College Student Conceptions about Changes to Earth and Life over Time

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ABSTRACT
While interdisciplinary collaboration is desired among researchers, traditional science instruction generally results in science disciplines being taught as separate entities. This study focuses on student understanding of concepts at the intersection of two isolated disciplines—geoscience and bioscience—across two purposeful samples of college-aged students (United States, Germany). Specifically, we explored: 1) how students conceptualize large-scale biologic and geologic changes on Earth over deep time; 2) the relationship between student's conceptions and their understanding of evolutionary and geologic theories; and 3) how those conceptualizations explicate the need for integration of concepts within school curricula. Students were asked to respond to items about seven major evolutionary events in Earth's history (biosciences) and perceived changes to Earth's size and continental positions over time (geosciences). Both groups exhibited difficulties understanding absolute ages in deep time, although Young Earth and Young Life perspectives were present in the U.S. group and absent in the German group. Conceptions about changes to Earth's size and continental positions over time were consistent across both groups. Findings highlight the need for scientific education instruction in both countries that is interdisciplinary in content.

INTRODUCTION
Interdisciplinary science is becoming an important component of the scientific landscape. Society is recognizing the importance of interdisciplinary work, and many science educators are advocating for interdisciplinary teaching approaches in scientific curricula (Hicks *et al.*, 2010; Begg *et al.*, 2014). Additionally, funding institutions are increasing their calls for interdisciplinary proposals for scientific research (e.g., the National Science Foundation in the United States), and programs to facilitate training of graduate students in interdisciplinary thinking are being developed (Bridle *et al.*, 2013). Interdisciplinarity applies not only to intersections of science and non-science fields, but also to the importance of moving the science disciplines from isolated silos into fields that communicate across traditional boundaries (Hicks *et al.*, 2010). While the need for interdisciplinary collaboration is well understood among researchers, traditional science instruction most often presents science disciplines as separate and disconnected entities. The complexity of today's increasing environmental problems and the profound changes Earth is experiencing signifies the critical need for interdisciplinary science instruction in the educational system. Today's students—citizens and future scientists alike—need to understand how scientific concepts are interrelated to be well equipped to solve Earth's looming socioenvironmental problems.

This study focuses on student understanding of concepts at the intersection of two disciplines (geoscience, bioscience) and across two purposeful samples (United States, Germany). While science education researchers have considered the importance of chemistry and physics within geoscience (Asghar and Libarkin, 2010; Neves *et al.*, 2013; Fakayode *et al.*, 2014) or bioscience (Cook *et al.*, 2014), very little work has evaluated the intersections of biologic and geologic phenomena in the context of

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student learning. Specifically, the theory of plate tectonics and the theory of evolution share a common need for conceptualization of deep time and provide a useful opportunity to explore the ways in which temporal conceptualizations impact simple plate tectonic and evolutionary conceptual understanding.

German and U.S. college students were included in this study as a purposeful sample and to expand beyond the common practice of investigating U.S. students in isolation. We want to point out that this is not a comparison study of the U.S. and German systems. However, Germany and the United States do share similar disaggregated educational systems and standards for conceptual understanding at the geoscience–bioscience nexus, making Germany an appropriate secondary sample. We view this paper as two studies in tandem in similar educational systems, done through purposeful sampling rather than quasi-experimental design (e.g., comparison). Looking at both systems (United States and Germany) is useful, particularly because the bioscience and geoscience education literature is dominated by studies of U.S. systems.

U.S. Education Context

Understanding college student conceptions of biologic and geologic concepts requires some knowledge of their precollege educational backgrounds. In the following sections, we provide a general background of the U.S. and German precollege educational systems. The United States has a complex educational system based primarily within state structures; mandatory national education standards for K–12 education do not exist in the United States (Labov, 2006). Educational requirements regarding teacher certification, educational standards, and curricula are left to the individual states and local districts, and sometimes even individual schools. As a result, the majority of states in the United States have instituted their own minimal to moderate regulations for curricula and outcomes measurement (Gal-Ezer and Stephenson, 2014), and these are inconsistent across districts and states. The complexity of the U.S. educational system carries over to college. In the United States, most colleges and universities house diverse admissions criteria that do not always align with state and district 12th-grade graduation requirements. Students enter college with varying educational backgrounds and levels of academic knowledge and skills.

Although there have been calls for establishing national educational standards for the U.S. public educational system, the idea of the federal government intruding into states' rights has been met with resistance by lawmakers and citizens (Peterson and Kaplan, 2013). Recognizing the need for the standardization of K–12 student outcomes, the National Research Council, the National Science Teachers Association, the American Association for the Advancement of Science, and Achieve, Inc., collaborated to develop the Next Generation Science Standards (NGSS). The NGSS are voluntary educational standards that states can choose to adopt and implement (or not) into their K–12 scientific curricula. The NGSS, released in 2013, outline the scientific constructs for which K–12 students should show proficiency at the end of each grade level. The NGSS seeks greater integration of sciences and engineering curricula in elementary, middle, and high school; before NGSS, most science and engineering courses were taught as separate entities without contextual overlap. The NGSS recognizes that integrated knowledge of all the sciences is required for science to have practical significance in the real world (Moore *et al.*, 2015). As such, the NGSS are composed of three dimensions: 1) disciplinary core ideas, 2) science and engineering practices, and 3) cross-cutting concepts. *Disciplinary core ideas* represent specific content in subject areas related to the physical sciences; the life sciences; the earth and space sciences; and engineering, technology, and applications of science. *Science and engineering practices* represent the methods and techniques that scientists and engineers employ in their fields. *Cross-cutting concepts* represent ways in which different domains of science intersect with each other (NGSS Lead States, 2013).

In this study, we focus specifically on the NGSS's HS-ESS2 Earth's Systems standard, which states that at the end of a 12th-grade education, graduating high school students should be able to "construct an argument based on evidence about the simultaneous coevolution of Earth's systems and life on Earth." In this specific standard, "the ability to construct an argument" refers to science and engineering practices, "simultaneous coevolution" refers to cross-cutting concepts, and "Earth's systems and life on Earth" refers to disciplinary core ideas.

German Context

Before attending a university in Germany, students normally graduate from an 8- or 9-year Gymnasium. German schools teach biology, chemistry, physics, and geography as single, isolated subjects, with geoscience integrated into geography. Responsibility for education lies with the individual German federal states; as in the United States, the school system in Germany can be characterized as very heterogeneous. Recently, many efforts have been made to achieve a more uniform level of education within Germany. Due to the so-called PISA shock (Waldow, 2009), the Standing Conference of the Ministers of Education and Cultural Affairs decided to develop national educational standards for individual subjects. The federal states committed themselves to using these national educational standards as a basis for designing their curricula up to class 10 for Gymnasium (Sekretariat der Ständigen Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland, 2004). For geography (which contains geoscience), the German Geographical Society developed national educational standards for the intermediate school graduation certificate, although these are not binding within each federal republic.

