Student Learning of Complex Earth Systems: Conceptual Frameworks of Earth Systems and Instructional Design

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ABSTRACT

Engaging students in authentic problem solving concerning environmental issues in near-surface complex Earth systems involves both developing student conceptualization of Earth as a system and applying that scientific knowledge using techniques that model those used by professionals. In this first paper of a two-part series, we review the state of the geoscience education research field related to systems thinking in the context of Earth systems. The purpose of this study is to build on previous syntheses by conducting a configurative literature review that addresses the following research questions: (1) What are the characteristics of studies that address systems thinking in the context of Earth systems? (2) What conceptual frameworks for systems are present in the geoscience education research literature on systems thinking in the context of Earth systems? (3) How are these conceptual frameworks operationalized in research and educational interventions aimed at understanding and supporting systems thinking in the context of Earth systems? Twenty-seven papers met inclusion and exclusion criteria. Content analysis was conducted on each of these papers, and systems ideas were analyzed using the constant comparative method. Four conceptual frameworks were identified: Earth systems perspective, Earth systems thinking skills, complexity sciences, and authentic complex Earth and environmental systems. This study is, to our knowledge, the first systematic review in this area and allows a more consistent comparison of new findings with previous work. It also facilitates strengthening connections with cognitive science and education research literature related to systems thinking and complex systems. © *2017 National Association of Geoscience Teachers*. [DOI: 10.5408/16-208.1]

Key words: systems thinking, Earth systems, complexity, complex systems

INTRODUCTION

The importance of an Earth systems approach to education (Mayer, 1991; Ireton et al., 1997) has been well documented for K–12 science education (NGSS Lead States, 2013; Orion and Libarkin, 2014; The College Board, 2016), geoscience literacy (Earth Science Literacy Initiative, 2009), and geoscience workforce expertise (U.S. Bureau of Labor Statistics, 2015). An inherent feature in this approach is the idea of learners' systems thinking abilities (Orion and Libarkin, 2014). Previous review papers have identified common systems thinking challenges that students face when attempting to learn about Earth systems, such as:

- developing accurate mental models of near-surface Earth systems (Herbert, 2006);
- seeing the Earth system as a whole instead of as disconnected parts (Orion and Ault, 2007);
- encountering "sophisticated, initially counterintuitive conceptions of causality and mechanism" (Stillings, 2012, 104); and
- recognizing that Earth is a dynamic system (Orion and Libarkin, 2014).

Significant progress has been made in curriculum development and assessment of systems thinking skills in the context of Earth systems education at the K–12 level (summarized by Orion and Libarkin, 2014), but studies that explicitly address complex systems ideas such as feedback loops and emergence are sparse (Stillings, 2012; Orion and Libarkin, 2014). This is an active area of education research in other disciplines, and there is significant potential for collaboration in teaching complex systems ideas across the curriculum (Stillings, 2012). Additionally, considering the role of humans in the Earth system is of increasing importance in designing educational interventions in the Earth sciences (Manduca and Kastens, 2012; Orion and Libarkin, 2014; InTeGrate Program, 2015b).

In this systematic literature review, we identified four conceptual frameworks that illuminate how teaching and learning of Earth systems have been presented in the geoscience education research literature. These frameworks can be utilized to guide future research, inform instructional design decisions, and serve as entry points into other disciplines to foster interdisciplinary collaborations. Our findings will be of interest to a broad range of educators in Earth and environmental sciences and scholars interested in discipline-based education research related to student development of systems thinking abilities. This paper is part of a related series of two review papers. The companion paper (Holder et al., this volume) presents a review of problem solving in the geosciences and a model for engaging learners in authentic problem solving about complex near-surface Earth systems.

"Complexity" in the Earth Sciences

There have been multiple calls over the past decade to incorporate ideas from the complexity sciences into the teaching of Earth Sciences (e.g., Herbert, 2006; Turcotte, 2006; Raia, 2012). Complexity sciences have origins in both

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the systems science ideas developed by members of the general systems community, principally an interdisciplinary and antireductionist approach to science that emphasizes the whole system and its interactions with the environment (Hammond, 2002, 2003), and the field of cybernetics, which is concerned with the flow of information in systems (Castellani and Hafferty, 2009). The landscape of complexity sciences is in itself an intricate network of intersecting and evolving disciplines and subdisciplines (for a comprehensive graphic, see Castellani, 2013) that generally seek to understand complex systems, i.e., those in which the behavior of the system as a whole is not easily predictable from looking at the individual components (Mitchell, 2009). Such emergent behavior is only apparent at the level of the whole system (i.e., it emerges from interactions between components in often surprising ways), and a system may be self-organizing in that the system's behavior is organized, but the mechanisms controlling this behavior are not centralized (Mitchell, 2009). Complex systems are also typically not at equilibrium, and components interact through feedback mechanisms (Fichter et al., 2010b). Classic examples of complex systems include ant colonies, stock markets, and hurricanes (Mitchell, 2009). In the geosciences, processes such as sediment deposition and earthquakes can be understood from a complex systems perspective (Bak, 1996). Fichter et al. provided a thorough discussion of what constitutes a complex system in the formal sense (Fichter et al., 2010b) and the application of complex systems theory to consideration of evolutionary processes in Earth systems (Fichter et al., 2010a). System dynamics is a discipline within the complexity sciences that emphasizes the flow of information and matter; stock-and-flow models are commonly used, and feedback mechanisms feature prominently (Meadows, 2008). System dynamics models can be used to investigate geoscience processes such as the hydrologic cycle (Stillings, 2012).

Complexity science research relies heavily on various methods of numerical modeling, and, while there has been little research into their impact on student learning, authors in the Earth Sciences have argued for incorporating these approaches into teaching of Earth systems concepts. Slingerland (2012) articulated the role of modeling in advancing hypothesis-driven research in the geosciences and called for the general need to train students in these approaches, which can support entry into complexity sciences research. Neuhauser (2012) described a course that supports student ability to use mathematical abstraction to study dynamical systems, a skill that is transferrable to multiple complex systems. Cellular automata models, numerical simulations that allow for visualization of complex processes that arise from a simple set of rules that govern interactions between components, can be used to model geological processes that display complex behavior, such as fractal stream distribution in drainage basins (Turcotte, 2006). Raia (2012) described the potential afforded by having students investigate complex systems through the combination of aggregate models (e.g., STELLA) that represent dynamic systems through equations that govern the flow of elements, such as water into and out of a reservoir (Meadows, 2008), and agent-based models (e.g., NetLogo) that focus on interactions between individual elements, such as atoms or molecules (Raia, 2012). She claimed that the former leads to understanding of relationships within a system at the same level, while the latter allows for investigation of emergence. Additionally, Raia (2012) argued for careful consideration of mechanisms and causality to support a shift to complex systems explanations of Earth Science phenomena.

Earth systems science is both a field of research and an organizing theme for novel interdisciplinary educational approaches at undergraduate levels (e.g., Ireton et al., 1997) and K–12 (most recently, NGSS Lead States, 2013). This interdisciplinary approach emphasizes interconnections and feedbacks among Earth's spheres (solid earth, biosphere, hydrosphere, atmosphere, and anthroposphere) as opposed to teaching in separate "silos" (Mayer, 1991; Ireton et al., 1997; Manduca and Kastens, 2012) and "may or may not involve formal complexity" (Manduca and Kastens, 2012, 93). Stillings (2012) further differentiated between geoscientific explanations that are "complex in the vernacular sense" and ones that "involve technical concepts of complex systems" (Stillings, 2012, 98). Manduca and Kastens (2012) presented a concept map of the domain of complex Earth systems that is a useful way to organize the vast array of concepts in the discipline, and it includes both complexity science and Earth systems science ideas. Understanding of these complex Earth systems concepts requires the use of systems thinking, but exactly what that looks like in practice varies widely.

Systems Thinking in the Earth Sciences

Characterizations of systems thinking have been found to vary by discipline and research focus (Orion and Libarkin, 2014), but they are generally concerned with understanding "systemhood properties" (Klir, 2001, 37). Within the Earth Sciences, there is also considerable variation in how education researchers and practitioners approach student systems thinking abilities in the context of "complex" Earth systems. Here, we contrast two commonly cited sets of studies to illustrate this variation.

