy, water, and watershed—and a fifth simulation on nitrogen is described in more depth. These science, technology, engineering, and math (STEM) education simulations illustrate design principles that make them engaging to students, such as dynamic visual environments that are controlled by the user and immediate visual feedback to user actions taken. The simulations are contextualized in real-world natural resources management challenges involving biogeochemical cycles, such as Gulf of Mexico hypoxia, which provide an opportunity to "win the game," while the introduction of complexity in steps provides scaffolding. Pretest versus posttest results indicate a substantial and statistically significant improvement in learning outcomes resulting from using the nitrogen simulation, though there was no comparable pedagogical control group. Attitudinal feedback indicates rich student engagement with the nitrogen simulation. © *2016 National Association of Geoscience Teachers*. [DOI: 10.5408/14-004.1]

Key words: biogeochemical cycles, educational computer-based simulations, Gulf of Mexico, hypoxia, Next Generation Science Standards

INTRODUCTION

Understanding of biogeochemical cycles and their interaction with socioenvironmental systems is an important element of the Next Generation Science Standards (2013a, 2013b). A model and modeling approach (Lesh and Doerr, 2003), such as the development of computer-based simulations, has the potential to improve understanding of these essential Earth systems and the natural resource management challenges they pose. For example, computer models can elucidate system properties or large-scale phenomena that are not reproducible in physical laboratories or textbook-based presentations. Moreover, McKagan et al. (2008) argue that computer simulations help students build quantitative intuition about physical systems.

Some have argued that constructivist approaches to learning (see Inhelder and Piaget, 1958) such as discovery, inquiry, and problem-based learning are unproven and inconsistent with well-established principles of educational psychology such as regulating cognitive load and targeting the development of long-term memory by avoiding unnecessary demands on short-term working memory (Kirschner et al., 2006). Yet others rebut that, while of course these pedagogies can be poorly implemented and students utilizing them do require guidance, fundamentally different forms of constructivist learning must be differentiated (Hmelo-Silver et al., 2007). Problem-based learning exercises and products, in particular, can be designed to contain the essential elements of "worked examples" praised by Kirschner et al. (2006) and, properly scaffolded through the strategic employment of affordances and constraints (see Podolefsky et al., 2010), can avoid cognitive overload and limit demands on working memory, thus enabling learning.

More specifically, a science, technology, engineering, and mathematics (STEM) education literature has been developed that considers the merits of well-designed computer-based simulations as complements or replacements for traditional science laboratories that focus on measuring phenomena using advanced equipment. Weiman et al. (2008) argue that anxieties about the potential for injury or breaking expensive equipment divert students' attention in physical laboratory settings. While Marshall et al. (2015) report that COSMOL Multiphysics did not improve students' understanding of groundwater hydrology compared to standard pedagogy, other experiments with simulations structured as problem-based learning were more successful in improving learning outcomes and engaging students. Pyatt and Sims (2012, 145) argue that equipment-based "hands-on" laboratories do not promote learning or modify understanding of concepts. They report rather that students viewed virtual laboratory experiences as realistic, complex, and effective in exploring and manipulating experimental variables. Computer modeling–based laboratory exercises can thus match or exceed physical laboratory exercises in student performance and contradict the notion that they are not "real" or "hands-on."

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The Physics Educational Technology (PhET) project has been particularly instructive in the design of STEM educational simulations and their pedagogical merits. Using a PhET simulation, Finkelstein et al. (2005) report that introductory physics students who had utilized a computer simulation of circuits not only scored significantly better on final examination questions than students who had performed a laboratory exercise with real circuits, but they were able to build a real circuit in less time. Perkins et al. (2006) report that only 27% of the students shown a traditional tygon tube demonstration correctly answered a test question, compared with 71% of the students shown a simulation. Weiman et al. (2008, 683) conclude:

> *Carefully developed and tested educational simulations can be engaging and effective. They encourage authentic and productive exploration of scientific phenomena, and they provide credible animated models that usefully guide students' thinking.*

In addition to these advantages, if simulations can be designed as a "game," where there are objectives that, if met, constitute "winning," students can be even more engaged. What we often call games are in fact models cleverly designed to engage intelligent, goal-oriented manipulation.

This paper describes in brief four human–environment systems simulations—carbon, energy, water, and watershed—and a fifth simulation on nitrogen in more depth (available at: http://research.erp.siu.edu/games/). The paper describes the manner in which the simulations were developed, and the design principles that were employed. Focusing on the nitrogen simulation, it also presents a natural resource management problem and the basis of the simulation's design and parameterization in scientific literature. The main study question addressed is: How can a simulation of a human–environmental system based in biogeochemical cycles be designed and utilized in the classroom in a manner that engages students and promotes learning of Next Generation Science Standards objectives? Finally, preliminary data are presented on the study questions: To what extent does the nitrogen simulation help students in a middle school science classroom achieve learning objectives? Do students find the simulation engaging?