According to the national educational standards in biology (Standard F.1.7), students should be able to describe interactions between the biosphere and other spheres of the Earth (Sekretariat der Ständigen Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland, 2005). Similarly, National Standards in Geography require (standard K2.S3) that students are able to "outline the natural spheres of the Earth system (e.g., atmosphere, pedosphere, lithosphere, biosphere, hydrosphere) and describe specific interactions" (German Geographical Society, 2014, p. 13).

The educational standards for biology and geography, as well as the curricula of the federal states, emphasize the importance of integration with other subjects. In practice, however, integration of different scientific disciplines is limited by the strict separation of individual subjects. For example, the Bavarian curriculum provides for an introduction to Darwin's theory of evolution in the eighth-grade biology class, but the theory of plate tectonics is first covered in 10th-grade geography class (ISB, 2009). As a consequence, students do not gain proficiency at recognizing relationships between concepts housed within individual disciplines.

This paper focuses on deep time as an important variable in understanding theories of evolution and plate tectonics, one that provides for integrated understanding across two theories recognized as foundational in bioscience and geoscience. This intersection of evolution and plate tectonics is an unstudied area of student misconceptions research.

Deep Time

Deep time refers to the large timescale of events dating back to when Earth first formed and is important for both geologic and biologic change. Understanding of deep time is reflected in knowledge about key events in geologic history that include both absolute and relative ages (Trend, 2000). Student (from elementary to college levels) and science educator understanding of deep time has been highly researched. Knowledge about relative ages often translates to understanding the temporal succession of key events in Earth's history. Studies demonstrate that individuals have an easier time understanding relative ages (e.g., land dinosaurs went extinct before humans evolved) than recalling absolute ages (e.g., 65 million years ago), partly because recalling absolute ages requires an understanding of large-scale numbers, a task difficult for many individuals (Cheek, 2012). Although deep time is primarily used as a "yardstick" in geologic history, Catley and Novick (2009) argue that it is also a useful framework for conceptualizing macroevolutionary processes.

Deep Time and Biologic Systems—The Theory of Evolution

The theory of evolution is integrated into most public secondary education settings globally and serves as the framework for all future biology courses (Kim and Nehm, 2011; Abraham *et al.*, 2012; Kalinowski *et al.*, 2013). Unfortunately, misconceptions about evolutionary processes are quite common among college students. For example, Bishop and Anderson (1990) demonstrated that, even when biology courses were designed to address common student misconceptions about natural selection, students still left introductory courses without scientific understanding. Studies relating deep time and evolution conceptions find that people across different age groups and levels of expertise, including experts and science educators, have difficulties conceptualizing the scale of evolutionary time and often hold inaccurate perceptions about evolutionary events (Trend, 2000, 2001; Akyol *et al.*, 2012; Kalinowski *et al.*, 2013; Czajka and McConnell, 2018).

At the same time, individuals are generally able to articulate the chronological order of major evolutionary events (Trend, 2000, 2001; Libarkin *et al.*, 2007). For example, Trend (2001) conducted studies examining children's and science educators' ideas about evolutionary events in Earth's history and found that, while individuals are unable to correctly identify absolute ages for evolutionary events in history, many individuals are familiar with the relative order of these biologic events. The same has been found to be true for college students. Catley and Novick (2009) examined college students' conceptions about deep time by testing their ability to accurately identify the absolute ages of seven major evolutionary events in Earth's history. They found that students extremely overestimated or underestimated the ages of these events and concluded that students do not have the adequate framework to make sense of large timescales. Libarkin *et al.* (2007) performed a study of college student conceptions and found that, while the majority of students in their study understood the relative order of evolutionary events in Earth's history, many misunderstood the time span between those events. This confirmed earlier findings that understanding of the relative order of major evolutionary events seems to be a positive outcome of precollege instruction and that absolute time is difficult to comprehend.

Deep Time and Earth's Systems—The Theory of Plate Tectonics

In the geosciences, the movement of Earth's tectonic plates over time is well documented and integrated into curricula internationally as the unifying paradigm of the theory of plate tectonics. Plate tectonic theory explains how the outer, solid shell of the Earth is broken into pieces that move and interact with one another. This theory allows geologists to gain a deeper understanding of Earth's history and the development of surface phenomena such as volcanoes, mountains, and ocean basins. Changes in continental positions have an effect on ocean circulation, atmospheric patterns, and landscape evolution, which in turn can affect climate, weather, and life on Earth. Over Earth's history, the movement of tectonic plates has resulted in supercontinents (one dominant continent) and multiple continents (such as exist today).

For the geosciences, the theory of plate tectonics is similar to bioscience's theory of evolution. It is essential for students to gain a strong foundational understanding of the theory of plate tectonics in order to build accurate conceptual models of Earth's systems as they progress in their studies. As such, the theory of plate tectonics is recognized as one of the key concepts that geologists and scientifically literate citizens should understand (Clark *et al.*, 2011).

Due to the importance of the theory of plate tectonics in the geologic disciplines, geoscience education researchers have examined students' and professionals' conceptualization and understanding of this theory (Dolphin and Benoit, 2016). Although research findings suggest that most individuals do not have a strong understanding of plate tectonic boundaries and their effect on land formations, most people understand that continents move over time. These findings remain consistent across different research studies. For example, in the United States, Kortz *et al.* (2011) proposed that student difficulties understanding plate tectonics phenomena were grounded in students constructing new ideas based on inappropriately applied prior knowledge. In Germany, Conrad (2015) analyzed interviews with students using a systematic metaphor analysis. He found that many misconceptions about lithospheric plates result from inappropriate application of everyday experiences. While these are a few examples of studies that explore student's understanding of geologic processes, we note few studies that explore conceptions or understanding of changes to Earth's processes over the course of deep time. Furthermore, although national standards (e.g., in the United States and Germany) call for student understanding of the coevolution of Earth (plate tectonics) and life on Earth (evolution), there is no research that explores student understanding of the relationship between the two concepts. Prior studies have focused primarily on understanding conceptions about evolution, deep time, and geologic processes in isolation and in recent time. This study is a first attempt at simultaneously exploring student perceptions of both biologic and geologic phenomena.

Historical Scientific Ideas and Misconceptions

When studying misconceptions, it is important to note that student ideas sometimes follow historical scientific views (Wandersee, 1985). Of importance to this current study are historical models related to: rates of biologic evolution and changes to Earth's size. The theory of evolution as recognized most widely today emerged in the 1850s and posited multi-generational change. Early in studies of biologic evolution, scholars struggled to understand the rate at which evolution could occur, particularly in macro-organisms such as mammals. Lamarck posited that macroevolutionary changes could occur within the span of a single generation; scholars attempted to evidence this theory through creating macro-changes (e.g., cutting off tails of mice) and looking for changes in future generations. This idea was contrasted with theories that posited long timescales for change, such that macroevolution in mammals would not necessarily be observable over human life spans (Evans *et al.*, 2012). Over time, research has shown that evolutionary changes can occur within both short and long timescales (Beaumont *et al.*, 2009; Uyeda *et al.*, 2011), although Lamarckian change for macro-organisms is unlikely.