Ben-Zvi Assaraf and Orion (2005a) identified eight characteristics of systems thinking for Earth systems education from a review of literature in organizational management, system dynamics, engineering, and Earth Science fields. They found that these skills could be arranged into a hierarchical structure, subsequently named the systems thinking hierarchy (STH). The characteristics (building from lower- to higher-level skills), as stated by Ben-Zvi Assaraf and Orion (2010, 1255) are: "(1) the ability to identify the components of a system and processes within the system, (2) the ability to identify relationships among the system's components, (3) the ability to identify dynamic relationships within the system, (4) the ability to organize the systems' components and processes within a framework of relationships, (5) the ability to understand the cyclic nature of systems, (6) the ability to make generalizations, (7) understanding the hidden dimensions of the system, (8) thinking temporally: retrospection and prediction." Ben-Zvi Assaraf and Orion (2010) reviewed how STH characteristics have appeared in systems thinking research in other fields, and Orion and Libarkin (2014) provided a recent summary of this body of work.

In contrast, Raia (2005, 2008) framed her research into student learning explicitly from a complex systems perspective, with complex systems characteristics such as emergence and self-organization at the forefront. She demonstrated that students tend to understand complex systems in linear terms, emphasizing isolated processes related to components of the system over mutual interactions and emergent properties (Raia, 2005), and that an intervention designed to address these challenges led to improved reasoning about complex system characteristics (Raia, 2008).

Implications for teaching and learning arise from the fact that Raia's research deals with *complexity in a formal sense* (i.e., emphasizing concepts central to complexity sciences) compared to Ben-Zvi Assaraf and Orion's focus on components, processes, and relationships in a *system that is complex* (i.e., complicated). It follows that student systems thinking abilities arising from instruction framed using STH characteristics (e.g., ability to identify relationships among system components) would be quite different than those grounded in complexity sciences (e.g., ability to identify emergent properties of a system). Additionally, we noted that it is rare for researchers to be specific about the complex systems tradition(s) on which their study is based. For example, Batzri et al. (2015) cited Raia (2005) without acknowledging that her studies deal specifically with complex systems, not just systems in general. While there is certainly a need for a variety of approaches to systems thinking for different types of systems and different educational contexts, it is at present difficult to compare research findings related to student systems thinking ability across different studies because they do not use a common conceptualization of a "complex" system.

Towards a Common Framework for Complex Earth Systems

Manduca and Kastens (2012) called for development of an epistemological framework for complex systems to guide research and instruction in Earth Sciences as well as the development of learning progressions to support systems thinking. We assert that in order to move forward with this agenda, the geoscience education research (GER) community needs a common understanding of "complex" Earth systems and the state of the field related to teaching and learning of these systems. There are multiple previous review papers in this arena (as described above), but we were unable to identify any reviews that reported their methodology for systematically identifying and examining previous work. Thus, this study builds on previous syntheses through conducting a systematic review of Earth Science education literature related to student development of systems thinking in the context of Earth systems. We hypothesized that there are multiple ways in which systems thinking in the context of Earth systems is discussed in the GER literature, and that these studies are inherently influenced by the conceptual framework within which the researcher or educator is operating. Additionally, explicitly identifying how systems thinking is approached in the GER literature will allow researchers and instructional designers to connect with systems thinking literature in other disciplines through the use of common theory bases, complexity sciences concepts, and/or similar approaches to systems thinking. To this end, the present study addresses the following research questions:

Research Question 1. What are the characteristics of studies that address systems thinking in the context of Earth systems?

Research Question 2. What conceptual frameworks for systems are present in the GER literature on systems thinking in the context of Earth systems?

Research Question 3. How are these conceptual frameworks operationalized in research and educational interventions aimed at understanding and supporting systems thinking in the context of Earth systems?

METHODS

We conducted a configurative review (Gough et al., 2012) in order to determine the attributes of GER papers with regard to our research questions. First, we reviewed titles and abstracts for citations in previous review papers (Herbert, 2006; Orion and Ault, 2007; Manduca and Kastens, 2012; Stillings, 2012; Orion and Libarkin, 2014) for relevance to the topic. Through this first-cycle review, we identified and refined inclusion and exclusion criteria (Table I). These criteria allowed us to focus the analysis on papers that were highly relevant to the research questions. The choice of a near-surface Earth environment context as an inclusion criterion is justified due to the fact that the development of environmental insight (Orion and Ault, 2007) and understanding of interactions between humans and Earth systems (Manduca and Kastens, 2012; Orion and Libarkin, 2014) have been identified as important outcomes of Earth systems education. Additionally, the majority of the relevant papers cited in previous reviews addressed systems thinking in near-surface contexts. Papers were excluded from the study if they met one of the eight exclusion criteria that allowed us to further refine the study. Exclusion of practitioner wisdom/expert opinion papers and conference proceedings ensured that the results of this study were based on refereed studies that reported some evidence to support their claims (as recommended by St. John and McNeal, 2015). There are a number of constructs related to the nature of geoscience and geoscientific thinking that can be investigated in addition to systems thinking, including: temporal thinking, spatial reasoning, problem solving, nature of science, and development and use of mental or physical models. In order to retain the focus of this review on systems thinking, we excluded papers that addressed these concepts if they did not also address systems thinking. Finally, we excluded studies that only included a teacher population in order to focus the study on implications for student learning.

We identified additional papers through two searches on the Education Research Complete database. Both were limited to papers published between 1991 and 2015. First, using the Boolean search string "systems thinking" AND "Earth" OR "geology" OR "geosciences" OR "environmental science" in all text yielded 396 papers. Second, searching the *Journal of Geoscience Education* for the term "system" in the paper title yielded an additional 64 papers. We examined titles and abstracts for all papers identified through these methods (including those from the review papers) and obtained full papers for those that initially met the criteria based on title and abstract. We examined the full papers to confirm that they fully met the inclusion and exclusion criteria. Based on this, 27 papers met the criteria to be included in the systematic review.

The first author (H.H.S.) conducted a content analysis on each paper in the review (following Patton, 2002) to

TABLE I: Inclusion and exclusion criteria for systematic review of systems thinking in the context of Earth systems.

Inclusion criteria: (must meet all criteria)
1. Student systems thinking skills addressed
2. Near-surface Earth environments context
3. Some interaction with the geosphere
4. SoTL or DBER (student data reported)
5. Grades 7–16
6. Case studies or above[1]
7. Date range: 1991–2015
Exclusion criteria: (only needs to meet one of these criteria)
1. Practitioner wisdom/expert opinion papers
2. Conference proceedings
3. Geologic time/temporal thinking only
4. Spatial thinking/spatial reasoning only
5. Problem solving only
6. Nature of science only
7. General models (mental or physical models) only
8. Teacher population

[1]Based on GER community claims pyramid (St. John and McNeal, 2015).

address Research Question 1. First, she identified the following characteristics of the papers: (1) Earth Science topic(s) addressed, (2) type of study, (3) student grade level, (4) level of evidence (i.e., case study or cohort study), and (5) phenomenon investigated (i.e., effectiveness of a teaching tool, effectiveness of an instructional module, effectiveness of a course, or student accounts of a phenomenon with no intervention). The type of study was classified as either discipline-based education research (DBER), i.e., studies that lead to theory-based understandings that can be applied in new settings, or scholarship of teaching and learning (SoTL), i.e., studies in which an instructor evaluates a particular educational intervention in their own course (National Association of Geoscience Teachers, 2017). Identification of the level of evidence was based on St. John and McNeal (2015), in which a case study is one that is conducted at the level of "a single course or institution that is taught by the researcher using curriculum or instructional methods that they developed and are testing in their class" and a cohort study is situated in "a broader cross section of courses, institutions, and/or populations."