METHODS

Simulation Development and Context

As part of a larger National Science Foundation–funded Coupled Natural and Human Systems project on "Climate, Hydrology, and Landscapes of America's Heartland," the initial goal, in order to complement the research component of the project, was to create a simulation of biogeochemical cycles and their management in watersheds. Discussion with a team of two middle school (science) and four high school teachers (agriculture, English, two science) revealed that such a simulation would create cognitive overload and required extensive scaffolding. Thus, in order to create building blocks for the understanding of more advanced watershed management and systems concepts, three targeted computer simulations were proposed, each focusing on a single biogeochemical cycle: carbon, nitrogen, and water. Scaffolded by the carbon simulation, an energy planning simulation was also developed. With these building blocks in place, a more advanced watershed game was then created.

The simulations were first programmed using MS Excel to set the mathematical structure and parameterization, while mock user interfaces were drawn in Adobe Illustrator for discussion and feedback with the teacher team. Next, each simulation was programmed in Adobe Flash to integrate the user interface with the data in MS Excel and to build a functional simulation, with further discussion, feedback, and modification by the team of six teachers.

Simulation Design Strategy

From the literature (see especially Weiman et al., 2008; Quintana et al., 2009), design elements partly drawn from video games were identified to make the simulations engaging for students. In addition to contextualizing the simulations in significant real-world natural resources management challenges, engaging design elements include: (1) dynamic visual environments, (2) that are controlled by the user, (3) providing immediate visual feedback to user actions taken, coupled with (4) challenging objectives that, where possible, (5) provide an opportunity to "win the game," and (6) the introduction of complexity in steps to provide scaffolding.

The manner in which these design elements are incorporated into each of the five simulations is summarized in Table I. In the nitrogen simulation (Fig. 1), the natural resource management problem is Gulf of Mexico hypoxia, resulting from nitrogen overload in the Mississippi River watershed. The user interface for the nitrogen simulation is superimposed on a map of the watershed (Fig. 1), with large slider bars controlling two management options that control the size of the hypoxic zone in real-time—fertilizer reduction and wetland restoration, both of which reduce aggregate crop production in a exponentially increasing manner (Fig. 2). The goal is to minimize and, if possible, to eliminate the hypoxic zone within a budget constraint. Discoverable through user experimentation, optimizing progress toward this goal entails employing the economic concept of equimarginality (Tietenberg and Lewis, 2015). Two user-selected scenario parameters—the price of crops (very low, low, medium, high, very high) and weather (dry, medium, wet) —provide moderate complexity and control the possibility to "win" by eliminating the hypoxic zone entirely without exceeding the budget. The set of crop price–weather scenarios in which this is possible expands by dividing the watershed into six subwatersheds (Fig. 3) with different degrees of hydrological connection to the Gulf of Mexico. This increases spatial complexity and the number of user-controlled actions from two to 12.

The relationships explored and parameterization of the simulations are based on peer-reviewed scientific literature. Along with phosphorus and potassium, nitrogen is a key nutrient in supporting plant growth and is the largest component of most fertilizers applied to crops. Nitrogen fertilizes algae blooms, which subsequently die off. Their decay demands large quantities of oxygen, diminishing

TABLE I: Design elements and scholarly basis of the five environmental simulations available at: http://research.erp.siu.edu/games/.