Similarly, theories about how changes to Earth's surface features occur posited both internal Earth and whole-Earth processes. The theory of plate tectonics—positing that the Earth's surface is broken into solid layers that move and interact—did not emerge until the early 1960s. Much earlier, the formation of mountains and oceans was considered the result of shrinking of the Earth caused by internal cooling (Tarbuck and Lutgens, 2009). This was later replaced by a theory of Earth's expansion (Carey, 1976; Falk *et al.*, 2002). As might be expected, there has been no statistically significant expansion or contraction of planet Earth (Wu *et al.*, 2011).

The history of scientific theories about rates of evolution and changes to Earth's size coupled with the documented relationship between student ideas and historical ideas suggests these two areas are important to examine. To our knowledge there is no existing research about student conceptions to changes in Earth's size.

The Current Study

The current study considers three research questions to address the gap related to the study of conceptions about the coevolution of Earth and life on Earth as delineated in U.S. and German standards. This work focuses on student conceptions of major biologic evolutionary events and their relationship to student conceptions about simultaneous changes to the Earth (continental position, size). We were interested in exploring the overarching understanding that college students have about the coevolution of biologic and geologic phenomena through three questions: 1) In what ways do students conceptualize large-scale changes to Earth's biology, continental positions, and size over long geologic time? 2) What relationships, if any, exist between student paradigms about absolute and relative times and their conceptions of changes (and underlying causes) that occur to life and the planet? 3) How do these conceptualizations explicate interdisciplinary integration of concepts within school curricula?

METHODS

Data Collection

U.S. and German students were chosen as purposeful samples with similar relationships to the concepts under study. U.S. participants were first-year students attending a large research institution in the Midwest. Surveys were completed by the U.S. students at a university orientation program required of all incoming first-year students in Spring 2015. German students were mainly in their first year of a geography program at a Bavarian university. Surveys were translated into German and were completed in Spring 2015 during a class tutorial on study techniques. Both samples were given as much time as needed to complete the survey.

Participants for this study were from the United States (N = 224) and Germany (N = 69). Collected demographic data included gender, collected from both German and U.S. samples, and age and ethnicity, collected from U.S. participants. Age was collected to ensure participants were over 18 years of age. Both gender and ethnicity were collected because of known performance gaps in general science understanding, wherein men and nonminorities typically score higher (Bacharach *et al.*, 2003). Only participants over 18 years of age were included. Of the German participants, 57.1% of participants identified as female, while 42.9% of participants identified as male. Of the U.S. participants, 55.6% identified as female, while 44.4% identified as male. No transgender students were identified. Further demographic information was not collected from German students (as is the norm for studies in Germany); specific age and ethnicity data were collected from U.S. students.

U.S. participants were mostly 18 years of age (n = 209), with five 19-year-old participants; 10 of the participants' ages were unknown. Three percent of U.S. participants identified as American Indian/Native American, 7% as Asian/Asian American, 17% as Black/African American, 6% as Latino/a/Hispanic, and 70% as white/Caucasian.

Survey

College student's conceptions of tectonic (geologic) and evolutionary (biologic) changes over deep time were measured through open-ended surveys (refer to Supplemental Material S1). Items related to absolute and relative geologic time were adopted from previously published work (Libarkin *et al.*, 2007). Items related to Earth's changes in time and space were modified from unpublished work previously piloted in a larger study (Libarkin *et al.*, 2005). The survey was divided into two parts that examined conceptions about 1) geologic and biologic events over time, and 2) changes in Earth's size and continental positions over time. For the first part of the survey, questions and instructions for the collection of student conceptions about changes in life over time consisted of a timeline on which participants placed five events: Earth's formation, appearance of life, appearance of dinosaurs, disappearance of four-legged dinosaurs, and appearance of man. Participants were also asked to document absolute ages for Earth's formation and appearance of life.

For the second part of the survey, participants were shown a circle containing the modern distribution of continents and representing Earth's current size (refer to Supplemental Material S1). Two questions asked about changes to Earth's size and continental positions in Earth's past (Think back in time to when you said the dinosaurs first appeared on Earth) and in the future (Think into the future the same length of time you think passed between the first appearance of dinosaurs and today). Participants were asked to choose which of three Earths—the same size, smaller, or larger than the representative Earth—represented Earth in the past (and again in the future). Participants were also asked to draw how continents were distributed across Earth's surface, again in both the past and future.

Coding

Thematic content analysis (Patton, 2002) was performed on explanations of responses to unpack reasoning for changes to or stability of Earth's size and continental positions. This thematic analysis resulted in both agreement between coders (see *Validity and Reliability*) and a coding schema as follows. For both past and future times, participant choices of Earth's size over time were coded as "smaller than," "larger than," or "the same size as" today. Similarly, Earth's continental positions were coded as "continents together," "continents apart," or "same position as today." The two depictions, past and future, provided us with a mechanism for evaluating perceived changes to Earth over time. For example, if Earth was depicted as smaller in the past but larger in the future, we coded that as "Earth grows." If the opposite occurred, we coded that as "Earth shrinks." Drawings that were inconsistent with Earth growing, shrinking, or remaining the same over time were coded as exhibiting mixed conceptions about Earth's size. A similar coding scheme was used for changes to Earth's continental positions.

Analysis

To analyze relative placement of events across timelines, we created ternary diagrams as per Libarkin *et al.* (2007). The ternary diagram provides a visual analysis of biologic events; specifically, the positioning of the first appearance of life and man relative to Earth's formation and today (see Figure 2, discussed later). In essence, the ternary diagram provides a window into relationships between placements of the two events within Earth's history. Relative placement of evolutionary events (appearance of life, appearance/disappearance of dinosaurs, appearance of man) was calculated through physical measurement of event placement on the survey timeline relative to Earth's formation (0) and today (100). Ternary diagrams evaluating three events (Earth's formation, appearance of life, and appearance of man) were created as per Libarkin *et al.* (2007) to analyze differences across the appearance of life groups (Young Life, Old Life). Each axis of the ternary diagram represents a proportion of the total time depicted on the timeline such that the sum of each of the three axes for a given point equals 100% (Herfort and MacPhee, 2019). The resultant ternary diagram see Figure 2, discussed later) depicts the relative spacing between four events on participants' timelines. The axes correspond to relative spacing between Earth's formation and the appearance of first life (Earth Forms–First Life), appearance of first life and the first appearance of humans (First Life–Man), and first appearance of humans and today (Man–Today).