The same author (H.H.S.) then analyzed each paper for systems ideas as they appeared in framing the study or intervention (typically in the introduction) and descriptions of student learning outcomes, research tools, and/or interventions and instructional approaches. During the first cycle of analysis, she analyzed each paper using the following approach (modified from the constant comparative method as described by Lincoln and Guba, 1985). She identified passages in the text that discussed systems or systems thinking concepts and assigned them a code (e.g., interactions among spheres). She compared new passages to existing ones and either assigned an existing code or a new code and grouped codes into themes based on common ideas. These groups (subsequently called conceptual frameworks of Earth systems) emerged from this cycle of analysis. She developed descriptions of each conceptual framework, debriefed them with the research team (coauthors), and identified connections to previous review papers and other systems thinking literature. During the second cycle of analysis, the research team reexamined the papers and grouped them according to the conceptual framework that most closely aligned with the topic that was emphasized by the authors of the paper (Research Question 2). Finally, one of us (H.H.S.) developed descriptions of the ways in which the conceptual frameworks were operationalized in each paper (Research Question 3), using direct quotes from the papers as illustrative examples throughout.

Trustworthiness for this study was addressed through techniques outlined by Lincoln and Guba (1985). We fostered reflexivity in the study through involving multiple researchers (authors of this paper) with different expertise. This, along with developing an audit trail, establishes confirmability of the study. The lead researcher (H.H.S.) has a background in teaching and learning of Earth Science at both K–12 and postsecondary levels and currently researches models for integration of science and agriculture in a range of educational settings. Prior to conducting the analysis for this study, she developed expertise in systems thinking and approaches to complexity through extensive reading of review papers, historical studies, and philosophical works. The second author (L.H.) is predominantly a qualitative researcher in the field of geoscience education who works with complex Earth systems at the postsecondary level. B.H. has written extensively on student conceptual model development in relation to complex near-surface Earth systems and has a research background in soil science and geoscience education.

We held debriefing sessions following the first cycle and second cycles of qualitative analysis in which we clarified the themes and grouping of papers. We established credibility by employing perspective triangulation and sensitivity to negative cases. One of us (H.H.S.) utilized reference materials during analysis to relate emergent themes to established systems approaches, interrogating the coding of each paper against previous work in order to develop a more robust conceptualization of the theme and minimize error in interpretation of systems ideas present. In assigning papers to the themes, she searched for evidence that the papers might be more consistent with a different theme and/or that the paper did not fit in the assigned theme. This led to modifications of groups and theme descriptions in some cases. We established dependability through explicitly describing our search criteria and methods of analysis here. This is reinforced due to the fact that our data sources, published papers, are available to other researchers who wish to perform an audit of our findings.

RESULTS

Research Question 1. Characteristics of Studies

Characteristics for the papers are presented in Table II, organized by conceptual framework, and summarized here. Out of 27 total papers, 52% ($n = 14$) were case studies, and 48% ($n = 13$) were cohort studies. All of the cohort papers were DBER studies, while 36% ($n = 5$) of the case study papers were DBER studies, with the rest being SoTL studies. No meta-analyses or systematic reviews were identified. The majority of the studies, 59% ($n = 16$), were

TABLE IIa: Summary of characteristics for papers included in systematic review of systems thinking in the context of Earth systems.

Paper	Topic	SoTL/DBER[1]	Grade Level[2]	Evidence Level[3]	Phenomenon Investigated[4]
Earth Systems Perspective					
Davies (2006)	Earth systems	SoTL	u-grad	Case	Course
Hurtt et al. (2006)	Earth systems	SoTL	Upper	Case	Course
Libarkin and Kurdziel (2006)	General	DBER	u-grad	Cohort	Accounts
Libarkin et al. (2005)	General	DBER	u-grad	Cohort	Accounts
Sunderlin (2009)	Earth history	SoTL	u-grad	Case	Module
Earth Systems Thinking Skills					
Agelidou et al. (2001)	Water	DBER	8–9	Cohort	Accounts
Batzri et al. (2015)	General	DBER	u-grad	Cohort	Accounts
Ben-Zvi Assaraf and Orion (2005a)	Water cycle	DBER	8	Cohort	Module
Ben-Zvi Assaraf and Orion (2005b)	Water cycle	DBER	7–9	Cohort	Accounts
Ben-Zvi Assaraf and Orion (2009)	Water cycle	DBER	7–8	Cohort	Module
Ben-Zvi Assaraf and Orion (2010)	Water cycle	DBER	7–12	Cohort	Module
Clark et al. (2009)	Cycles	SoTL	u-grad	Case	Tool
Kali (2003)	Rock cycle	SoTL	7–12	Case	Module
Kali et al. (2003)	Rock cycle	DBER	7–8	Cohort	Tool
Sibley et al. (2007)	Cycles	DBER	Intro	Case	Tool
Complexity Sciences					
Fichter et al. (2010b)	Chaos/complexity	SoTL	u-grad	Case	Module
Haigh (2001)	Gaia	SoTL	u-grad	Case	Course
Haigh (2014)	Gaia	SoTL	u-grad	Case	Course
Hmelo-Silver et al. (2014)	Ecosystem	DBER	7–8	Cohort	Module
Raia (2005)	General	DBER	Upper	Case	Accounts
Raia (2008)	Multiple	DBER	u-grad	Case	Tool
Shepardson et al. (2014)	Climate system	DBER	7	Cohort	Accounts
Authentic Complex Earth and Environmental Systems					
Appel et al. (2014)	Cycles	SoTL	u-grad	Case	Module
Grotzer et al. (2013)	Ecosystem	DBER	7–8	Cohort	Module
Gunckel et al. (2012)	Water	DBER	7–12	Cohort	Accounts
McNeal et al. (2008)	Eutrophication	DBER	u-grad	Case	Module
Sell et al. (2006)	Eutrophication	DBER	Upper	Case	Module

[1]SoTL = scholarship of teaching and learning; DBER = discipline-based education research.
[2]u-grad = general undergraduate/unspecified; Intro = introductory undergraduate; Upper = upper-level undergraduate.
[3]Evidence level based on geoscience education research community claims pyramid (St. John and McNeal, 2015).
[4]accounts = student accounts of a phenomenon (no intervention); tool = effectiveness of a teaching tool or technique; module = effectiveness of a teaching module; course = effectiveness of an entire course.

at the undergraduate level, with the remaining 41% (n = 11) addressing grades 7–12. Finally, the highest frequency phenomenon investigated was the effectiveness of a teaching module (41%, $n = 11$), followed by student accounts of a phenomenon (30%, $n = 8$), effectiveness of an entire course (15%, $n = 4$), and effectiveness of a teaching tool or technique (15%, $n = 4$).

Research Question 2. Conceptual Frameworks

We identified four conceptual frameworks for Earth systems in the literature that addressed systems thinking. They are presented here in order of increasing specificity with respect to systems thinking abilities, ranging from a broad ability to conceptualize Earth as a system to reasoning about a particular complex system. The frameworks, with associated frequencies (Table II), are:

- Earth systems perspective (19% of papers, $n = 5$);
- Earth system thinking skills (37% of papers, $n = 10$);
- complexity sciences (26% of papers, $n = 7$); and
- authentic complex Earth and environmental systems (19% of papers, $n = 5$).

TABLE IIb: Titles of papers included in systematic review of systems thinking in the context of Earth systems.