Simulation	Nitrogen	Carbon	Energy	Water	Watershed
Natural resources management problem	Gulf of Mexico hypoxia from nitrogen flux in the Mississippi River watershed	Atmospheric, oceanic carbon reduction; restoring landscape carbon, conserving fossil fuels	Create a U.S. energy plan for 2020, 2030, 2040, and 2050 in the electricity, vehicle fuel, and heating sectors	Allocating scarce water in the Rio Grande basin under prior appropriation	Multifunctionality: Produce crops and generate ecosystem services in a watershed
Dynamic visual environment controlled by user	Slider bars to reduce fertilizer and restore wetlands, which shrink hypoxic zone	Slider bars to implement multiple options in energy efficiency, energy production, and land management	Slider bars to select energy sources controlling graphs of energy generated in three sectors, money spent, oil consumed, greenhouse gases (GHGs) emitted	Width of river reflects water flow; unmet water needs highlighted; dialog boxes for water trading, dam building, minimum flow requirement	Drag colored land-use assignments (corn, soybeans, hay, forest) on three-dimensional map of subwatersheds
Objectives	Minimize or eliminate Gulf of Mexico hypoxic zone	Maximize carbon points by utilizing cost-effectiveness principles	Satisfy multiple objectives: meet energy needs, within a budget, with oil and greenhouse gas limits	Maximize water-use points for urban, industrial, mining, and irrigation; fish habitat	Combined points for crop value and ecosystem service performance along a Pareto front
Scaffolding	Past hypoxic zones provided; crop price, weather scenarios; Single and multiple subwatersheds	Carbon options categorized into energy production, energy efficiency, and land management sectors	1990, 2000, 2010 energy systems provided; five difficulty levels; GHG, oil limits optional	30 water users use the simulation in a collaborative classroom setting	Graphs of land-use effects on: revenue, soil erosion, water pollution, carbon retention, peak water flow
Key references	Doering (2002) Goolsby et al. (1999) Hanson et al. (1994) McCorvie and Lant (1993) McIsaac et al. (2002) Mitsch et al. (2005) Ribaudo et al. (2001) Scavia et al. (2003) Tietenberg and Lewis (2015)	Baral and Guha (2004) IPCC (2007) Pacala and Socolow (2004) Searchinger et al. (2008) Sims et al. (2003) Tietenberg and Lewis (2015)	Interacademy Council (2007) IPCC (2007) NRC (2008) U.S. EIA (2013) Yergin (2011)	Acreman and Dunbar (2004) Dellapenna (2002, 2005) Dumars et al. (1984) Getches (2008) Howe et al. (1986) Ostrom (2000) Reisner (1986) Ward and Michelsen (2002) Young (2005)	Arnold et al. (1998) Bekele et al. (2013) Daily (1997) Foley et al. (2005) Haight (2007) Lant et al. (2005) MEA (2005) Nelson et al. (2008) Novotny and Chesters (1989) Ruhl et al. (2007)

dissolved oxygen to levels too low for fish and other aerobic aquatic and marine species (called hypoxia) (Scavia et al., 2003). In this manner, fertilization of crops is linked, through eutrophication, to fish kills. Wetlands can ameliorate the problem through denitrification by transforming nitrate back to N_2 gas (e.g., Hanson et al., 1994). Goolsby et al. (1999) and McIsaac et al. (2002) provide a quantification of nitrogen inputs and outputs for the Mississippi River basin and the two primary options of fertilizer reduction and wetland restoration. Mitsch et al. (2005) quantify denitrification rates per acre of wetlands restored. Scavia et al. (2003) provide a relationship between nitrogen load of the Mississippi River and the hypoxic zone area in the Gulf of Mexico. Doering (2002) and Ribaudo et al. (2001) provide data on the cost of fertilizer reductions and wetland restoration, the importance of increasing marginal costs, the role of crop prices in controlling nitrogen abatement costs, and the reality that Gulf of Mexico hypoxia cannot be eliminated at a reasonable cost except under dry weather conditions with low crop prices. McCorvie and Lant (1993) provide a background on the history and geography of wetland drainage in the Mississippi watershed.