Finally, to observe patterns across subgroups of students (as per Libarkin *et al.*, 2007), participants were placed into two groups based on their conceptions of absolute ages for appearance of life. Participants who indicated appearance of life occurring at or more than 100,000 years ago were classified as Old Life. Participants indicating life appeared less than 100,000 years were classified as Young Life. Some students ($N = 97$) did not provide enough absolute age information to be grouped within life appearance groups.

Validity and Reliability

Several steps were taken to ensure validity and reliability during survey development and analysis (Table 1). Three forms of content validity were addressed during survey development. First, the content of the test (content validity: test blueprint) was determined through review of literacy documents (NGSS Lead States 2013); in this case, the survey probed large-scale concepts related to Earth and evolution of life in alignment with NGSS HS-ESS2 as well as German Geography standard K2.S3. Timelines were derived from items validated in prior work (e.g., Libarkin *et al.*, 2007). Items probing changes to Earth's shape and size were derived from items and alternative conceptions documented in Libarkin and Anderson (2005) and Libarkin *et al.* (2005). Second, item appropriateness was maintained through translation of the survey into German by a native speaker and ascertained through calculation of the Flesch-Kincaid grade-level score. The survey was designed (content validity: design principles) by two researchers and reviewed by a third researcher, with alignment to norms across the two study countries. The survey was also piloted with student colleagues working in J.L.'s lab to ensure the survey was easy to use and required no more than 10–15 minutes to complete.

During analysis, coding of continental positions and Earth size responses was conducted primarily by P.J., with discussion and revision until agreement was reached with a second author. Coding of all text responses was conducted by J.C. and P.J. in collaboration, with iterative revision of codes through discussion and consensus to reach agreement (interrater reliability). Cultural validity was also established during analysis through continuous comparison of analytical results across the two samples (United States, Germany). Although results differed, there were no obvious discrepancies in how the survey was interpreted by the two samples, indicating that the survey was viewed similarly across the two contexts.

RESULTS

We provide first a summary of our most interesting results, followed by detailed analysis across each data set. In general, most students in both groups recognized Earth as old in absolute terms, although a subset of U.S. students (and no German students) held a belief that the Earth is quite young (<100,000 years old). German students, in fact, tended to hold scientifically correct conceptions of absolute ages for all timeline events. U.S. students, on the other hand, held a wide array of misconceptions about the absolute age of major biologic events (Table 2). A handful of students in both groups believed that dinosaurs still exist today; we note that this belief does not appear to align with an understanding of birds as dinosaurs, as

TABLE 1. Validity and reliability measures used in this study

Validity/reliability	Description	Approach used in this study
During survey construction		
Content validity: test blueprint	Alignment of item content with discipline, expert, and student views of the domain	Content of items derived from multiple sources: 1) NGSS item HS-ESS2; 2) student alternative conceptions and validated multiple-choice items documented in published literature
Content validity: item appropriateness	Ensuring items are usable for all target populations	Language: Survey offered in English and German Readability: Flesch-Kincaid grade level of 6.1 for English version, indicating test is easily understood by U.S. sixth to seventh graders
Content validity: design principles	Extent to which items are written in accordance with research-based best practices	Iterative design and revision until team reached consensus Piloting with student colleagues to ensure appropriate time-on-task and ease of use
During analysis		
Interrater reliability	Extent to which different coders agree	Iterative coding by multiple researchers until consensus reached for all surveys
Cultural validity	The extent to which items perform equally across two samples	Coding process consistent across the two samples, indicating no obvious differences in how different student groups (United States, Germany) interpreted items

the survey explicitly mentioned the extinction of *four-legged* dinosaurs. When examining the relative placement of events, we found that students in both groups tended to provide an accurate chronological occurrence of events. Spacing in between those events was not accurate, however, suggesting that students in both groups had trouble comprehending the relative scale of time separating major biologic events.

The major geologic concepts related to Earth's size and continental positions were generally understood by most participants in both groups. Although the majority of the students believed that Earth's size remains the same over time, 15–25% of students in the U.S. and German groups, respectively, believed that Earth either grew or shrank over time. Finally, most students (>80%) in both groups depicted Earth's continents changing position over time.

TABLE 2. Response rates and maximum, minimum, and median values for absolute age of events in years

	Scientific[a]	U.S. (n = 224)	German (n = 69)
Earth's formation	4.6 billion	Median: 4.6 billion Min.: 365 Max.: 690 billion (n = 121)	Median: 4.6 billion Min.: 200 million Max.: 500 billion (n = 63)
Appearance of first life	3.5 billion	Median: 500 million Min.: 100 Max.: 50 billion (n = 127)	Median: 1.5 billion Min.: 1 million Max.: 280 billion (n = 62)
Appearance of dinosaurs	245 million	Median: 56 million Min.: 100 Max.: 750 billion (n = 132)	Median: 200 million Min.: 500,000 Max.: 260 billion (n = 59)
Disappearance of dinosaurs	66 million	Median: 500 million Min.: 100 Max.: 50 billion (n = 101)	Median: 65 million Min.: 5000 Max.: 250 billion (n = 48)
Appearance of man	200,000	Median: 500 million Min.: 100 Max.: 50 billion (n = 132)	Median: 150,000 Min.: 2500 Max.: 2 billion (n = 64)

[a]Absolute ages from Catley and Novick (2009).

Absolute Ages of Earth's Formation and Biologic Events

Within our study sample, conceptions of the absolute age of Earth's formation ranged from 365 years ago to 690 billion years ago. Within the U.S. sample, absolute ages ranged from the low of 365 years ago to a high of 690 billion; the median value of Earth's age was 4.6 billion, which is scientifically accurate. German students depicted more tightly constrained absolute ages (200 million to 500 billion years ago), with a median view of Earth's age lying at an accurate 4.6 billion years ago. That said, only 19% (N = 12) of the German respondents indicated Earth was between 4.5 and 4.6 billion years old. Among the U.S. participants who wrote down an absolute age for Earth, 7% (n = 9) were classified as Young Earthers based on a belief that the Earth is less than 100,000 years old. No Germans held this view.

Within this study sample, conceptions about the appearance of life ranged from 100 years ago to 280 billion years ago. Within the U.S. sample, most ages ranged from 100 years ago to 50 billion years ago, with a median age of 500 million years ago. Only 9% (N = 11) of U.S. respondents indicated accurately that the appearance of life occurred between 3.0 and 3.5 billion years ago. Young Life beliefs (based on a belief that appearance of life occurred less than 100,000 years ago) were also only present in the U.S. sample (20%, n = 25). Within the German sample, the minimum age of the appearance of life was 1 million years ago, while the maximum age was 280 billion years ago. The median age was 1.5 billion years ago. In this group, 14% (N = 9) indicated appearance of life occurring between 3 and 3.5 billion years ago, and no biblical references were made. Finally, for both Earth's formation and the appearance of life, a subset of U.S. participants (n = 27) made biblical references (these participants are termed "Creationists"). These included references to "god," "the great flood," and use of "B.C." as a stand-in for "years." It is important to clarify that "Creationists" and "Young Earthers/Lifers" as defined in our study are not necessarily the same. Creationists are those who made biblical references in text responses, while Young Earthers/Lifers are those who believe the Earth is less than 100,000 years old and/or that life first appeared less than 100,000 years ago.