Author	Paper Title
Earth Systems Perspective	
Davies (2006)	Implementing Earth systems science curriculum: Evaluating the integration of urban environments for an urban audience
Hurtt et al. (2006)	Broadening student horizons: The development, delivery, and assessment of a new course in Earth system science
Libarkin and Kurdziel (2006)	Ontology and the teaching of Earth system science
Libarkin et al. (2005)	Qualitative analysis of college students' ideas about the Earth: Interviews and open-ended questionnaires
Sunderlin (2009)	Integrative mapping of global-scale processes and patterns on "imaginary Earth" continental geometries: A teaching tool in an Earth history course
Earth Systems Thinking Skills	
Agelidou et al. (2001)	Interpreting how third grade junior high school [grades 8 and 9] students represent water
Batzri et al. (2015)	Understanding the Earth systems: Expressions of dynamic and cyclic thinking among university students
Ben-Zvi Assaraf and Orion (2005a)	Development of system thinking skills in the context of Earth system education
Ben-Zvi Assaraf and Orion (2005b)	A study of junior high students' perceptions of the water cycle
Ben-Zvi Assaraf and Orion (2009)	A design based research of an Earth systems based environmental curriculum
Ben-Zvi Assaraf and Orion (2010)	Four case studies, six years later: Developing system thinking skills in junior high school and sustaining them over time
Clark et al. (2009)	A novel approach to teaching and understanding transformations of matter in dynamic Earth systems
Kali (2003)	A virtual journey within the rock cycle: A software kit for the development of systems thinking in the context of Earth's crust
Kali et al. (2003)	Effect of knowledge integration activities on students' perception of Earth's crust as a cyclic system
Sibley et al. (2007)	Box diagrams to assess students' systems thinking about the rock, water, and carbon cycles
Complexity Sciences	
Fichter et al. (2010b)	Expanding evolutionary theory beyond Darwinism with elaborating, self-organizing and fractionating complex evolutionary systems
Haigh (2001)	Constructing Gaia: Using journals to foster reflective learning
Haigh (2014)	Gaia: "Thinking like a planet" as transformative learning
Hmelo-Silver et al. (2014)	Comparing expert and novice understanding of a complex system from the perspective of structures, behaviors, and functions
Raia (2005)	Students' understanding of complex dynamic systems
Raia (2008)	Causality in complex dynamic systems: A challenge in Earth systems science education
Shepardson et al. (2014)	When the atmosphere warms it rains and ice melts: Seventh grade students' conceptions of a climate system
Authentic Complex Earth and Environmental Systems	
Appel et al. (2014)	Effect of a soil microbial activity laboratory on student learning
Grotzer et al. (2013)	Learning to reason about ecosystems dynamics over time: The challenges of an event-based causal focus
Gunckel et al. (2012)	A learning progression for water in socio-ecological systems
McNeal et al. (2008)	The effect of using inquiry and multiple representations on introductory geology students' conceptual model development of coastal eutrophication
Sell et al. (2006)	Supporting student conceptual model development of complex Earth systems through the use of multiple representations and inquiry

Earth Systems Perspective

Papers in this group cite the shift in Earth Science toward recognizing that interactions between the Earth systems are important to emphasize. Systems thinking abilities articulated in this group are limited to conceptualizing the Earth system as a whole and understanding interconnections between Earth's spheres, but specific systems concepts (e.g., boundaries, flux, system behavior) are not discussed. Studies often include human interactions and environmental decision making, such as this course revision goal stated by Davies (2006, 365): "provide students the scientific knowledge base to empower their decision making regarding the interconnection of Earth's physical systems and human activities."

Earth Systems Thinking Skills

This group of papers has strong connections to Ben-Zvi Assaraf and Orion's (2005a) conception of systems thinking skills for Earth system education and emphasizes cyclic and dynamic thinking in the context of transformation of matter in Earth cycles (e.g., water cycle). Papers in this framework investigated specific systems thinking abilities (or a subset) as they are articulated in the STH, though not all papers explicitly cited Ben-Zvi Assaraf and Orion (2005a). Some papers also added additional components to their framing of systems. Batzri et al. (2015) expanded the conception of dynamic thinking to more explicitly include identifying feedback loops. Agelidou et al. (2001) also included feedbacks and levels in their study. Clark et al. (2009) also considered student learning of the underlying causes of processes (e.g., heat driving evaporation of water). While these papers contain some ideas consistent with complex systems, the emphasis is on STH abilities, and/or they do not approach complexity from a specific tradition.

Papers in this framework also commonly cite affiliations with the Earth system science movement (Mayer, 1991) and environmental education. For example, Ben-Zvi Assaraf and Orion (2005a, 519) stated "the main goals of the schools' science education should be to provide students with the skills needed to translate environmental problems, such as water pollution, into a more coherent understanding of the environment." While this framework is related to the Earth systems perspective in this emphasis on interconnected Earth systems, it is distinguished by the inclusion of specific systems thinking abilities as articulated in the STH.

Complexity Sciences

The papers in this framework are grounded in specific theoretical and scientific traditions in the study of complex systems. Systems thinking abilities draw directly from these traditions, literature in these areas is frequently cited, and authors emphasize complexity science ideas in their research and interventions. There is a high degree of variability in the specific ways in which systems thinking is framed in the papers in this group, reflecting the current landscape of the complexity sciences (Castellani and Hafferty, 2009). For this reason, we discuss each tradition separately as subthemes.

System dynamics

Shepardson et al. (2014), the sole paper in this group, take a system dynamics perspective, citing this literature in their framing of climate change. They stated that "understanding climate change is further complicated by a climate system that functions with time lags, buffers, stock and flow structures, multiple feedback processes, and nonlinear relationships between components (Sterman and Booth Sweeney 2002)" (Shepardson et al., 2014, 337). They also use system dynamics terminology to articulate systems thinking abilities, such as student ability to "identify the stock and flow relationships" and "recognize delays in the feedback process and its impact" (337).

Complex systems theory

Papers in this group rely on foundational ideas from complex systems theory such as emergence, downward causation, feedbacks, and self-organization. They may also include mathematical approaches to investigating nonlinear phenomena, such as chaos theory in the case of Fichter et al. (2010b). Systems thinking abilities are framed in terms of student understanding of these concepts, and citiations include prominent authors in the development of systems ideas, such as von Bertalanffy (a founding member of the general systems community) in this excerpt from Raia's (2005, 297) paper: "a system approach focuses on the arrangement of and relations among the parts, which connect them into a whole (von Bertalanffy, 1968)." Fichter et al. (2010b) aim to build student understanding of (1) universality principles of chaos theory, (2) principles of elaborating complex evolutionary systems, and (3) principles of self-organizing complex evolutionary systems.

Gaia theory

Gaia theory, which relies heavily on complex systems ideas (such as feedbacks, chaos, and self-organized criticality), is the basis for the two papers by Haigh (2001, 2014) that make up this group. Student learning outcomes are explicitly related to understanding of Gaia theory, and Haigh cites prominent proponents of Gaia theory, as exemplified by this excerpt: "theory of the Earth that seeks to explain environmental conditions in terms of biological regulation and biological forcing (Lovelock, 1979, 2000)....Gaia has been called 'symbiosis seen from space' (Margulis, 1998)" (Haigh, 2001, 168).

Structure–behavior–function analysis

Hmelo-Silver et al. (2014), the sole paper in this group, uses the structure–behavior–function (SBF) approach in framing analysis of systems. SBF was originally developed in the context of supporting reasoning about complex engineered devices (such as an automobile power train; Weld, 1983) and was adapted for use in education (Hmelo-Silver and Pfeffer, 2004). This approach is used to frame student systems thinking in terms of "thinking about how a system works and what its functions are rather than thinking largely about components" (Hmelo-Silver et al., 2014, 407).

Authentic Complex Earth and Environmental Systems

Papers in this framework draw their systems ideas from the scientific study of environmental or ecological systems with clear connections to human activities and environmental decision making. They are grounded in different systems perspectives, but each paper utilizes models or tools that mimic how experts study the system. For example, Grotzer et al. (2013, 291) discuss the idea that the "expert stance attends to the event as important information and contextualizes it within a broader context that includes proximal and distal causes." Most papers include elements of formal complexity, but the systems thinking emphasis is on student model-based reasoning about a particular real-world environmental system or phenomenon that transcends a singular Earth system, cycle, or process (Herbert, 2006). A key characteristic of this framework is the highly contextual nature of systems thinking abilities; the emphasis is on learning to reason about a particular system, not on developing transferable systems thinking skills.

Research Question 3. Operationalization of Conceptual Frameworks

In this section, we describe how each framework is used in the papers (Table II) to frame research studies (DBER) and interventions (SoTL). For DBER papers, we provide examples of research tools (prompts, tasks, interview questions, etc.) to illustrate the way that the systems ideas inherent in the framework were employed in data collection and summarize key findings related to student systems thinking abilities. For SoTL papers, we describe how educational interventions (teaching tools, modules, courses, etc.) aim to support the development of student systems thinking abilities from the perspective of their respective framework.