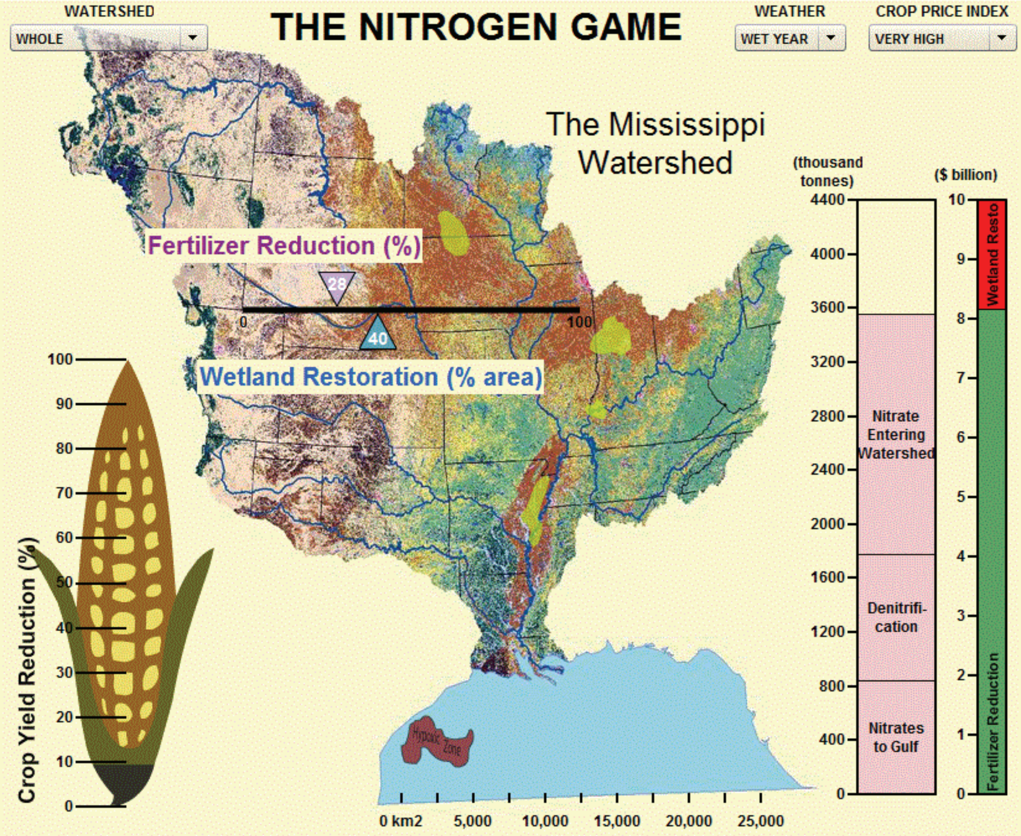

FIGURE 1: The nitrogen simulation interface. In this case of a wet year and very high crop prices, it is not possible to eliminate the hypoxic zone entirely without exceeding the budget of $10 billion. The darkened bottom of the corn cob shows that the student's choice to reduce fertilizer by 28% has reduced yields by about 9%. The 40% area of wetlands the student restored is also evident.

Measurement of Learning Outcomes and Attitudinal Response

With Institutional Review Board and administrative approval, the nitrogen simulation was pilot-tested in a prekindergarten through 8th grade rural–suburban school with 693 students and a slightly higher student mobility rate and percentage of low-income students than the Illinois average, but similar percentages of English learners and students with disabilities. Learning outcome data were collected in two 8th grade environmental science classes taught by the same teacher during spring 2014. Both classes had 23 students, but due to either missing pretest or posttest data, the analyses were run on 19 students (12 girls and seven boys) and 20 students (15 girls and five boys), respectively, in class 1 and class 2.

The nitrogen simulation was introduced as one of four 4-week exploratory science classes the 8th graders took in rotation over the course of the semester. Utilizing prepared lesson plans (see: http://research.erp.siu.edu/games/), students were first introduced to concepts related to watershed geography, such as divides, tributaries, and outlets. Second, to introduce the concept of eutrophication borne of nutrient enrichment, students added different chemicals to beakers of water, noting how phosphates initiated algae blooms over a time span of several days. Arranging students into several groups of three to four per table, the area of past hypoxic zones was then graphed by introducing these data from the nitrogen simulation. Guided by the instructor, the interplay between the effect of fertilizer reductions and wetland restoration on hypoxic zone area was explored. Students then utilized the simulation individually with the objective of minimizing hypoxic zone area. Finally, strategies for reaching this objective were discussed as a class.

The simulation was performed using simple individual netbook laptop computers and tablets, with a smartboard and projector available to the instructor. Shared computer stations is another option for utilizing the simulations.

A 21 item multiple-choice test (available at: http://research.erp.siu.edu/games/), developed by the teacher to assess learning outcomes related to the concepts of the nitrogen simulation, was administered to the students before and after the lesson plan was implemented. Because nitrogen cycling is not ordinarily part of the curriculum in the classes tested, there was no control group using conventional pedagogy as a basis of comparison. During posttest administration, students were also asked to complete an attitudinal response survey with 10 Likert-type

