Integrated Interdisciplinary Science of the Critical Zone as a Foundational Curriculum for Addressing Issues of Environmental Sustainability

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ABSTRACT

Earth's critical zone (CZ) is the uppermost layer of Earth's continents, which supports ecosystems and humans alike. CZ science aims to understand how interactions among rock, soil, water, air, and terrestrial organisms influence Earth as a habitable system. Thus, CZ science provides the framework for a holistic-systems approach to teaching Earth surface and environmental science, especially related to environmental sustainability. Here, we describe efforts by an interdisciplinary team to create a full-semester, university curriculum that introduces upper-division students to CZ science. Course topics include a background in CZ science, key concepts and methods of CZ science, and units on land–atmosphere interactions, water budgets, landscape evolution, and biogeochemistry. The course culminates with a unit on human interactions within the CZ. Through interactive activities that use data sets from U.S. CZ observatories, the course emphasizes how a CZ framework is appropriate for teaching concepts across scientific disciplines, concepts of environmental sustainability, and the usefulness of CZ science for considering humanity's grand challenges. Materials can be integrated into existing courses or used as an independent course to maximize instructor flexibility; all materials were piloted in eight separate courses across a range of university settings. Although preassessments and postassessments of geoscience literacy did not show much change, students overwhelmingly agreed that they could use what they learned to help society overcome grand challenges. Thus, the holistic-systems approach advocated by CZ science and explored throughout this curriculum provides a unique opportunity to engage students in thinking about complex issues related to environmental sustainability. © *2017 National Association of Geoscience Teachers*. [DOI: 10.5408/16-171.1]

Key words: interdisciplinary science, critical zone, undergraduate education, environmental sustainability

INTRODUCTION

This article describes the development of a course through the Science Education Resource Center (SERC) at Carleton College (Northfield, MN) and their National Science Foundation (NSF)–funded Interdisciplinary Teaching about Earth for a Sustainable Future (InTeGrate) program. The semester-long, undergraduate-level course is aimed at introducing the interdisciplinary science needed to understand the critical zone (CZ), the uppermost portion of the continents, ranging from the top of the vegetation canopy down through soil and the parent material (unconsolidated material, bedrock) that hosts fresh groundwater. The course includes knowledge development of transdisciplinary science that contributes to CZ science, as well as multiple data-based activities that directly address the sustainable use of CZ resources and services. A primary tenet of the course is that to achieve environmental sustainability, society must first understand the CZ system—the natural processes and services of the CZ that are of value to society—and how those processes operate with and without the presence of humanity. Broad assortments of integrated, pedagogical strategies are used in the course to help students grasp the challenging, interdisciplinary science of the CZ. Students accomplish that through a variety of graded activities, including in-class discussions and presentations and multiple graphing, modeling, data analysis, and other discovery activities, including worksheets, short essays, report writing, and a semester-long project. With the framework and resources provided by this course, students from multiple Earth surface and environmental science disciplines can connect the emerging field of CZ science to sustainability issues facing global societies.

Context for Course Development

The InTeGrate program champions sustainability as meeting the needs of current and future societies while sustaining the critical support systems for life on Earth, with a special focus on the geosciences and the role geoscientists are expected to have in the broader scheme of living in a more-sustainable world. Geoscientists are likely to think in terms of Earth resources, environmental

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TABLE I: Synopsis of information regarding the settings in which the ITCZS course was taught and tested.

Institution	Type	Population	Department	Enrollment	Course Type
University of New Hampshire	R2; large, 4-y, highly residential	~15,400	Natural Resources and the Environment	8 (Spring 2015)	Upper-class elective for environmental science majors
University of Arizona	R1; large, 4-y, primarily nonresidential; top-20 public research institution	~42,200	Cross-listed in Environmental Science, Hydrology, Water Resources, Geoscience	5 (Fall 2014); 11 (Fall 2015)	Graduate symposium with advanced undergraduates
University of Dubuque	Small, private, liberal arts college	~2,000	Natural and Applied Sciences	9 (Spring 2014) 1 (Summer 2015) 6 (Spring 2016)	Upper-level elective for biology and environmental science majors
University of Nebraska, Omaha	R3; large, 4-y, primarily nonresidential	~15,500	Geography/Geology	14 (Fall 2015)	Upper-level elective for geology, geography and environmental science undergraduate and geography graduate students
University of California, Merced	R2; medium, 4-y, primarily residential	~6,500	School of Natural Sciences	18 (Fall 2015)	Upper-level elective for environmental engineering, earth system science, and biology majors

stability and change, and health and hazard issues. For example, the American Geophysical Union (AGU), the leading scientific society for Earth scientists, has created a new journal entitled *GeoHealth*, which specifically aims to connect the Earth sciences and geosciences to issues of human health.