Earth Systems Perspective

Libarkin et al. (2005) and Libarkin and Kurdziel (2006), in a related pair of DBER cohort studies, documented how undergraduate students categorize geologic phenomena (i.e., assign them to ontological categories) as a step towards supporting Earth systems science education. The model for ontological categories used to code interview data includes four levels: matter, transformation, process, and systems. In this model, "systems are made up of interacting Processes" (Libarkin and Kurdziel, 2006, 410). Significantly, no participants in either study were found to hold a systems-level ontology, which suggests that "that students may not be ready for [Earth System Science] instruction at the start of an introductory course" (Libarkin and Kurdziel, 2006, 412).

The remaining three papers in this group were SoTL case studies at the undergraduate course or major project level in which the Earth systems perspective was evident in the course or project learning objectives. Sunderlin (2009) describes an integrative mapping capstone project for an Earth history course in which students predict patterns on an "imaginary Earth" given synthetic data sets. Sunderlin (2009, 73) claims that the project "integrates Earth system patterns and processes...with the developing spatiotemporal intuition of students." Hurtt et al. (2006) and Davies (2006) both describe development of Earth systems courses. Davies' (2006) course uses urban place-based education, active learning classroom strategies, and academic service learning in order to incorporate human connections with Earth systems and support student learning of "systems oriented processes" (365). Hurtt et al. (2006)'s course supports student ability to "Analyze the causes of change in the Earth System over varied temporal and spatial scales" and "Build simple models of key Earth System interactions; apply this knowledge to key scientific questions in Earth System Science" (331). This is accomplished in an inquiry-based environment in which students engage with primary literature, computer modeling laboratory activities, visiting scientists, and interdisciplinary research projects (Hurtt et al., 2006).

Earth Systems Thinking Skills Framework

Three DBER papers in this group investigated student accounts (e.g., representations, perceptions, etc.) related to Earth systems. Ben-Zvi Assaraf and Orion (2005b) and Agelidou et al. (2001) investigated junior high school (grade 7–9) student perceptions about water, and Batzri et al. (2015) examined how undergraduate students expressed dynamic and cyclic thinking. The research tools used in these studies were intended to elicit STH-related knowledge and abilities and included analysis of drawings of the water cycle (Ben-Zvi Assaraf and Orion, 2005b) and questionnaires to identify abilities related to constructs such as the "dynamic nature of the groundwater system" (Ben-Zvi Assaraf and Orion, 2005b, 367), causal relationships within the water cycle (Agelidou et al., 2001), and dynamic and cyclic thinking (Batzri et al., 2015). In general, it was found that junior high students lacked a systems view of the water cycle that included the cyclic and dynamic nature of the system (Agelidou et al., 2001; Ben-Zvi Assaraf and Orion, 2005b) and that geology undergraduate students displayed more sophisticated cyclic and dynamic thinking about Earth systems when compared to their peers (Batzri et al., 2015). Interestingly, Batzri et al. (2015, 774) also found that geology students did not explicitly discuss feedback mechanisms, and they acknowledged that this "may be the result of limitations in our research tool."

Five DBER studies in this framework investigated student ability to demonstrate systems thinking hierarchic abilities in relation to a particular intervention (module or tool) aimed at a particular Earth cycle or system (or set of cycles). For example, Ben-Zvi Assaraf and Orion (2009, 49) reported on an intervention that "promotes students' conceptualization of the water cycle as a dynamic, cyclic system." Descriptions of Earth systems content in the interventions placed an emphasis on identification of components, processes, and relationships in a system as lower-level systems thinking skills for the Earth systems context. Research tools for the studies in this group varied and were specific to the intervention, but they were designed to elicit student STH abilities in order to understand the role of the intervention in developing these abilities. In the case of Ben-Zvi Assaraf and Orion (2005a), they used a suite of 10 different research tools in order to characterize the entire suite of STH abilities. Characteristics of curricular units that were shown to be effective in improving student systems thinking abilities as articulated in this framework include knowledge integration activities (Kali et al., 2003; Ben-Zvi Assaraf and Orion, 2005a, 2010), scientific inquiry (Ben-Zvi Assaraf and Orion, 2005a, 2009, 2010), and outdoor learning (Ben-Zvi Assaraf and Orion, 2005a, 2009, 2010). Additionally, Sibley et al. (2007) employed box diagrams to elicit student ideas about transformation of matter in Earth cycles and found that students were challenged when it came to identifying hidden components of the system; this impeded their ability to appropriately construct box diagrams of systems that involved chemical components.

There were two SoTL papers in this group. Kali (2003, 165) described a game in which students could take a "virtual journey" through the rock cycle in order to develop a more robust "dynamic and cyclic understanding of the earth's crust system." Clark et al. (2009, 233) introduceda teaching tool, called Cause-MaP, that aids students in describing and diagramming transformations of matter in Earth systems to support learning goals related to systems thinking and "the underlying causes for the dynamic nature of systems."

Complexity Sciences Framework

System dynamics

Shepardson et al.'s (2014) DBER study of 7th grade students' accounts of the climate system framed the prompts to which students responded in terms of fundamental system dynamics concepts. For example, "the first prompt required students to explain how the components of the climate system influence climate" (Shepardson et al., 2014, 339). This prompt emphasizes the behavior of the system as a whole by asking students about the relationship between components and the system output (climate). Their key findings were that students hold linear cause and effect ideas about the climate system and its components.

Complex systems theory

There were two related DBER papers in this group by the same author. In the first study, Raia (2005) elicited information about how students approach complex dynamic systems through a survey. She identified a linear monocausal approach as most common with the undergraduate participants in the study. In the second study, students responded to interview questions that "address processes of non-linear interactions, emergence, adaptation, and self-organization" (Raia, 2008, 85). Students were then exposed to the idea that there are different forms of causality: efficient (e.g., cause-and-effect relationship), material (how properties of materials influence a system's evolution), formal (pattern or structure), and functional (e.g., maintaining system stability). Interviews were coded based on these causality principles to investigate the effect of the intervention, and results demonstrated that the intervention helped students move towards a complex dynamic systems approach (Raia, 2008).

In their SoTL paper, Fichter et al. (2010b) described a series of modules for undergraduate students in which learning activities utilized mathematical representations and computer simulations to build conceptual understanding of complex systems concepts. For example, positive and negative feedbacks were introduced through examining the logistic system because "this is a concept that students, when thrown into a natural complex system with many feedbacks operating, may have trouble grasping. The logistic system being so simple makes the influence of positive and negative feedback transparent" (Fichter et al., 2010b, 70). Similarly, a boids (bird-like objects) program that "demonstrate[s] that the flocking behavior of birds [can] be explained by the action of simple rules being followed by each boid" was used to help students learn that "self-organization arises spontaneously without design, or purpose, or teleological mechanisms" (Fichter et al., 2010b, 79).

Gaia theory

Haigh (2001, 2014), in two SoTL papers, described the use of learning journals to support student learning in an undergraduate geography course based on Gaia theory. This theory was the central topic for the course, and it was framed as a transformative learning experience to help students confront their preconceived notions about Earth and the place of humans within the Earth system (Haigh, 2014).

Structure–behavior–function analysis

A DBER study presented by Hmelo-Silver et al. (2014) applied the SBF approach to supporting 7th and 8th grade students' reasoning about aquatic ecosystems through a technology-based intervention with a hypermedia component. Agent-based modeling simulations made "behaviors visible" and allowed students to manipulate the system (Hmelo-Silver et al., 2014, 407). Research tools for this study included a pre- and posttest in which students were asked to draw and indicate relationships between components, answer open-ended questions, and solve problems related to the system. Student responses were coded based on a scheme specifically related to SBF analysis of aquatic ecosystems. Consistent with this approach, findings were reported in these terms, stating that "students were able to adopt the SBF conceptual framework as a language to express complex notions about ecosystems" (Hmelo-Silver et al., 2014, 412).

Authentic Complex Earth and Environmental Systems

Each paper (or set of related papers) is discussed separately here due to the variability that arises because these studies were investigating student reasoning about a particular real-world system.

Coastal eutrophication

Sell et al. (2006) and McNeal et al. (2008) developed and investigated an intervention for undergraduate students about coastal eutrophication. The intervention and research in these DBER studies were framed in terms of supporting and investigating "student conceptual model development of eutrophication" (McNeal et al., 2008, 202) through the use of inquiry activities and multiple representations (including physical and technology-supported) of the phenomena. Student work completed throughout the intervention was evaluated using rubrics based on real-world scientific skills (Sell et al., 2006), with the addition of analysis of student drawings using a rubric that included "understanding of system processes" in the second study (McNeal et al., 2008). These approaches were found to be more effective than traditional workbook-style laboratory teaching techniques (Sell et al., 2006; McNeal et al., 2008).