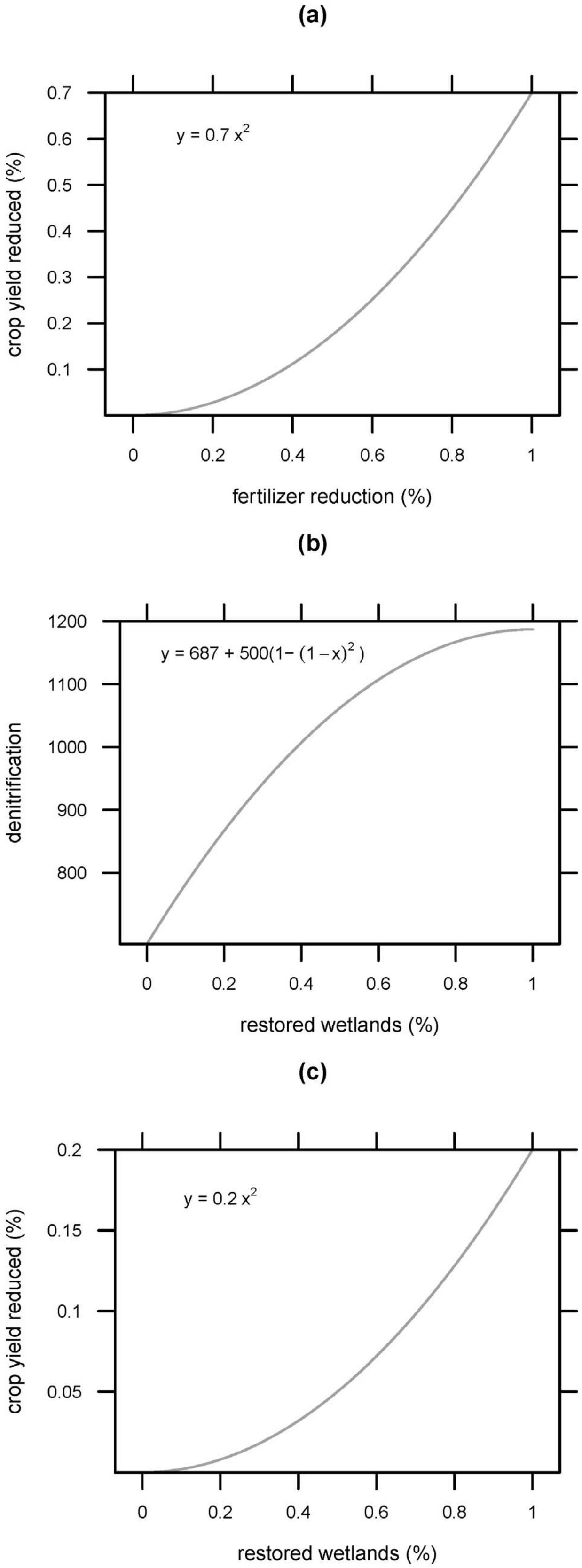

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FIGURE 2: Functions for the nitrogen simulation: (a) response of crop yield to fertilizer reduction, (b) response of denitrification to wetland restoration, and (c) response of crop yield to wetland restoration.

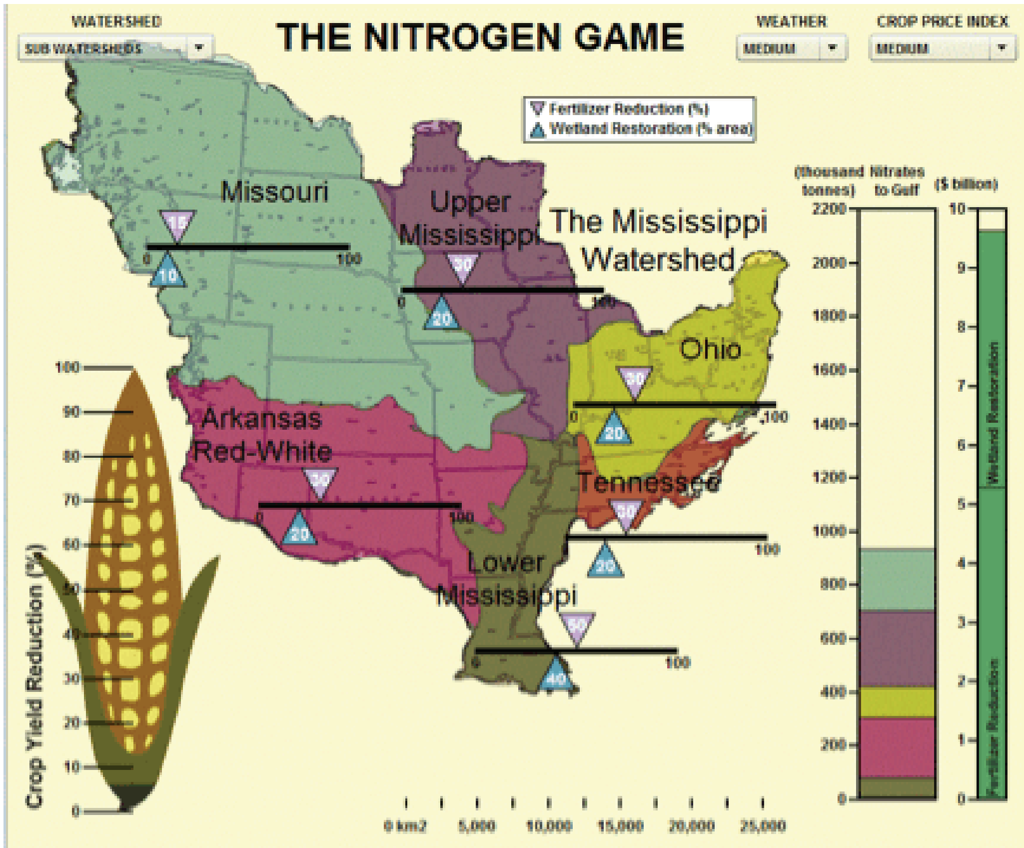
questions (van Laerhoven et al., 2004). The test and survey were reviewed by the simulation development team.