One of the primary objectives of the InTeGrate program is to support the teaching of geoscience and societal issues in a widely accessible context. *Sustainability* is one such topic that requires a multidisciplinary approach, which identifies both problems and solutions. Merging sustainable principles with a set of geoscience grand challenges (devastating earthquakes and volcanoes, sea level rise, less-available and more-expensive fossil fuel–based energy resources, and a warmer climate with more extreme weather events, all superimposed on the challenges of a global population soon to be greater than 8 billion) is the basis for the materials produced through the InTeGrate program. As a result, InTeGrate projects strive to build an innovative curriculum that prepares students for addressing current and future sustainability challenges by engaging and empowering them with a holistic and highly collaborative approach to Earth Science and environmental sustainability (InTeGrate, 2016a).

InTeGrate professes that teaching geoscience in the context of societal issues is a key aspect of student engagement and empowerment. Other key themes of InTeGrate's pedagogy include (InTeGrate, 2016b)

1. Connecting to the geoscience-related grand challenges facing societies,
2. Developing students' ability to address interdisciplinary problems,
3. Improving students' geoscientific thinking skills,
4. Making use of authentic and credible geoscience data, and
5. Fostering systems thinking.

CZ science provides a perfect context for presenting students with fundamentally transdisciplinary knowledge of natural processes that are critical toward understanding the future sustainability of Earth's continental surfaces. Critical Zone Observatories (CZOs) and their public data archives provide a consistent, authentic, and research-quality basis for addressing InTeGrate's pedagogical goals.

Process of Course Development

InTeGrate fosters adherence to its developmental model through a series of author and team checkpoints (including multi-institutional pilot testing), internal and external reviews, and team meetings. The large CZ course development team (geographically dispersed across the country representing 5 of 9 CZOs) held weekly teleconferences for nearly 1 y after an initial planning meeting at Carleton College. The team, drawn from CZ scientists and educators, brought diverse scientific expertise reflecting the transdisciplinary nature of CZ science, as well as teaching and educational diversity to bear on this challenging project. Additionally, the course was piloted in a wide range of educational settings, from a small private liberal arts college to a large Tier 1 public research university, major and nonmajor courses, undergraduate- and graduate-level courses, online and face-to-face courses, and small- and medium-sized classes (Table I). The result is a well-balanced and challenging series of seven modules that explore the scientific principles and realities of a large, ongoing, scientific-research, collaborative, and transdisciplinary endeavor. The data are not always pretty, and the system's boundaries are not always well defined, but the course builds