The placement of the remaining three events on the timeline (appearance of dinosaurs, disappearance of dinosaurs, appearance of man) provided additional insight into participant conceptions about absolute ages of biologic events throughout Earth's history. As with Earth's formation and the appearance of life, participant responses varied from very young (100 years ago for U.S. respondents; 1 million for German respondents) to quite old (50 billion for U.S. respondents; 280 billion for German respondents) across the three events. Overall, German students generally thought of all events as being quite old, while U.S. students articulated a range of absolute ages from young to old (Table 2).

Relative Placement of Biologic Events

The relative placement of biologic events on timelines provided insight about student conceptions of the relationships between biologic events. Overall, participants tended to place events in the correct order regardless of absolute age conceptions.

As with absolute ages, German students generally depicted biologic events with more accuracy—both in terms of relative placement and order of events (Figure 1). Timeline A in Figure 1 is a typical German student drawing. Essentially accurate, first life (*erstes Leben*) is placed shortly after earth forms (*Entstehung der Erde*) and the appearance of dinosaurs, disappearance of dinosaurs, and appearance of man are placed very close to today (*heute*). Similarly, a U.S. participant (Figure 1B) also exhibited accurate placement of evolutionary biologic events on the timeline. Both participants (Figure 1, A and B) also provided absolute ages of these biologic events that were close to scientific models.

More generally, most participants in both groups accurately predicted the order of evolutionary events as: 1) first life, 2) appearance of dinosaurs, 3) disappearance of dinosaurs, and 4) appearance of man. However, the spacing between these events along the timeline was often inaccurate. Timeline C in Figure 1 illustrates a common U.S. Young Life understanding of the occurrence of biologic evolutionary events. In many of these timelines, man appears: 1) close to first life, 2) often before dinosaurs, and 3) relatively early in Earth's history. Timeline D in Figure 1 offers an example of inaccurate perceptions about the relative and absolute ages of major evolutionary events. This U.S. timeline depicts appearance of life occurring about halfway through Earth's history, with the appearance and disappearance of dinosaurs occurring very close to the appearance of man.

Regarding the relative placements events, German and U.S. participants were similar in their conceptual understanding of the relative occurrence of first life on Earth, with about 20% (n = 50 U.S.; n = 12 German) placing this event close to the correct position. On the other end of the timeline, conceptual understanding of man's appearance was different across the two samples. Greater then 50% (n = 35) of Germans accurately placed man's appearance, while only 21% (n = 48) of U.S. participants did so. Similarly, the coexistence of man and dinosaurs was different for the two groups. Similar proportions of U.S. (n = 73) and German (n = 14) respondents did not include the disappearance of dinosaurs on their timelines; this suggests a belief that dinosaurs still exist. We note that the survey discussed four-legged dinosaurs living on land—this was intentional to avoid references to birds (technically dinosaurs). While participants who noted the modern existence of dinosaurs might have been referring to birds, many explicitly and incorrectly indicated that crocodiles, alligators, or other reptiles are dinosaurs. The remaining participants indicated that dinosaurs disappeared at some point before today. Of those participants who did include a disappearance of dinosaurs, 22% of U.S. (n = 36) and 7% of German (n = 4) students indicated that man and dinosaurs coexisted through inclusion of appearance of man before the disappearance of dinosaurs.

Ternary Diagrams

Ternary diagrams offer a mechanism for comparing timeline event placement with scientific models. On the German side, most participants recognized that man appeared late in Earth's history. However, a wide array of models about the appearance of life existed within the German group; that is, the data are spread out along the left side of the triangle instead of clustering around the scientifically accepted model (the dashed square in Figure 2). On the U.S. side, most participants depicted life appearing early in Earth's history, although the subgroup of Young Lifers tended to place the appearance of life within the

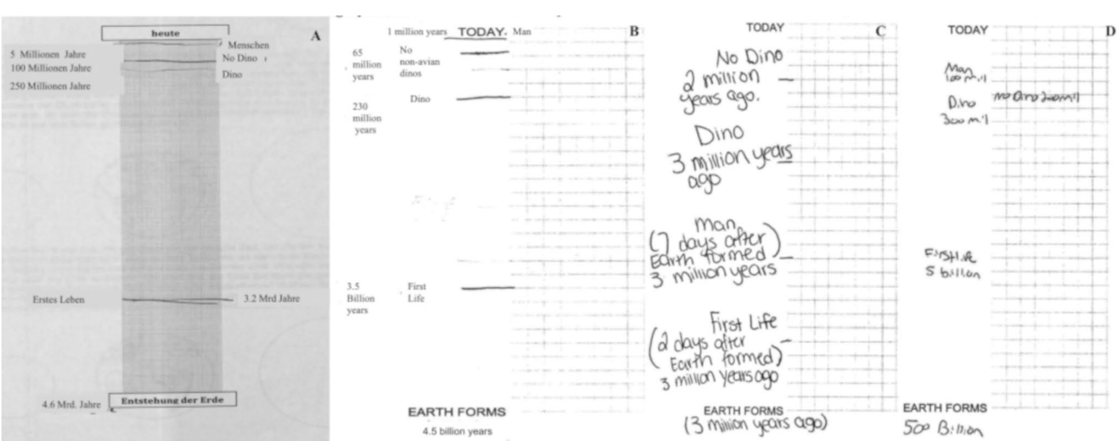

FIGURE 1. Example timelines from German (A) and U.S. (B–D) participants. Timelines A (German) and B (U.S.) demonstrate a close to accurate relative placement and general occurrence of evolutionary events in Earth's history. Timeline C (U.S.) is an example of someone with a Young Life perspective. Timeline D is an example of an inaccurate relative positioning of evolutionary events.