The questions were designed to follow the sequence of instructional preparation and use of the simulation, starting with cause of algae blooms and watershed spatial concepts, and then proceeding to hypoxia as an ecological problem and specific effects of simulation variables (fertilizer, wetlands, crop prices) on the gulf hypoxic zone. While not a 1-to-1 matching, test questions such as, "Why is it important to reduce the size of the hypoxic zone?" and "What effect does fertilizer reduction in Iowa have on the hypoxic zone?" address Next Generation standards in Interdependent Relationships in Ecosystems such as "e. Use evidence to construct explanations and design solutions for the impact of human activities on the environment and ways to sustain biodiversity and maintain the planet's natural capital," Engineering Design standards, such as "d. Use a computer simulation to test the effectiveness of a design under different operating conditions, or test what would happen if parameters of the model were changed, noting how the simulation may be limited in accurately modeling the real world," and Links Among Engineering, Technology, Science and Society, such as "Construct or critique arguments based on evidence concerning the costs, risks, and benefits of changes in major technological systems related to agriculture, health, water, energy, transportation, manufacturing, or construction, needed to support a growing world population."

RESULTS

Table II presents the statistical outcomes for the multiple-choice test, separately for the two classes. A repeated measures *t*-test was used to examine whether there was a statistically significant increase in performance on the multiple-choice item test as a result of implementation of the lesson plan and computer simulation. The results of a repeated measures *t*-test, separately for each class, were statistically significant, thus supporting a substantial increase in performance from pre- to posttest. Specifically, for class 1, $t(18) = 7.19$, $p < 0.0001$ (mean difference of 6.22, $r = .50$, and Cohen's $d = 1.65$), and class 2, $t(19) = 7.42$, $p < 0.0001$ (mean difference of 4.85, $r = .53$, and Cohen's $d = 1.65$).

The attitudinal response survey consisted of 10 Likert-type questions on a scale from 1 = strongly disagree to 5 = strongly agree (Table III). It is noteworthy that 58% of students enjoyed playing the computer simulation (item 2), 74% indicated that the computer simulation was easy to understand (item 6), and 85% preferred this mode of instruction as compared to a textbook (item 8). Only 8% of students indicated, however, that they would use the computer simulation outside of class (item 3), 21% indicated that they were excited to learn more about the topic



WATERSHED: SUB WATERSHEDS

WEATHER: MEDIUM

CROP PRICE INDEX: MEDIUM

FIGURE 3: The nitrogen simulation interface with multiple subwatersheds. In this case of medium weather and a medium crop index, the hypoxic zone can be completely eliminated by geographically targeting fertilizer reductions and wetland restoration.

introduced by the computer simulation (item 7), and 28% indicated that as a result of using the computer simulation, their interest in the topic has increased (item 5). These attitudinal outcomes mirror those resulting from use of similar STEM-education simulations.

Representative open-ended responses (Table IV) illustrate the students' level of engagement in using the simulation emerging from the design principles employed, while comments on how the simulation could be improved focused on the absence of the visually stimulating features of high-end commercial games. Other pilot tests using the nitrogen and the other simulations at the university level corroborate that students find them engaging. For example, on a five-point Likert scale rating the carbon, energy, and nitrogen simulations, 41 of 66 students at a state university rated them a "5," and 13 rated them a "4"; the mean of 4.35 was higher than for any other curricular element in the class.

DISCUSSION

Relationships of the Simulations to Next Generation Learning Objectives

The nitrogen and the other simulations presented help to meet learning goals of the Next Generation Science Standards for learning (Table V) as proposed by the National Research Council (NRC) and developed by Achieve, Inc. They are designed to engage students in various ways in an effort to appeal to as many different students as possible, regardless of their preferred learning style (Cassidy, 2004; Pashler et al., 2008). Through this

TABLE II: Statistical results for comparison of pretest and posttest learning outcomes.

Class	Test	Sample Size	Mean Score	Standard Deviation	*t*-Test Results		
					t	df	Significance
1	Pretest	19	9.89	3.62	7.19	18	$P < 0.0001$
	Posttest	19	16.11	3.91			
2	Pretest	20	11.65	3.36	7.42	19	$P < 0.0001$
	Posttest	20	16.50	2.44			

TABLE III: Attitudinal responses for the two classes jointly.