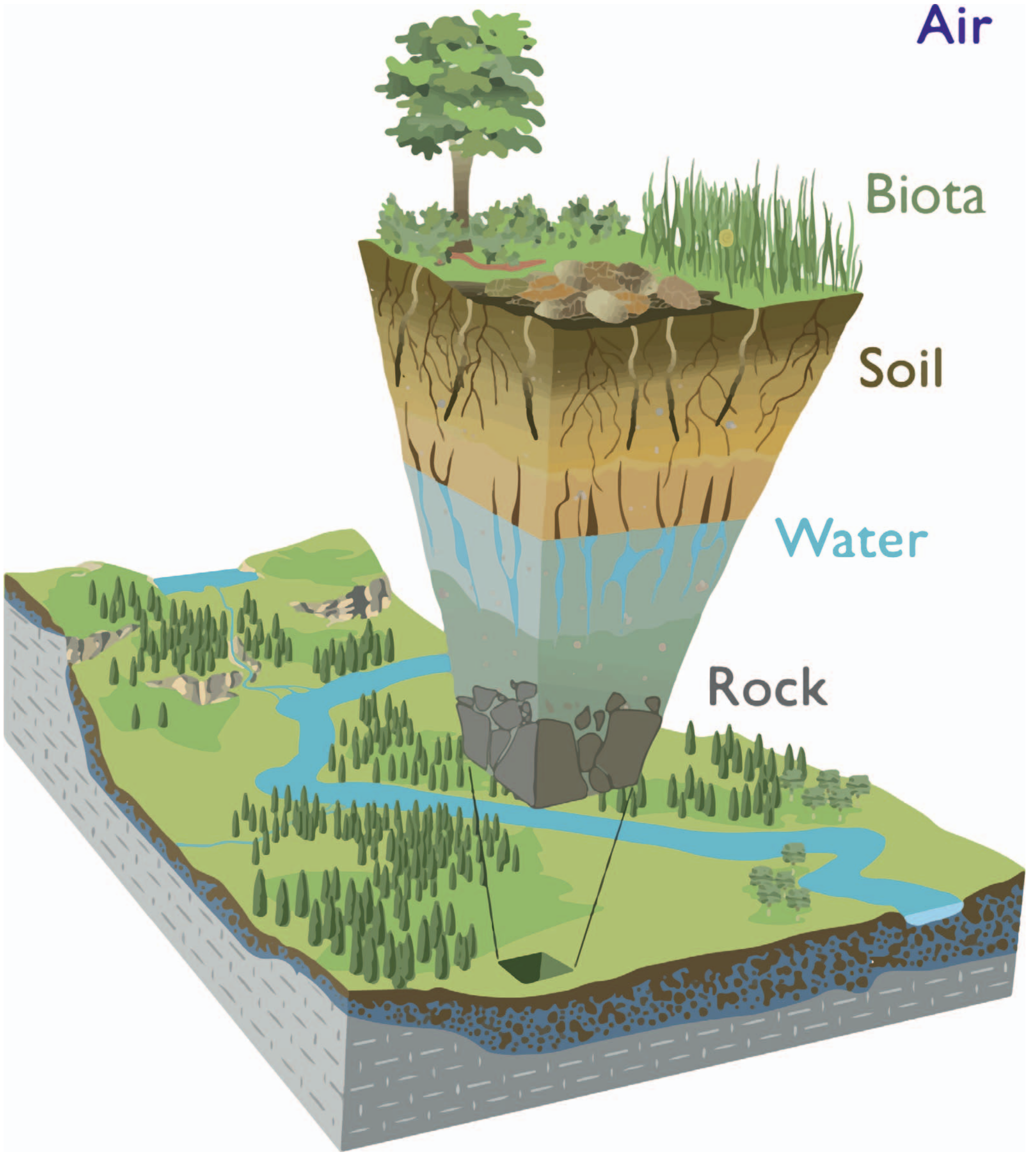

FIGURE 1: The CZ encompasses the thin, outer veneer of Earth's continental surfaces, extending from the top of the vegetation canopy down to subsurface depths of fresh groundwater. The interdisciplinary nature of CZ science and the overarching objective of the ITCZS course presented here is to describe and characterize how interactions among the atmosphere, biosphere, pedosphere, hydrosphere, and lithosphere support and influence life. Image modified by Critical Zone Observatory National Office, from Chorover, J., Kretzschmar, R., Garcia-Pichel, F., and Sparks, D. 2007. Soil biogeochemical processes in the critical zone. Elements, 3:321–326 (artwork by R. Kindlimann).

in such a way that students fully appreciate the complexities of the effort. Of all the comments received, this opinion is one of the most common—that students can now see how the whole effort is greater than the sum of the parts.

CZ SCIENCE AND OBSERVATORIES

The CZ encompasses the thin, outer veneer of Earth's continental surfaces, extending from the top of the vegetation canopy down to subsurface depths of fresh groundwater (National Research Council, 2001; see Fig. 1). Scientific expertise from an array of disciplines is needed to understand the coupled biogeochemical–physical processes throughout the CZ, which transform rock and biomass into soil and support much of the terrestrial biosphere, including humanity (Brantley et al., 2007). CZ structure and function have evolved in response to climatic and tectonic perturbations throughout Earth history, but the processes driving change have more recently accelerated because of human activities. Despite that, the science of understanding and managing anthropogenic threats remains mostly embedded within individual disciplines, and the knowledge needed to slow or reverse environmental degradation in a sustainable fashion appears beyond society's current capacity (Banwart et al., 2013; White et al., 2015).

An immediate challenge is to develop a predictive ability for how the CZ may respond to climate and land-use changes and to address quantitatively the value of CZ functions and services (Banwart et al., 2013). This predictive ability must be founded on broad knowledge of

FIGURE 2: The U.S. CZO network consists of five sites developed since 2007 (two linked as one CZO in New Mexico and Arizona) shown as stars, with an additional four sites recently designated in 2014 shown as squares.

1. *The CZ system and CZ processes*, to describe the interactions of the varied climatic, ecologic, and geologic factors that distinguish different geographic regions—a primary focus of the scientific and educational efforts at CZOs (White et al., 2015 and references therein);
2. *CZ resiliency*, the ability of the CZ to continue key functions that provide ecosystem services in the presence of disturbance (Amundson et al., 2007); and
3. *A CZ perspective*, which expands the context of ecosystem services by considering that the geological framework of the CZ sets the spatial and temporal template that directs the coevolution of physical and biological systems and ultimately results in societal benefits (Field et al., 2015).

In this manner, CZ science is an organizing concept around which environmental sustainability and resource management can be understood by considering all of the Earth surface processes and environmental factors that interact to influence the biosphere and its productivity.