Ecosystem dynamics

Grotzer et al. (2013) described a DBER study of a technology-based intervention for middle school students that was designed to help them reason about ecosystem dynamics in a way that would be more consistent with experts. The virtual environment used by Grotzer et al. (2013), EcoMUVE, was set up to support student learning related to a nonequilibrium view of ecology. EcoMUVE allows students to "walk" around a golf course area, make observations, and collect data in a pond as a scientist would. Students are not given the problem, "they must discern the problem themselves" as it unfolds in the virtual environment with subtle changes and an "attention-grabbing" fish kill event (Grotzer et al., 2013, 291). Research questions addressed movement away from an event-based to process-based focus for causality in the ecosystem, and open-ended assessments were coded using this causality framework. Grotzer et al. (2013, 295) found that the intervention had positive effects on students use of evidence and "focus on the broader processes and patterns in the pond ecosystem."

Water in socioecological systems

Gunckel et al. (2012) conducted a DBER study in order to identify a learning progression for water in socioecological systems that accounted for the "connected nature of human

TABLE III: Potential strengths and limitations of conceptual frameworks for systems thinking in the context of Earth systems.

Conceptual Framework	Strengths	Limitations	Key References
Earth systems perspective	• Widely used in education • Supported by policy documents (Next Generation Science Standards, literacy documents)	• Systems thinking not well defined • Lack of DBER studies on interventions	Mayer (1991); Ireton et al. (1997); Manduca and Kastens (2012)
Earth system thinking skills	• Consistent with common ways of organizing Earth science ideas (cycles of matter) • Clearly defined systems thinking skills for Earth Science context • Robust GER body of work	• Feedbacks rarely included • Emphasis on starting with parts and their connections; may lose sight of systems-level behavior and function • Connections to research traditions in multiple systems science	Mayer (1991); Orion and Libarkin (2014)
Complexity sciences	• Complex systems concepts formally described • Connections to other disciplines • Emphasis on systems level • Can be visualized with computational models	• Difficult concepts • Mathematics preparation required • Not commonly addressed in education • Challenges current student ontologies	System dynamics: Booth Sweeney and Sterman (2007); complexity science: Jacobson and Wilensky (2006)
Authentic complex Earth and environmental systems	• Authentic, real-world systems • Ties to environmental science community • Supports environmental decision making	• Difficult to reduce to simple models • Variety of systems concepts employed • Focus on context may limit transfer of systems concepts	Near-surface Earth systems: Herbert (2006); socioecological framework: Gallopín (1991)

socio-economic and environmental systems" (Gunckel et al., 2012, 847). Their model was based on a real-world framework, the Loop Diagram from the Long Term Ecological Research Network (Long Term Ecological Research Planning Committee, 2007), which was employed in the design of this study.

Assessment items used in this study were designed to elicit student knowledge and reasoning abilities in relation to the water cycle as viewed in the context of this framework. The upper anchor of the learning progression presented by Gunckel et al. (2012) emphasized an accurate, scientific, model-based understanding of these systems that could be used for environmental decision making.

Soil microbial activity

In their SoTL paper, Appel et al. (2014) described an undergraduate laboratory activity that engages students in the practices of soil scientists, including hypothesis generation and testing through data collection. In this exercise, students collect data that allow them to assess soil microbial activity in multiple situations, allowing for comparison of different soil treatments. This paper did not refer to elements of formal complexity, but it did emphasize the relevance of the real-world subject matter, stating "nitrogen cycling plays a large role in soil fertility and environmental quality (Vitousek et al., 2009). Therefore, it is crucial that ... students be exposed to and begins [sic] to understand the role soil microbes play in organic matter and nitrogen cycling" (Appel et al., 2014, 129).

DISCUSSION

We identified four conceptual frameworks in this study:

- Earth systems perspective: This framework emphasizes high-level interconnections among major Earth spheres (bio-, hydro-, lithosphere, etc.) and systems thinking abilities related to conceptualizing the Earth system as a whole and identifying connections between the spheres.
- Earth system thinking skills: This framework emphasizes transformation of matter in Earth cycles (e.g., water cycle) and systems thinking abilities related to identifying and organizing system components, processes, and relationships and dynamic and cyclic thinking.
- Complexity sciences: This framework emphasizes the scientific study of complex systems and systems thinking abilities related to recognizing complex system characteristics such as feedbacks, emergence, and self-organization.
- Authentic complex Earth and environmental systems: This framework emphasizes knowledge of a specific complex near-surface Earth system (e.g., a lake) or phenomenon (e.g., coastal eutrophication) and systems thinking abilities related to reasoning about the specific system or phenomenon.

Each framework has potential strengths and limitations that can inform how and when to use them in designing research and instruction in the Earth Sciences (Table III). In this discussion, we provide additional insights into the four conceptual frameworks by relating the frameworks to key systems thinking challenges and identifying cognitive science and educational research in other areas that can inform future work. Next, we illustrate how, when applied to the same topic, the frameworks can lead to different student learning outcomes and instructional design decisions.

Relating the Frameworks to Systems Thinking Challenges

Nature and Function of the System

Systems in the geosciences can be either complicated systems or display complex systems characteristics, and this distinction has important implications for learning to reason about systems (Stillings, 2012). Additionally, Meadows (2008, 16) provided this insight: "The least obvious part of the system, its function or purpose, is often the most crucial determinant of the system's behavior." In the complexity sciences framework, the function of the system and its overall behavior are central considerations. For example, Shepardson et al. (2014) made a step in this direction by framing student understanding of the climate system in terms of how components, events, and processes affect the behavior of the system (climate); this approach elicits ideas about the system as a whole from the beginning. In complex systems theory, the nature of the system becomes even more important due to the fact that the behavior of the system emerges from simple interactions at lower levels in nonobvious ways (Mitchell, 2009). These types of systems are irreducible; the whole is truly more than the sum of its parts.

In contrast, the Earth systems thinking skills framework tends to focus on complicated systems that are not formally complex (primarily cycling of matter in closed systems). This presents some nontrivial challenges for educators. If we emphasize recognizing cycle components, processes, and their interactions, eventually building into the concept of an integrated system, how do we ensure that students are thinking about the system holistically? Also, as Stillings (2012) articulated, how do we help students shift from thinking about complicated cycles to complex systems with feedbacks and emergent behavior? We suggest that a more effective approach may be to teach students that there are different types of systems that function differently. Moreover, within the landscape of the complexity sciences, there are different approaches to studying complex systems that students can learn about (Castellani, 2013). Booth Sweeney and Sterman (2007) provided important insights from research into systems thinking abilities from a system dynamics perspective, such as a frequently displayed (33% of students and 77% of teachers in their study) ability to recognize that different dynamic systems have similar underlying structures. Goldstone and Wilensky (2008) demonstrated that students can develop generalizable ideas about formally complex systems to promote transfer to novel scientific contexts. These types of studies can inform teaching and learning of complex Earth systems by providing strategies for developing student learning of fundamental ideas about the nature of complex systems (see also Booth Sweeney and Meadows, 2010). Important systems thinking components might be the ability to recognize the nature of the system and its function and compare the current system to previous systems they have encountered; instruction about a system should include explaining the type of system it is.