Item	Mean[1]	Std. Dev.	Percent of Reponses[2] (Sample Size = 39)					
			SD	D	N	A	SA	NR
1. The classroom demonstration of the computer simulation was presented in an interesting way.	3.59	0.55	0.0	0.0	43.6	53.9	2.6	0.0
2. I enjoyed playing the computer simulation.	3.58	0.83	0.0	10.5	31.6	47.4	10.5	2.6
3. I would play the computer simulation outside of class.	2.13	0.89	25.6	43.6	23.1	7.7	0.0	0.0
4. The classroom demonstration of the computer simulation was presented in a clear way.	3.90	0.64	0.0	0.0	25.6	59.0	15.4	0.0
5. As a result of playing the computer simulation, my interest in the topic introduced by the simulation has increased.	2.85	0.96	10.3	23.1	38.5	28.2	0.0	0.0
6. The computer simulation was easy to understand.	3.84	0.82	0.0	7.9	18.4	55.3	18.4	2.6
7. I am excited to learn more about the topic introduced by the computer simulation.	2.63	1.10	15.8	31.6	31.6	15.8	5.3	2.6
8. I liked this mode of instruction (playing the computer simulation) rather than just learning from a textbook.	4.18	0.76	0.0	2.6	12.8	48.7	35.9	0.0
9. The computer simulation was challenging.	3.69[3]	0.77	10.3	41.0	33.3	12.8	2.6	0.0
10. As a result of playing the computer simulation, my interest in other science topics has increased.	2.87	0.98	10.3	20.5	43.6	23.1	2.6	0.0

[1] Means were computed based on a 1–5 scale (1 = strongly disagree to 5 = strongly agree).
[2] SD = strongly disagree; D = disagree; N = neutral; A = agree; SA = strongly agree; NR = no response.
[3] Item 9 was reverse scored for computation of the mean and standard deviation.

strategy, they address major elements of the three dimensions of the framework for science education proposed by the NRC: (1) scientific and engineering practices, (2) crosscutting concepts, and (3) disciplinary core ideas (NRC, 2012). It is useful to see the extent to which the simulations encompass specific elements of each of the three dimensions of the NRC framework. They involve students in all eight elements of the dimension "scientific and engineering practices": (1) asking questions and defining problems, (2) developing and using models, (3) planning and carrying out investigation, (4) analyzing and interpreting data, (5) using mathematics and computational thinking, (6) constructing explanations and designing solutions, (7) engaging in argument from evidence, and (8) obtaining, evaluating, and communicating information (Next Generation Science Standards, 2013a).

The second dimension of the NRC framework is crosscutting concepts that unify study through their common application to scientific disciplines and activities and provide students "with an organizational framework for connecting knowledge from various disciplines into a coherent and scientifically-based view of the world" (NRC, 2012, 83). Of the seven crosscutting concepts, the simulations deal directly with five: (1) observation of patterns and relationships, (2) cause and effect—mechanism and explanation, (3) systems and system models, (4) energy and matter—flows, cycles, and conservation, and (5) stability and change (Next Generation Science Standards, 2013b). Using one of the simulations with variable parameters permits these crosscutting concepts to be put into play, effectively permitting the students to "experience the practices in varied combinations and in multiple contexts" (National Research Council, 2015, 5), one of the recom-

TABLE IV: Representative student quotes from the open-ended questions.

What did you like about the computer simulation?
It gave a very clear idea of the things we are doing/should do and how it would affect the environment, namely the hypoxic zone.
It was a unique and interesting way to learn. It was better than the textbook and more hands on.
I liked changing everything and seeing what it would come out to be.
It was simple to use and I liked that it was interactive, a lot more fun than using a textbook.
We could change different factors and see how they affected other things.
I enjoyed learning about how changing the wetland restoration and fertilizer can affect the hypoxic zone size.
As an interactive activity, it allowed me to work on my own/with a partner and never left me bored, because I was the one making the decisions.
What do you think could be done to improve the computer simulation?
More in-depth controls and variables (like a button that randomizes the weather).
It was okay, but learning about watersheds isn't fun, but the game did the best it could.
If there were more vivid pictures and actions, it might have looked and become more interesting.

TABLE V: Elements of the Next Generation Science Standards advanced by the nitrogen simulation.