CZOs are natural watershed laboratories focused on investigating Earth surface processes mediated by freshwater (Brantley et al., 2006). Transdisciplinary research at the CZO scale seeks to understand the complex, coupled processes of the CZ through monitoring climate/weather, streams, groundwater, soils, biogeochemistry, and vegetation. CZOs are instrumented for hydrogeochemical measurements and are sampled for soil, canopy, and bedrock materials. In the U.S., a CZO network includes nine observatories (Fig. 2) and a national office. Of all the environmental observatories and networks, the CZOs are the only ones to integrate ecological and geological sciences in combination with computational simulation through the entire CZ and to project from the deep geologic past into that of human life spans. As such, CZOs represent a unique opportunity to transform our understanding of coupled Earth surface processes to guide societal adaptations toward a more sustainable future (White et al., 2015). The transdisciplinary scientific concepts and strategies that underpin CZ science have been widely accepted with more than 200 self-identified CZOs globally and formally funded observatory networks established in the European Union, China, Germany, and France.

Purpose of an Introduction to CZ Science Course

The overarching goal of the education and outreach efforts of the U.S. CZO program (see http://criticalzone.org) is to introduce CZ concepts into the mainstream lexicon of both Earth science educators and citizens to deeply influence and help guide society on a path toward sustainable use of Earth resources and services. The course described here includes knowledge development in diverse Earth surface science disciplines as well as activities that directly address the environmental science aspects of sustainability, a need identified by Zoback (2001). The course was designed, in part, recognizing the value of presenting integrated science to students who may not have experienced such transdisciplinary approaches early in their educational career. The course, overall, takes advantage of the scientific literature and multiple hands-on learning activities that access authentic and credible CZO data.

FIGURE 3: The SoilCritZone logo: representing atmosphere (yellow arc [top], biosphere [green arc, right], hydrosphere [blue arc, left], and lithosphere [brown arc, bottom]) surrounding the acronym SoilCritZone. See http://sustainability.gly.bris.ac.uk/soilcritzone/ for more information on this program in the European Community.

To a first approximation, the CZ system is directly linked with the broader notion of Earth system science but with a very specific geographical focus. Although many disciplines are equally important for understanding the CZ, they are linked by the presence of soil (pedosphere), considered by many to be the central component of the CZ. This concept is well illustrated by the SoilCritZone logo (Fig. 3): a four-leaf, clover-like emblem, with each arc representing one of the "spheres" that overlap in the CZ: atmosphere, biosphere, hydrosphere, and lithosphere. This overlapping and highly integrated relationship is what defines the interdisciplinary nature of CZ science and the overarching objective of the Introduction to CZ Science (ITCZS) course: to describe and characterize how interactions among the atmosphere, lithosphere, hydrosphere, biosphere, and soil (that is, the CZ) support and influence life. Once the complex interactions between the "spheres" are understood, effective and sustainable management of the functions and services available to life, including humanity, can be attained. The semester-long, undergraduate-level course described here aims at introducing the transdisciplinary science needed to understand the CZ and CZ processes.

Format and Pedagogy of the ITCZS Course

The ITCZS course is framed by some of the central InTeGrate project goals that serve to develop CZ knowledge related to sustainability (Gosselin et al., 2013). The course goals include

1. Examining geoscience-related grand challenges facing society, especially soil and ecosystem services;
2. Developing students' ability to address interdisciplinary problems (i.e., sustainable agriculture, conservation, resource management, energy, carbon) by using data visualization and analysis skills with authentic data;
3. Improving student understanding of the nature and methods of geoscience and developing scientific and geoscientific habits of mind by investigating natural and anthropogenic influences on the CZ, using journal articles as background reading, visualizing data with student-made graphs, and using simple, conceptual models to help explain differences;
4. Making use of authentic and credible geoscience data, such as data from CZOs, the Ameriflux Network, and the scientific literature; and
5. Incorporating systems thinking by employing examples and activities that demonstrate the connection between water, air, soil, and organisms in biogeochemical processes within the CZ, including the application of conceptual systems models to the analysis of field data.

Table II provides a synopsis of how each of these goals is addressed in the ITCZS course modules.

The ITCZS modules are easily adaptable to different structures, formats, and schedules, and include learning objectives, activity materials, descriptions, assessments, and teaching tips for each of the 15 units within the seven modules. Each module was designed to stand alone; thus, instructors may choose modules, units, or individual activities within units, to integrate into their existing courses. The entire set of modules was developed as an independent course, although more material than needed for one semester is provided to maximize instructor flexibility in tailoring and fine-tuning the course to their expertise, as well as the level and interest of students. The diversity of resources ensures that by opting to omit some activities, the overall structure and integrity of the curriculum will remain, and students will have a complete introduction to CZ science. The course has been taught in a variety of formats, including in person, online, and with and without a laboratory. In addition, a .zip file is available that is compliant with the IMS Common Cartridge format (IMS Global Learning Consortium, Lake Mary, FL), which means instructors can upload the .zip file directly into local learning management systems (e.g., Blackboard [Blackboard Inc., Washington, DC], Moodle [Moodle Pty Ltd, Perth, Australia], Canvas [Learning Management System, Salt Lake City, UT], etc.). Answer keys available only to instructors can be accessed from the InTeGrate homepage.