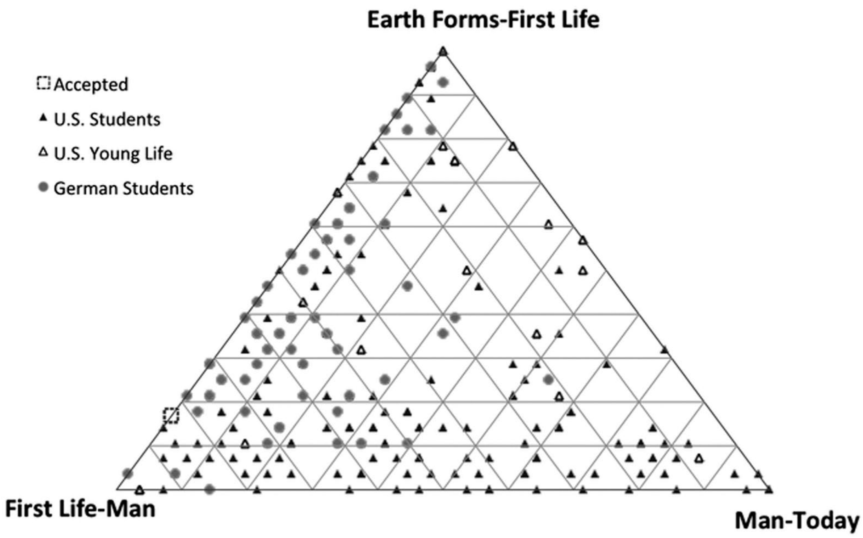

FIGURE 2. Ternary plot of appearance of life and appearance of man relative to Earth's formation and today. "U.S. Students" are all U.S. students except those with a Young Life (life first appeared less than 100,000 years ago) perspective. "German Students" refers to all German students. "Accepted" refers to the accepted scientific perspective. While German participants recognized that man appeared late in Earth's history, within this sample there was a wide array of models for the appearance of life. Most U.S. participants depicted first life appearing early in Earth's history, with the exception of the Young Lifers, who mostly believed that life first appeared late in Earth's history. U.S. participants had a wide array of models of when man appeared.

last half of Earth's history. The accurate model held by many U.S. participants about the appearance of life did not translate to conceptual understanding of the relative appearance of man. A wide range of models of when man appeared is evident by the spread of U.S. participants along the bottom axis (Figure 2).

Earth's Size

The majority of students—72% (N = 144) of U.S. students and 90% (N = 62) of German students—indicated no change in Earth's size over time (e.g., Figure 3, A and B) for both the past and future. Eight U.S. students (4%) and two German students (2.9%) indicated that Earth's size would grow over time, while five U.S. students (2.5%) and one German student (1.4%) indicated Earth shrinking over time. For example, Figure 3D depicts Earth growing over time, with the participant choosing the smallest Earth for the past and the biggest Earth for the future. Finally, 43 U.S. students (22%) and four German students (5.8%) portrayed mixed conceptions about Earth's size throughout time. Figure 3C is an example of a drawing that was coded as having mixed conceptions, with the participant choosing the biggest Earth for both the past and future, indicating Earth shrinking between the past and today and then growing in the future.

Students in both samples were asked to explain their reasoning behind their responses to changes or lack of changes to Earth's size over time. Table 3 presents the most common explanations found in both groups along with example quotes from students. Students who indicated Earth's size would not change either left the response blank or restated that size would not change. Common explanations for changes to Earth's size included impacts to Earth, plate tectonics, expansion of the universe, volcanic eruptions, global warming, and erosion. These explanations were typically simple, without any discourse about connections between these processes and changes in Earth's size. We included more U.S. quotes than German ones, because the belief that Earth changed size over time was more common in the U.S. group than in the German group.

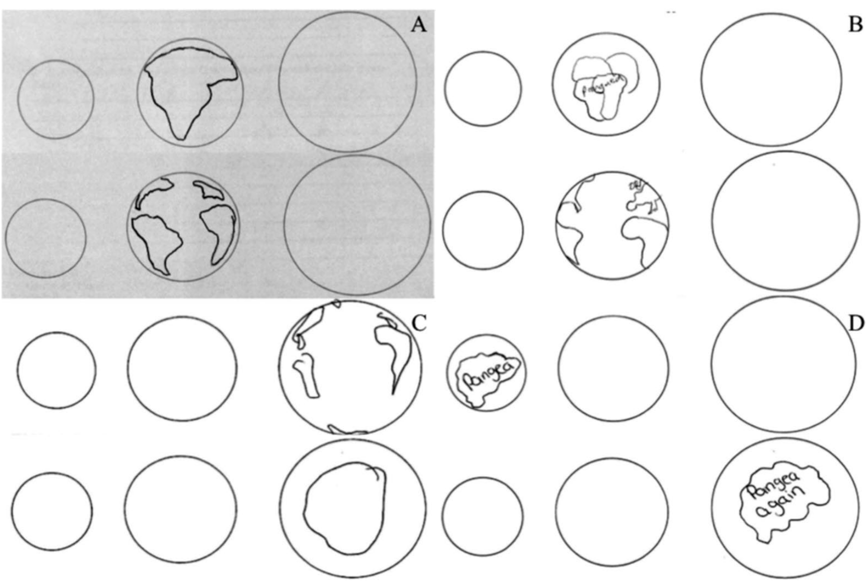

FIGURE 3. Example drawings from German (A) and U.S. (B–D) participants of their perceptions of changes to 1) Earth's size and 2) continental positions over time. (A,B) Examples of Earth's size remaining the same while continents grow apart over time. (C) Example of a mixed conception about Earth's size and continents moving apart over time. (D) Example of Earth growing over time and a mixed conception about continental positions over time.

Earth's Continental Positions

We also examined U.S. (n = 214) and German (n = 69) students' perceptions about changes to continental positions over time. For U.S. responses, this resulted in 3.7% (N = 8) being left out of the past Earth responses and 1.9% (N = 13) being left out of the future Earth responses. For German students, this resulted in 10% (N = 7) being left out of past Earth responses and

TABLE 3. Common explanations made by U.S. and German participants for their causal explanations for changes to Earth's size and continental positions over time

Student explanations for:		Example student quotes
Changes to earth's size over time	Impacts to Earth	"Because of material from space size and volume of Earth will grow."—German participant
	Plate tectonics	"I think it changes because of how our continents have spread apart."—U.S. participant
	Expansion of universe	"The expansion of the universe."—U.S. participant
	Global warming	"I think Earth's size changes over time due to pollution expanding & breaking the o-zone and heat makes things expand."—U.S. participant
	Volcanic eruptions	"It grows over time b/c of volcanic eruptions."—U.S. participant
	Erosion	"I think it could become smaller as it is eroded by the sun/pollution over long periods of time."—U.S. participant
Changes to Earth's continental positions over time	Plate tectonics	"Earths [*sic*] surface is constantly changing b/c of the plates moving and separating or joining countries together."—U.S. participant, Creationist
	Erosion	"The Earth's surface changes because of wind erosion, global warming, and other environmental factors."—U.S. participant
	Natural disasters	"Natural disasters such as Earthquakes or volcanic eruptions erode and change the Earth."—U.S. participant

14.3% (N = 10) being left out of future Earth responses. Most U.S. students (N = 174; 81%) drew Earth as having a supercontinent in the past. Only 8.4% (N = 18) drew the continents as apart in the past, and 1.4% (N = 3) drew continents in the same position as today. For German students, 79% (N = 55) drew Earth having a supercontinent in the past, 10% (N = 7) depicted continents apart in the past, and 1.4% (N = 1) drew continents in the same position today as in the past. In the U.S. group, 14% (N = 30) of the participants drew Earth as having another supercontinent in the future, 70% (N = 150) drew continents apart in the future, and 4.7% (N = 10) depicted continents in the same position as today. In the German group, 39% (N = 27) of the participants drew Earth as having another supercontinent in the future and 46% and (N = 32) drew continents being apart in the future. None of the German students drew the continents in the same position as today.