Learning Standard	Elements Addressed by the Nitrogen Simulation
HS.LS-IRE Interdependent Relationships in Ecosystems	a. Evaluate data to explain resource availability and other environmental factors that affect carrying capacity of ecosystems.
	b. Design solutions for creating or maintaining the sustainability of local ecosystems.
	e. Use evidence to construct explanations and design solutions for the impact of human activities on the environment and ways to sustain biodiversity and maintain the planet's natural capital.
MS-ETS-ED Engineering Design	a. Evaluate ideas for solving an environmental problem to determine which designs best meet the criteria and constraints of the problem and take into account scientific principles and short- and long-term consequences.
	d. Use a computer simulation to test the effectiveness of a design under different operating conditions, or test what would happen if parameters of the model were changed, noting how the simulation may be limited in accurately modeling the real world.
	e. Refine a design by conducting several rounds of tests, modifying the model after each test, to create the best possible design that meets the most important criteria.
	f. Communicate information about a proposed solution to a problem, including relevant scientific principles, how the design was developed, how it meets the criteria and constraints of the problem, and how it reduces the potential for negative consequences for society and the natural environment.
HS-ETS-ED Engineering Design	a. Ask questions and collect information to quantify the scope and impacts of a major global problem on local communities and find evidence of possible causes by breaking the problem down into parts and investigating the mechanisms that may contribute to each part.
	c. Evaluate different solutions to a problem by identifying criteria (e.g., cost, safety, reliability, aesthetics) and possible impacts on society and the natural environment, and using a trade-off matrix or numerical weighting system to choose the best solution.
	e. Use computational thinking to create, simulate, and compare different design solutions, checking to be certain that the simulation makes sense when compared with the real world.
HS-ETS-ETSS Links Among Engineering, Technology, Science, and Society	d. Construct or critique arguments based on evidence concerning the costs, risks, and benefits of changes in major technological systems related to agriculture, health, water, energy, transportation, manufacturing, or construction, needed to support a growing world population.

mendations for the Second Generation Science Curriculum. Alternatively, a teacher could elect to use a number of the simulations to illustrate the crosscutting concepts. Through the suggested activities accompanying the simulations, an instructor has an opportunity for developing and using formative assessment of student thinking (National Research Council, 2015).

Classroom Resources and Utilization

Available at http://research.erp.siu.edu/games/, the five simulations are suitable for use in middle to high school classrooms. Detailed lessons plans are available for nitrogen and are under development for the carbon, energy, water, and watershed simulations. Instructors would need to review these materials and enjoy gaining mastery of the simulation operations before introducing them in the classroom. The water simulation functions best as a classroom exercise, while the other four simulations function best when introduced by the instructor and used by individual or small groups of students. For group use, only an Internet connection and projector are required; a multiple-computer laboratory is needed for in-class use of the simulations by individual or small groups of students. Exercises based on the simulations that can be assigned as homework are available in the online lesson plans.

In addition to providing references and background on underlying scientific concepts, a detailed lesson plan provides scaffolding enabling teachers to use the nitrogen simulation effectively. It contains an initial exercise to introduce the watershed concept and its significance for water quality and downstream effects, and it follows with an activity focused on the causes of rapid algae growth and eutrophication. Background material on the role of wetlands in the landscape and the response of crops to fertilizer is presented in the lesson plans; suggested activities permit the teacher to further develop these concepts through the use of the simulation. The lesson plan also contains suggestions for the assessment of learning outcomes and connects the simulation to the Second Generation Science Standards.

Relationship of These Simulations to Other STEM Education Simulations

While produced independently, the environmental system simulations explored here share the six common design elements described above and therefore visually resemble the several dozen simulations available through PhET (https://phet.colorado.edu/). They share a common programming language for development of the user interface (Flash) and run in a similar fashion through Internet browsers on PC and Mac. The carbon, energy, nitrogen, water, and watershed simulations differ from PhET simulations, however, in that the latter are designed to illustrate fundamental concepts at the heart of traditional science curricula, while the former are illustrative of ongoing natural resource management challenges based on biogeochemical cycles. The simulations discussed here also make greater use of the four psychologically and educationally relevant components that define a game: a goal, rules, a feedback system, and voluntary participation (Suits, 1990). These simulations thus build upon the PhET and other STEM educational products by introducing simulations with a focus on problems of managing for environmental sustainability, in contrast to core concepts and phenomena in science disciplines.

CONCLUSIONS

Guided by the Next Generation Science Standards, five environmental simulations (carbon, energy, nitrogen, water, watersheds) were developed using MS Excel and Adobe Flash, with detailed lesson plans developed and classroom pilot testing employed for the nitrogen simulation. Pretest versus posttest results indicate a substantial and statistically significant improvement in learning outcomes resulting from using the simulation, though there was no comparable control group. Attitudinal feedback indicates rich student engagement consistent with most prior use of computer-based simulations to teach science concepts. These results suggest the efficacy of developing and using environmental simulations or games that help meet broadly developed learning standards in lieu of, or in combination with, more traditional approaches to geoscience and environmental science education.

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