The introductory portion of the course, Module 1, was designed to offer students a framework for considering CZ science and an introduction to the U.S. CZO program that provides much of the data and framework for the learning activities. The module is divided into three units: (1) an overview of key CZ concepts, (2) the role of soil in the CZ, and (3) systems models. CZ science is described as an interdisciplinary and international pursuit, stressing an observatory and environmental gradient approach. An introductory explanation of the roles of each sphere within the CZ, as well as the major processes extant within them, links between spheres, outstanding research questions in CZ science, and primary threats to CZ function are considered. Students are introduced to the notion that much of CZ science is applied to conceptualizing systems models that allow scientists to predict the effects of ongoing land-use and climate change.

The body of the course focuses on transdisciplinary science in the CZ using large data sets available from the existing NSF-funded CZOs. Module 2, Methods of CZ Science, introduces students to different types of data and

TABLE II: Synopsis of how course goals are addressed in each module of the ITCZS course.

Module	Geoscience-Related Grand Challenges	Interdisciplinary Problems	Nature/Methods Of Geoscience, Developing Geoscientific Habits of Mind	Use of Authentic and Credible Geoscience Data	Systems Thinking
1. CZ: Background	Review the foundational literature and Web links for the rationale behind the CZO program	Consider four questions in CZ science that deal with interconnections between the "spheres"	Reviews the methods and strategies employed at CZOs	Explores the NRCS Web Soil Survey	Considers systems diagrams that illustrate interconnections between CZ components
2. Methods in CZ science	Illustrate how geoscience-related grand challenges are addressed by CZ methods	Produce annotated bibliography on a question of interdisciplinary nature of CZ science	Use methods of biogeochemistry and isotope geochemistry to investigate natural and human influence on CZ	Assess students' data visualization and analysis skills using authentic data	Investigate systems models as a method to illuminate CZ processes
3. Land–atmosphere exchange	Focus on radiative forcing, H_2O and C cycling, effects on ecosystem differentiation	Integrate energy, C and biophysical knowledge into a model that helps explain observations	Use journal articles, filter and graph real field data to visualize and analyze fluxes and balances	Incorporate CZO met flux data in analysis of energy and C fluxes; Explore Ameriflux database	Apply conceptual energy/C cycle models to the analysis of field data
4. Water transfer through the CZ	Evaluate water balance of an ecosystem; challenge with unpredictable water supplies and rising demand	Learn about links among the water cycle and the different components of the CZ	Understand water transfers and decisions to aid students in civil and academic endeavors, even outside the field of hydrology	Use water-balance data gathered by researchers at CZOs	Use mathematical and symbolic models and a systems-based approach to analyze water balance
5. Landform and landscape evolution	Introduce processes responsible for an array of geologic hazards	Develop understanding of geomorphology and various supporting disciplines	Use journal articles, examine maps and aerial photography, and use models to explain CZ processes	Examine national databases of geologic maps and remotely sensed image data	Apply conceptual rock-cycle models to the characterization of CZ environments
6. Geochemistry and biogeochemistry	Consider eutrophication, erosion, environmental stability, food production, climate, H_2O and C cycling	Examine sustainable agriculture, conservation, resource management	Examine biogeochemistry using hands-on activities	Use CZO data from the geochemical and biogeochemical literature base	Activities that demonstrate connection of H_2O, air, soil, and life with biogeochemistry in the CZ
7. Humans in the CZ	Introduce human impacts on the CZ	Examine how humans affect CZ processes and how to reduce impacts	Use Web applications to analyze human impacts on H_2O and soil	Activities that evaluate human impacts on local H_2O and soil	Examine best-management practices that reduce human impacts to CZ

techniques for interpreting data and information. In Module 3, Land-atmosphere Exchange, energy and carbon fluxes are explored as drivers of many CZ processes. Module 4, Water Transfer through the CZ, builds on Module 3 but focuses on CZ water budgets. This module especially encourages systems thinking, with a focus on mass balance and considering processes across scales. Students are introduced to how diverse geological processes interact to form landscapes in Module 5, Landform and Landscape Evolution. A key concept presented here is that commonalities exist within landscape diversity, marked by landforms that often indicate similar formation processes that, in turn, control CZ processes. Module 6, Geochemistry and Biogeochemistry, examines the integrated roles that geology, biology, and chemistry have in driving energy and nutrient fluxes within the CZ. By engaging students in examining data from real world systems, this module highlights the complexity of the CZ and leads students to think about how humans have modified biogeochemical systems.