Cycles Versus Feedbacks

Feedbacks feature prominently in recent reviews of complex systems in Earth Sciences (Manduca and Kastens, 2012; Stillings, 2012) as an important consideration in developing conceptual understanding about Earth systems. Few papers in this study, however, explicitly discussed feedbacks in the context of research or interventions. Notable exceptions are Fichter et al. (2010b), who addressed feedbacks as an integregal component of complex systems theory, and Batzri et al. (2015), who framed their study within the Earth systems thinking skills framework and acknowledged that their research instrument may not have addressed this component of systems. Stillings (2012), in his review paper, used the example of the water cycle to describe how development of learning progressions can support students in developing an understanding of feedbacks in Earth systems. Booth Sweeney and Sterman (2007, 305), however, provided an important caution when considering scaffolding feedback ideas by starting with cycles, stating: "The term 'cycle' as used in school texts often means a closed loop of material or energy flow, as in the hydrological, carbon, or Krebs cycles, obscuring the notion of closed information feedback loops." This distinction between the flow of matter or energy (cycles) as used in the Earth systems thinking skills framework and the flow of information (feedback) in dynamic systems as used in the complexity science framework requires a different conception of mechanisms within the system (Stillings, 2012). The system goes from one of simple inflow and outflow to a system capable of internal regulation (balancing) or runaway behavior (reinforcing) where the overall behavior of the system becomes less predictable (less like "clockwork") and more likely to exhibit sensitive dependence on initial conditions (Meadows, 2008). These are important considerations in choosing the framework in which to design an intervention or research study, and we posit that it would be unlikely for students to predict complex systems characteristics such as feedback loops without first being introduced to the idea that systems can exhibit complex and unpredictable behavior.

Causality

Raia (2012, 117) asserted that "the geosciences are in the midst of a paradigm shift from a reductionist/mechanistic to complexity science," and Stillings (2012) identified the counterintuitive nature of causality in complex systems as a major systems thinking challenge for students to overcome. Raia's (2005, 2008) work (in the complexity sciences framework) establishing that students hold a linear monocausal conception of causality highlights a fundamental challenge in teaching about complex systems. It can be argued that "dynamic" and "cyclic" thinking, as operationalized in the Earth systems thinking skills framework, works within such a mechanistic paradigm. As discussed above, a typical representation of the water cycle is as a closed system operating under equilibrium conditions. This can be modeled in terms of reservoirs and fluxes with a series of linear cause-and-effect relationships that eventually make a closed loop. The underlying causes of movements and phase transitions in this type of system can be considered individually. In contrast, the emergent behavior modeled by Fitcher et al. (2010b) is a result of relatively simple interactions between individual components and cannot be predicted by considering causes at this level. Due to these, and other, characteristics, reasoning about causality in complex systems is unlikely to arise naturally and requires explicit reflection on modes of causality (Grotzer and Solis, 2015). Techniques to support students in developing alternatives to a linear causal (mechanistic) approach to scientific inquiry by approaching instruction from a complexity sciences framework have significant potential (Raia, 2012) and need to be more fully developed within the Earth Sciences. Grotzer and Solis (2015) provided a recent review of the cognitive science literature related to how people reason about complex causality, which could inform this work.

Human–Earth Interactions

Human interactions with Earth systems are an emerging area for research and teaching in the geosciences (Manduca and Kastens, 2012; InTeGrate Program, 2015b) and warrant consideration in conceptualizations of systems thinking. Considering humans as an integral component of the system (as opposed to an external actor) was also a key idea in early conceptions of systems thinking (Hammond, 2003). This presents a challenge for geoscience educators in that it requires a shift from only teaching natural systems (where graduate training typically focuses) to considering the roles played by humans as part of the Earth system. Papers in both the Earth systems thinking skills and the Earth systems perspective frameworks call out connections between humans (anthroposphere) and other Earth systems as important, but what this relationship looks like is not formalized in these frameworks. Complexity sciences have been used to understand human systems in sociology (Castellani and Hafferty, 2009) and relationships in coupled human–natural systems (Liu et al., 2007), but none of the complexity sciences framework papers in this study formally included a human component, with the exception of Gaia theory (Haigh, 2001, 2014).

Orion and Ault (2007, 657) argued that there is "no clear or useful demarcation between learning earth sciences and learning environmental sciences"; Orion and Libarkin (2014) reiterated this idea and proposed collaboration with the environmental education research community. The applied Earth and environmental systems framework could serve as an entry point to such collaboration. The way in which Gunckel et al. (2012) framed water in terms of a socio-ecological system provides a model for how to formally account for humans in Earth systems. Learning progressions have also been developed for carbon cycling (Mohan et al., 2009) and energy (Jin and Anderson, 2012) in socioecological systems; the model has been used elsewhere in the environmental education community to link local and global processes (Gallopín, 1991) and as a context for framing resilience (Krasny, 2009; Krasny and Roth, 2010).

Implications for Instructional Design: An Example Case

Systems thinking and student learning about complex systems are important goals for Earth Science education in that they support student ability to engage in reasoning and decision making about Earth systems. As we have shown, there is a wide range of conceptualizations of what systems thinking abilities look like, and there are strengths and limitations to each of the frameworks identified in this study (Table III). In this section, we provide an example of how these different frameworks can influence instructional design decisions and lead to different student learning outcomes. To do this, we examine a portion of *A Growing Concern: Sustaining Soil Resources Through Local Decision Making*, an introductory undergraduate teaching module (Fortner et al., 2014a) developed through the InTeGrate project (InTeGrate Program, 2015a). This module was chosen as a case study because systems thinking is a required component of InTeGrate modules (InTeGrate Program, 2015b), and the context of agricultural systems lends itself to the consideration of systems thinking. The full module is available online, and development and evaluation of the module were presented by Fortner et al. (2016). *Unit 5: Predicting the Effects of Climate Change on Soil Loss* (Fortner et al., 2014b), developed by the first author of this paper (H.H.S.), supports the overarching module learning goal of "Predict, using systems thinking, agricultural challenges that might result from climate change" and the following unit learning goals:

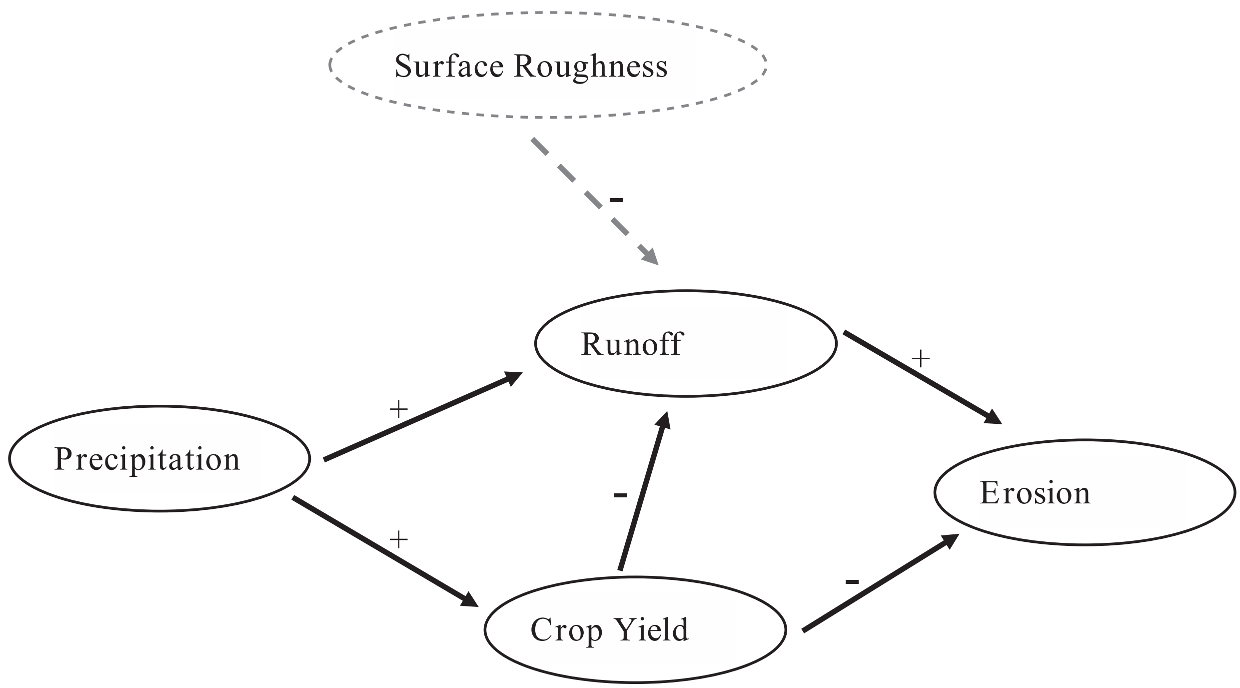
1. Explain how rainfall and runoff erosivity, soil properties, landscape characteristics, and agricultural practices contribute to soil erosion.
2. Differentiate between natural and human influences on soil sustainability.
3. Analyze, using systems thinking, how changes in precipitation predicted in climate change models for their region will impact erosion rates.