U.S. and German students generally depicted a change in continental positions over time; only one U.S. student indicated no changes in continental positions in both the past and future. One hundred and thirty-five (70%) U.S. students and 25 (42%) German students portrayed continents moving apart in their drawings. Two examples of this can be seen in Figure 3, A and B, where the drawings both depict a supercontinent in Earth's past and continents apart in Earth's future. One U.S. student (0.52%) and one German student (1.7%) portrayed continents coming together over time to form a supercontinent. Figure 3C is a U.S. student's drawing depicting Earth's continents apart in the past and coming together to form a supercontinent in the future. Drawings that were inconsistent with Earth's continents moving apart, coming together, or remaining the same, were coded as exhibiting mixed conceptions about Earth's continental positions over time. Many students in both samples (29% [N = 55] of U.S. students and 56% [N = 33] of German students) portrayed mixed conceptions about changes to the continental positions throughout time. An example of a mixed-conceptions drawing can be seen in Figure 3D, where a student depicted Earth being smaller than today in the past, and predicting that it will be bigger than today in the future.

The majority of participants in both groups demonstrated the understanding that Earth's continents moved over time. U.S. participants were asked to explain the reasoning behind their responses to changes or lack of changes to Earth's continental positions over time. Germans were not asked to explain their reasoning behind changes to Earth's continents over time, and thus we only include U.S. responses. Table 3 shows the most common themes found in the U.S. group, along with representative quotes from students. The majority of students indicated a change to continental positions over time and provided an explanation for their responses (n = 202). A common explanation for the movement of continents included the theory of plate tectonics, the commonly accepted cause; this response appeared in 82% of responses. Misconceptions about continental movement included causal mechanisms resulting from erosion, natural disasters, global warming, and humans (Table 3). The presence of misconceptions for continental movement in nearly 20% of responses suggests entrenched conceptions despite instruction.

DISCUSSION

Stemming from a cross-cultural recognition that biology and earth science need to be integrated (Danielson and Tanner, 2015), this research investigated how a purposeful sample of U.S. and German college students conceptualize large-scale changes to Earth's biology, size, and continental positions throughout long geologic time, including the relationships that exist between student paradigms related to the timing of Earth's formation and their conceptions of physical and biologic changes to Earth. To our knowledge, this is the first study examining college student conceptions about the coevolution of Earth's systems and life on Earth, and as such serves as a proof of concept for investigating two complex sets of phenomena simultaneously. Analysis of these conceptions is important, as it provides insight into how college students perceive and understand the simultaneous geologic and biologic changes occurring throughout Earth's history, especially as these phenomena may not be cotaught. Here, we present our main findings along with conclusions and implications for future research into student's conceptions and misconceptions about the coevolution of biologic and geologic events on Earth.

The majority of participants in the two study samples held accurate understandings of the chronological occurrence of evolutionary events, with Earth forming first, followed by the appearance of life, appearance and disappearance of dinosaurs, and appearance of man. At the same time, most participants in both groups had a poor understanding of the absolute ages of events and the time spans between those events. Both U.S. and German samples hold similar understanding about evolutionary events, including absolute and relative ages of those events, with the major difference between the groups being that participants with Creationist and/or Young Earth/Young Life perspectives were only observed in the U.S. group. The presence of Creationist views among U.S. participants and lack of such a perspective among our German participants suggests a higher level of conflict between religion and scientific understanding (or lack thereof) in the United States than in Germany. This is likely due to religion playing such an influential (and controversial) role in U.S. culture when it comes to policy, education, and U.S. citizens' ways of life (Gallup, 2017), something not as prominent in German or European culture.

Common misconceptions about changes to Earth's size among both groups of students may be rooted in historical and intuitive scientific views such as the expanding Earth theory. Historical and intuitive thinking about the world has been examined often in the bioscience education realm when exploring how individuals, across all age groups, understand biologic concepts (Trend, 2000; Dodick, 2007; Libarkin *et al.*, 2007). When examining misconceptions among college biology students, Coley and Tanner (2015) found a linkage between certain misconceptions in biology and what they described as "cognitive construals," an intuitive way of thinking about the world. Although only a small portion of individuals from the current study portrayed changes in Earth's size over time, further research in exploring the relationship between cognitive construals and geologic phenomena might be useful, specifically on perceptions about a growing or shrinking Earth. This is important when considering that students will be exposed to many ideas about Earth for the first time in science classrooms and thus will likely create new ideas as they are exposed to new concepts.

To the best of our knowledge, this is also the first study examining student perceptions about changes to Earth's size, and further research across age groups is warranted when we consider common misunderstandings about plate tectonics (Clark *et al.*, 2011). Given the NGSS expectation that college-bound individuals should understand the coevolution of Earth's systems (geologic) and life on Earth (biologic), it might be beneficial to understand how intuitive ways of thinking influence understanding of Earth's systems and explore how those perceptions influence understanding and/or acceptance of both geologic and biologic concepts.

It is important to note that reasons for student misconceptions cannot all be attributed to historical scientific theories. Student explanations for changes in the size of the Earth also indicate typical learning difficulties of students in understanding geosciences. For example, students commonly have difficulty handling spatial-scale levels (Trend, 1998, 2001; Libarkin *et al.*, 2007; Catley and Novick, 2009; Cheek, 2013). One of our participants indicated that Earth will grow "Because of material from space." While material from space certainly accretes to Earth, this accretion is negligible relative to the actual volume of the planet. Similarly, the tendency to structure processes as linear or additive, rather than cyclic, results in violations of basic principles of conservation. For example, students may believe that processes that move material from one place to another will result in growth in the planet. One student, for example, suggested that "Earth will grow over time because of volcanic eruptions." This aligns with research about student conceptions related to earth science concepts in adolescents (Felzmann, 2014) as well as among young children (Libarkin and Schneps, 2013).

What Relationships, If Any, Exist between Student Paradigms about Absolute and Relative Times and Their Conceptions (and Underlying Causes) That Occur to Life and the Planet?

Both the German and U.S. groups had misconceptions relating to relative and absolute ages of evolutionary events; a struggle not unique to a specific sample or country. This echoes findings from previous studies on student conceptions related to student understanding of evolutionary timescales (Trend, 1998, 2001; Trend *et al.*, 2007; Catley and Novick, 2009). However, many of the studies that examine these perceptions among students are mostly done on U.S. samples and in the context of historical geologic events. This study was unique in that we explored conceptions across two samples, one from the United States and the other from Germany, and focused on *both* biologic and geologic events throughout history.