The final module of the course (Module 7), Humans in the Critical Zone, specifically looks at the impact and role of humans and societies within the CZ. The module focuses on how interdisciplinary and collective CZ science is accomplished and considers the state and management of the CZ, especially the idea that all humans live in the CZ and depend on it for resources and their livelihoods. Humans affect natural CZ processes upon which they depend, a two-way interaction explored through readings, computer simulations, and discussions. Connections are made between human activities and previously discussed CZ concepts. For example, skills learned in Module 2, such as how to interpret the distribution of elements within soil profiles (i.e., soil tau plots), are applied to the effects of land management on soil carbon stocks in Module 7, by presenting the concept of soils as a limiting resource for humanity (e.g., Banwart, 2011). The summative course assessment includes a mock panel review of proposals for new CZOs, thus, providing students with an additional opportunity to engage in authentic science practices.

A broad array of integrated pedagogical strategies is used in the course to help students grasp the challenging transdisciplinary science of the CZ. Foremost among these strategies is active learning, in which students use online resources, data and worksheets, and peer-to-peer instruction to share their strengths and to collaborate across disciplinary boundaries (Grabinger and Dunlap, 1995; Freeman et al., 2014). Students are challenged to analyze real-world data to think more deeply and completely about CZ systems and to develop the computational and communication skills they will use throughout the course and their careers as scientists (Stillings, 2012). The real-world data are heavily focused on the CZOs and on areas within CZ science of the student's choosing, thus, giving students an opportunity to take advantage of the noted benefits of place-based learning in the geosciences classroom to solve real-world problems (Gosselin et al., 2016). Using Excel spreadsheets (Microsoft, Redmond, WA) helps improve data analysis and graph-building skills, as does locating well-integrated data sets or dealing with missing data issues; such skills are important methods used by scientists (Kastens et al., 2009) and are fundamental to CZ science. Student-directed learning is an expected product of this approach, as students work with datasets before detailed explanations and instructions are provided (Kober, 2015). In addition, students engage in multiple activities to develop their spatial skills, an area often lacking in geoscience students (Liben and Titus, 2012).

Preclass readings and other homework assignments, typically as carryover from an in-class activity, are used in most units and are designed to give students practice developing critical reading and writing skills they will use throughout their academic and professional careers. Group discussions are also frequently used to organize class discussions, especially a think–pair–share approach to metacognition (Smith et al., 2009). In brief, a question is posed, time is provided for students to think and discuss with a subset of nearby classmates, and then the discussion is completed with the full class. To facilitate covering and comprehending a large number of readings, a group approach is recommended in which each group must prepare a short summary of one of the assigned readings to share with the class. Group selection of the readings is encouraged because student leaders pick a topic related to their major, thus allowing them to share considerably greater insights and understanding of the reading than if the readings had been randomly assigned, ultimately promoting better peer-to-peer instruction (Tien et al., 2002).

Other pedagogical strategies include directed Web site or video browsing (4 units), individual or group presentations (3 units), preclass and postclass quizzes (2 units), concept mapping (1 unit), creating annotated bibliographies (1 unit), and one-on-one in-class meetings with students (1 unit). A computer laboratory classroom with tables for collaborative work is recommended for most activities, although a small classroom to accommodate and encourage in-class activities and interactions can also be used.

CZ SCIENCE AS IT RELATES TO SUSTAINABILITY

The CZ provides all the terrestrially based resources and services required for sustaining healthy and functioning natural environments that all terrestrial organisms and human communities rely on for survival. A primary tenet of this course is that, to achieve environmental sustainability, society must first understand the CZ system and the coupled physical, chemical, and biological processes and services of the CZ that are of value to society. Understanding how such processes operate, with and without the presence of humanity, and how those processes can be altered by global climate and land-use changes, are essential for developing future environmental management protocols and sustainable resource-consuming practices. The ITCZS course specifically focuses on the *environmental and Earth system component* of sustainability and provides guidance as it relates to the fourth sustainability learning outcome outlined by the American College Personnel Association (ACPA, Washington, DC): "Each student will be able to explain how *environmental*, social, and economic systems are interrelated" (ACPA 2014, p. 19). More specifically, the ITCZS course relates to student competencies regarding the interdependence of humans and life-supporting natural systems as well as systems theory regarding healthy natural systems (ACPA 2014).

All the ITCZS course modules contribute to the overall goal of developing knowledge of the CZ and associated, complex, coupled processes as fundamental to making more-informed decisions about environmental sustainability. The course emphasizes the use of real data to hone analytical and critical thinking skills and ultimately develop students' ability to address environmental sustainability issues. Thus, the overall topic of environmental sustainability is implied throughout the course and provides the framework around which the course was designed. Explicit lessons in environmental sustainability are also included and are described below.