In this unit, students are presented with scientifically accurate models from the literature and are introduced to how to interpret a schematic diagram of relationships in a system. The summative follow-up homework assignment for this unit is presented in Fig. 1 as an illustrative example. In this assignment, students are asked to use information from the in-class portion of the unit to expand the model (Questions A and B), interpret the model (Question C), and use the model to step back and make predictions about interactions among the atmosphere, biosphere, hydrosphere, and geosphere (Question D). Following the backwards design approach in which learning goals drive the activities (Wiggins and McTighe, 2005), we recast the learning goals here through the lens of each framework and provide examples of how the homework assignment, unit, or module could be modified to be more consistent with those learning goals.

Earth Systems Perspective

This framework deals with systems thinking at the level of a course or larger assignment. Thus, we consider the overarching module goal: "Predict, using systems thinking, agricultural challenges that might result from climate change." If this module were recast in the Earth systems perspective framework, the learning goal would emphasize higher-level connections between Earth systems as opposed to the implications of a specific interaction. The module goal might become: "Explain how perturbations in the climate system (atmosphere) could impact agricultural sustainability by producing changes in the geosphere, hydrosphere, and biosphere." This is similar to Question D in the Unit 5 homework assignment, but it is now elevated to the level of a module learning goal. The homework assignment could be modified to support this better by emphasizing the Earth systems early in the introductory paragraph, framing the problem of soil conservation as an interdisciplinary one that

Soil conservation (reducing soil loss due to erosion) is a crucial aspect of agricultural sustainability. There are many different things that can contribute to soil erosion in agricultural areas. Below is a schematic diagram of primary pathways whereby changes in precipitation may impact runoff and erosion (modified from Pruski and Nearing, 2002).



Climate change impacts on soil erosion

A. List three components that you think are most likely to be influenced by climate change in your region.

B. Add the three components you listed above to the diagram, using arrows and +/- signs to indicate relationships between the components and precipitation, runoff, crop yield and/or erosion. *Surface roughness, which has a negative relationship with runoff, is provided as an example.*

C. Use the diagram to explain the relationship between one of your components and soil erosion. Write a complete sentence that describes the relationships between causes and effects. *Ex. If surface roughness increases, this will cause a decrease in runoff and, therefore, a decrease in erosion.*

D. Based on the pathway you described in Part c, describe how perturbations in the climate system (atmosphere) can impact the geosphere, hydrosphere, and/or biosphere.

FIGURE 1: Example of a homework assignment from Unit 5 follow-up homework in *A Growing Concern: Sustaining Soil Resources Through Local Decision Making* (Fortner et al., 2014b).

involves multiple Earth systems. Additionally, throughout the assignment, the idea that these processes are components of different Earth systems needs to be reinforced (e.g., for each question, in addition to the given task, also ask students to identify the Earth system to which the components belong). Instructional modules such as this may support systems thinking as articulated in the Earth systems perspective framework through defining an appropriate overarching goal and by moving back and forth between contextual examples and global-scale interactions among the spheres.

Earth Systems Thinking Skills

A fundamental difference between how Unit 5 is framed and the way that the STH abilities are used in this framework lies in the fact that agricultural systems are open systems in which matter and energy do not cycle within the boundaries of the system. As written, the lower-level abilities of identifying components, processes, and relationships within the system and organizing these within a conceptual framework are supported by learning goals 1 and 2 for Unit 5, but they are not explicitly stated. Additionally, the third learning goal supports reasoning about the system by employing prediction. In order to fully support the STH abilities, a separate learning goal that addresses cyclic thinking and the "hidden dimensions" of the system would need to be added that links out to appropriate cycles of matter and energy, such as: "Identify physical and biochemical cycles that influence agricultural systems." In Unit 5, this could rely on student prior knowledge of these cycles (e.g., hydrologic, carbon, nitrogen), or it would need to be significantly expanded to include teaching about these cycles. If they do have sufficient prior knowledge, the homework assignment could be modified to include a question that prompts students to consider the role of these cycles, such as: "This model of soil erosion emphasizes relationships in a local agricultural system. Many of the processes that occur within this system are governed by cycles that operate on a larger scale. For example, precipitation and runoff are part of the water cycle. Can you think of any other physical or biochemical cycles that are represented in an agricultural system?" Additionally, STH abilities would be better supported by affording students the opportunity to practice identifying components and processes in an agricultural system as opposed to giving them the diagram, as is the case in this assignment.

Complexity Sciences

As written, students do not develop systems ideas related to formal complexity in this module. The first consideration in aligning it with the complexity science framework would be whether or not the system is actually complex and, if so, determining the theoretical or scientific tradition with which it aligns. In this case, Liu et al. (2007) studied agricultural systems, a type of coupled human–natural system, from a system dynamics perspective and found that they do exhibit characteristics of complex systems, such as feedbacks, thresholds, time lags, and resilience. Thus, it would be appropriate to reframe Unit 5's learning goals in terms of these system dynamics concepts. For example, learning goal 1 could become: "Describe potential positive and negative feedbacks in models of soil erosion." Learning goal 2 could become: "Explain how soil conservation practices could contribute to resilience in an agricultural system." Within the scope of this unit, these ideas could be supported by engaging in activities that promote understanding of these general concepts (for engaging exercises that can be used in any context, see Booth Sweeny and Meadows, 2010) and interpreting stock-and-flow diagrams. The final question (Question D) in the homework assignment could then be replaced with a question that asks students to apply these system dynamics concepts by giving them a skeletal stock-and-flow diagram of soil in an agricultural system and having them locate potential feedback mechanisms and places where conservation practices could affect the system. These early attempts would likely need to be revisited during an in-class discussion during the next class period to continue developing the students' ability to apply and recognize these ideas. These types of changes would allow for students to make more sophisticated predictions and recommendations for agricultural practices, but they may be challenging for an introductory-level class without adequate scaffolding.

Authentic Complex Earth and Environmental Systems

The learning goals for Unit 5 as it was written most closely align with the authentic complex Earth and environmental systems framework because it is focused on a particular type of system, agriculture, and grounded in real-world environmental challenges related to soil sustainability. Learning activities in this unit support these learning goals by engaging students in investigating scientifically authentic models of the system. For example, the model provided in the homework assignment is from a scientific research study of soil erosion in agricultural systems that utilized climate models and field data. Throughout the unit, students are supported in thinking about specific components of the system and their interactions (learning goal 1). They explicitly consider how humans influence soil sustainability (learning goal 2), which is unavoidable in coupled human–natural systems such as agriculture, and they use the model of the system to make predictions (learning goal 3). Consistent with this framework, systems concepts are highly contextualized in the homework assignment for this unit, with the exception of Question D in the follow-up homework (Fig. 1).

CONCLUSION

In this paper, we systematically surveyed the landscape of geoscience education research for insights into the ways in which DBER and SoTL researchers frame their research and instruction in Earth systems and systems thinking. The four conceptual frameworks identified in this study provide a step forward in developing an epistemological framework in which to guide Earth systems science instruction. Our findings echo the concept map of Manduca and Kastens (2012) showing "the domain of thinking and learning about complex Earth systems" and extend this work by identifying specific ways that these ideas are employed in geoscience education research. Additionally, our work allows instructors to connect more explicitly with the ways in which scientists think about Earth systems and complex systems. The frameworks provide future researchers a way to operationalize teaching and learning about Earth systems in a way that allows comparison with previous findings in a more systematic way. It also allows researchers and instructors to more easily connect with cognitive science and education research literature related to systems thinking and complex systems.

Our findings suggest that instruction designed within different conceptual frameworks will lead to students developing different mental models of complex Earth systems. Thus, student model-based reasoning and environmental problem-solving approaches would be influenced by the conceptualization of complex Earth systems that they hold. We explore this further in our companion paper, ''Student learning of complex Earth systems: A model to guide development of student expertise in problem solving'' (Holder et al., this volume).

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