While U.S. student participants with Creationist perspectives were likely influenced by their religious beliefs when responding to our survey (as indicated by the many biblical references in their responses), participant responses with a Young Earth or Young Life perspective can be attributed to other factors. Conflicts between religion and science, as well as societal anti-evolution messages are more predominant in the United States than in Germany or Europe (Lombrozo *et al.*, 2008; Institut für Demoskopie Allensbach, 2009; Barone *et al.*, 2014; Gallup, 2017), which may explain why Creationist perspectives were only seen in the U.S. group. Though negative attitudes toward evolution are often attributed to religious beliefs (Lombrozo *et al.*, 2008; Barnes and Brownell, 2016), we note that studies suggest that understanding the nature of science, thinking dispositions, and statistical reasoning may also influence understanding and/or acceptance of evolution (Deniz *et al.*, 2007; Lombrozo *et al.*, 2008; Akyol *et al.*, 2012; Dunk *et al.*, 2017; Ha *et al.*, 2019; Fiedler *et al.*, 2019).

Knowledge of the nature of science may contribute to better understanding and/or acceptance of evolution (Lombrozo *et al.*, 2008; Kim and Nehm, 2011). It has been recommended that educators focus on the nature of how science works during scientific instruction (Lammert, 2012; Scharmann, 2018) and utilize culturally competent teaching practices (Barnes and Brownell, 2017) to connect with a diverse range of students. Though Lombrozo *et al.* (2008) point out that having a better understanding of how science works may not engage students who endorse Creationism or other alternative conceptions in rejecting those beliefs, this approach may be most beneficial to students who are undecided about evolution and not committed to a particular alternative conception (e.g., Creationism). Understanding the nature of science may help students think critically about anti-evolution messages they may encounter in society and may foster easier understanding and/or acceptance of evolutionary concepts following scientific instruction (Johnson and Peeples, 1987; Lombrozo *et al.*, 2008; Akyol *et al.*, 2012).

How Does This Research Explicate Interdisciplinary Integration of Concepts within School Curricula?

As we stated earlier, similar misconceptions existed among both groups of students (United States, Germany), the biggest difference being the presence of individuals with a Creationist or Young Earth/Young Life perspective in the United States. Interestingly, individuals with Creationist perspectives did not have difficulties with referencing the theory of plate tectonics in their survey responses when asked to explain changes to continental positions over time. This raises an interesting question of why one theory is easier to accept and understand than another for individuals with highly religious beliefs? Would coteaching the two theories (evolution and plate tectonics), while also using a culturally competent teaching approach (Barnes and Brownell, 2017), allow for easier understanding and/or acceptance of the theory or evolution and other scientific concepts?

Traditionally, the theory of evolution and the theory of plate tectonics are taught as separate entities in bioscience and geology/geography courses, respectively. Some science education researchers argue that, in order to understand biologic evolution, it is necessary to also have an understanding of geologic history and vice versa (Catley and Novick, 2009; Cotner *et al.*, 2010). From a geologic perspective, continental positions greatly influence evolution of life on Earth. For example, recent research suggests that continental shifting has direct and indirect effects on biodiversity (Leprieur *et al.*, 2016; Zaffos *et al.*, 2017). One benefit to coteaching the two subjects could be better understanding of the two disciplines, thus achieving NGSS and German educational standards relating to the understanding of the coevolution of Earth's systems (geologic) and life on Earth (biologic)

Newly developed educational standards in the United States (NGSS Lead States, 2013) and in Germany (Sekretariat der Ständigen Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland, 2004) have sought to integrate the teaching of biologic and geologic concepts. In the United States, the NGSS represent a consensus view of concepts that students across the United States should know and understand as they move through the K–12 curriculum and enter postsecondary educational institutions. The inclusion of coevolution of geologic and biologic phenomena as a core standard raises interesting questions about how well the current curriculum is providing the context needed for achieving this standard. We suggest that one approach is for teachers to use conceptual change theory as a jumping-off point for teaching coevolution with students (Posner *et al.*, 1982). As Hewson (1992) and Richmond *et al.* (2010) have noted, encouraging students to depict their views of evolution (in bio- or geoscience) can serve as a foundation for further exploration of difficult concepts. Conceptual change and acceptance of scientific theories can be difficult (Dole and Sinatra, 1996), especially for students with strong religious, sociocultural, or intuitive beliefs. In line with other recommendations from Lombrozo *et al.* (2008), we suggest that a way to achieve this goal is to teach students the nature of how science works. Science educators should not aim to change their students' beliefs, but rather should provide the foundational knowledge needed to understand (and possibly accept) difficult concepts within the context of scientific inquiry. Recent research by Fiedler *et al.* (2019) has also suggested statistical reasoning as another factor that may contribute to evolutionary understanding. To achieve the NGSS and German standards regarding student understanding of the coevolution of geologic and biologic systems, we follow the recommendations of Fiedler *et al.* (2019) and suggest that science educators integrate quantitative literacy into their curricula in order to develop effective biologic evolution curricula. Quantitative reasoning may similarly impact student ability to grasp geologic change.

An approach for teaching the theory of evolution to individuals who may experience conflicts between their religion or culture and evolution education is to provide instruction using culturally competent educational practices, such as those suggested by Tanner and Allen (2007) and Barnes and Brownell (2017). In general, cultural competency can be understood as the ability to understand, communicate, and interact with individuals from different cultures (Tanner and Allen, 2007). Barnes and Brownell (2017) first introduce the framework of Religious Cultural Competence in Evolution Education (ReCCEE) and suggest utilizing the framework as a way to organize the teaching of evolution. This approach may bridge the gap between biology instructors and the religious cultures of their students, allowing for an inclusive classroom environment and reducing perceived conflict between religion and evolution (Barnes and Brownell, 2017; Truong *et al.*, 2018).

STUDY LIMITATIONS AND FUTURE DIRECTIONS

This study provides a first step toward understanding students' conceptions of the coevolution of Earth's systems and life on Earth through simple investigation of the relationships between large-scale evolution and changes to the Earth. At the same time, this study did not probe deeper knowledge about Earth's systems or evolution. Future studies should consider examining student's conceptions of smaller evolutionary or geologic events and time periods. This would allow for a more accurate understanding of students' conceptions of the simultaneous relationship between these two linked systems. Another major limitation in this study is that our results are based on student samples at two colleges, one in the United States and one in Germany. To get a larger, more representative sample in the future, it will be important to expand research to other universities across both countries and into other countries. Other researchers have specifically inquired about their subjects' political and religious beliefs (Cotner *et al.*, 2010), although we did not probe for these variables. Although research studies have found that students with conservative or religious beliefs are less likely to accept evolution (Barnes *et al.*, 2017), investigation of the role of similar beliefs in shaping ideas and acceptance of geologic evolution would be invaluable. Certainly, many studies have found that worldview impacts conceptions of climate change (Goebbert *et al.*, 2012; Libarkin *et al.*, 2018), and related studies in the context of other geologic phenomena would be worthwhile. We hope this paper serves as a starting point for many more studies at the intersection of geo- and biosciences and believe collaborations between the two disciplines within science education are vital for any future work.

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