Module 1, Unit 2: Role of Soil

In Module 1, Unit 2 (Role of Soil), students are introduced to and use the U.S. Department of Agriculture Natural Resource Conservation Service (NRCS, Washington, DC)'s online WebSoilSurvey software package to generate a land-use planning report that includes a soil map of a chosen study site and identifies the dominant soil type at the site, dominant soil characteristics that affect land use, whether or not the effect is positive or negative, and the primary threats to soil at the site. Understanding soil diversity, variability, and vulnerability across the CZ directly relates to decision-making regarding sustainable agricultural and food-production practices and carbon storage.

Module 4, Unit 2: Water Balance Impacts

Water-management decision-making is considered in Module 4, Unit 2 (Water Balance Impacts). Students learn to apply environmental sensor data to water-balance calculations at both the catchment and regional scales, then use a model to simulate management decisions for water resources. The resource management simulation activity, called ''SimWater'' (https://criticalzone.org/images/national/associated-files/1National/SSCZO_WaterSim.pdf), also considers water-management decisions at the community scale. Students allocate land for residential, agricultural, and commercial uses, then balance water supply and demand, given a simplified spatial model that represents California's Central Valley and mountain ranges. As they progress through the activity the students answer questions, such as (1) What is the maximum amount of food that could be produced from these lands, given space and water constraints? (2) What happens to food production as cities grow? (3) How many people can a region support if all of the food is produced locally? (4) What kind of modifications could be made to facilitate agriculture? (5) Does commercial or industrial use come with additional space constraints?

Module 6, Units 1 and 2: Biogeochemical Cycling

Watershed nutrient management and denitrification are explored in Module 6, Units 1 and 2, on Biogeochemical Cycling. Denitrification and nutrient uptake is considered in the context of an ecosystem service provided across biomes, land use, and as it relates to biodiversity. Students apply data sets and observations from six CZOs to test ideas and to summarize CZ services. The module includes an activity entitled *Nutrient Challenge*, in which students devise a transformative strategy for reducing excess nutrients in waterways. Understanding how the CZ retains and removes nutrients is directly applicable to the sustainability of coastal fisheries and aquaculture practices, both of which provide large quantities of food for regional and global communities.

Module 7, Unit 1: Humans in the CZ

Finally, in Module 7, Unit 1, students focus on the land–water connection and how human-induced land-use change affects local hydrology. Students use the watershed-modeling Web app Model My Watershed (http://wikiwatershed.org/model/) to predict the amount and destination of water as it moves through a built environment. They also evaluate the impact of human alterations to the landscape and how best-management practices can minimize those effects. Such land alterations are then considered again in Unit 2 of this module, in which students discuss implications of various agricultural practices and how land conversion can affect soil carbon storage and cycling.

Across lessons and modules within the ITCZS course, students are able to connect natural CZ, ecosystem, and environmental processes and function to human actions and decisions, natural and human-induced perturbations, and the associated effects on fertile soils, healthy waterways, and water availability, for example. Providing one of the best examples of this interconnectedness is the study and associated readings (e.g., Montgomery 2007; Banwart 2011) of the Dust Bowl in Module 7, which connects back to multiple other modules, including Modules 2 and 6. In this section, students learn how human alteration of the CZ, including the manual and mechanical removal of native biota, coupled with large-scale drought, caused widespread environmental disturbance and erosion, affected soil carbon stocks, and ultimately, resulted in the collapse of both agriculture and communities, as well as human diaspora.

ASSESSING THE EFFECTIVENESS OF THE ITCZS COURSE

As part of the InTeGrate project, precourse and postcourse assessments were conducted relating to academic and career ambitions, personal behaviors and attitudes, and academic achievement relating to geosciences literacy. Of the students surveyed, 69% were in their senior year, and 14% were graduate students, with an average reported age of 24 y (range, 19–40 y). Fifty-eight percent of the surveyed students ($n = 37$) were female. Sixty-three percent of students identified as white, 20% as Hispanic, and 16% as Asian Americans.

The survey included a question regarding the student's declared major, for which very little change was observable in the precourse–postcourse survey. Similarly, very little change was expressed with respect to interest in specific career paths, noting, however, a change from 50% to 64% reporting interest in employment in a government agency and a change from 25% to 33% reporting interest in a career as a professor. The lack of pre/post change for the survey questions was likely due to the predominantly junior, senior, and graduate student composition in the piloted courses, i.e., students already deeply invested in their educational path to graduation.

There was not much observable change in data collected regarding concerns over various aspects of environmental degradation, and the trends shown were mixed. Eighty-one percent of the students expressed concern about climate change, a value that rose to 86% in the postcourse survey. Concerns about biodiversity loss also showed an increase from 64% to 78%, whereas concerns about population growth (28% to 19%) and water limitations (94% to 89%) both dropped after the course. These observations were likely due, in part, to the relatively large percentage of students reporting concerns in the precourse survey, although the results regarding water limitations were surprising.

The Geoscience Literacy Exam (GLE) was administered by SERC to examine the students' understanding of sustainability by measuring geoscience literacy, their understanding of the process of geoscience, and their systems thinking (Gosselin et al., 2013; Fortner et al., 2016). Overall, the student's scores increased from 7.8 to 8.1 out of 10, whereas for individual questions, one-half showed an improvement from the pretest to the posttest (Table III). Because the GLE is a one-size-fits-all assessment, many GLE test questions were not relevant to the ITCZS course, and the questions in which students did not show improvement were content areas not heavily (in most cases, not at all) covered by the course.

The InTeGrate Attitudinal Assessment was used to determine the interest of students majoring in geosciences or planning a career in the geosciences, and motivation to contribute to solving grand challenges of environmental

TABLE III: Percentage of students (precourse, $n = 30$; postcourse, $n = 27$) answering each Geoscience Literacy Exam (GLE) question correctly before and after taking the ITCZS course.

Question Subject	Answered Correctly (%)	
	Precourse	Postcourse
Natural hazard	96.7	88.9
Tectonic plates	60.0	70.4
Life in oceans	60.0	63.0
Human and oceans	40.0	29.6
Atmosphere and biosphere	46.7	55.6
Carbon sources	33.3	44.4
Climate modeling	93.3	92.6
Climate measurements	10.0	35.9

sustainability, depletion of natural resources, and natural hazards (Kastens, 2016). One of the most important outcomes of this course was demonstrated by student responses to the question: As you think about your future, can you envision using what you have learned in this course to help society overcome problems of environmental degradation, natural resources limitations, or other environmental issues? The high percentage of students responding "yes" to this specific prompt suggests that the holistic, systems approach to environmental science and sustainability advocated by CZ science in this course was successful (Fig. 4).

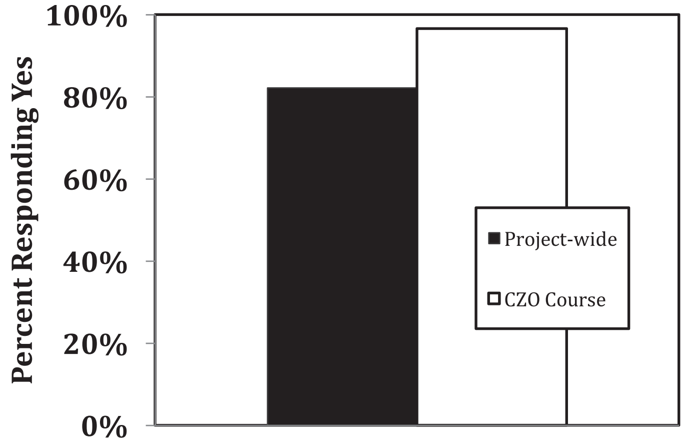

FIGURE 4: Students responding "Yes" to the question: As you think about your future, can you envision using what you have learned in this course to help society overcome problems of environmental degradation, natural resources limitations, or other environmental issues? $n = 1125$ for InTeGrate project-wide student responses; $n = 29$ for the ITCZS-course student responses.

CONCLUSIONS

The ITCZS course aims to provide students with an understanding of CZ structure and function and to enable students to identify grand challenges facing society and how CZ science can help minimize anthropogenic impacts on the CZ. A primary tenet of the course is that to achieve environmental sustainability, society must first understand the CZ system, the natural processes and services of the CZ that are of value to society, and how those processes operate with and without the presence of humanity. The course includes knowledge development in diverse Earth surface and environmental science disciplines as well as activities that directly address environmental sustainability. All of the course modules contribute to the overall goal of developing knowledge of the CZ and associated complex, coupled processes as fundamental to making better decisions about sustainability. Thus, the overall topic of sustainability is implied throughout the course and provides the framework around which the course was designed. Explicit lessons in environmental sustainability are also included.

The course emphasizes the use of real data to hone analytical and critical thinking skills and ultimately to develop students' ability to address sustainability issues. Course development involved a transdisciplinary team, and the resulting curriculum provides numerous opportunities for students to engage collaboratively. Although precourse and post course assessments demonstrated only small gains in geoscience literacy, changes to career aspirations or college major, or personal habit and attitudes relating to overall environmental consciousness, qualitative assessments were overwhelmingly positive, indicating that students completed the course with a strong, working knowledge of the interconnectedness of the atmosphere, biosphere, hydrosphere, and lithosphere and the importance of the CZ concept.

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