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To cite this article:

You, H. S., Delgado, C. & DeAtley, K. (2021). Experts' model-based reasoning and interdisciplinary understanding of carbon cycling. *International Journal of Research in Education and Science (IJRES)*, 7(2), 562-579. <https://doi.org/10.46328/ijres.1494>

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Article Info

Article History

Received:

11 August 2020

Accepted:

19 February 2021

Keywords

Carbon cycling

Drawing-based models

Interdisciplinary

understanding

Standards

Abstract

The global carbon cycle (CC) is a key environmental literacy issue related to climate change, ocean acidification, and energy sustainability. Understanding the CC requires interdisciplinary knowledge informed by multiple science disciplines such as biology, chemistry, earth science, and physics. To examine the core principles and interdisciplinary nature of CC, we interviewed 10 experts from various science disciplines and asked them to create their own models of the carbon cycle. We utilized the data to identify emerging core concepts of CC and discover commonalities and differences across the experts' models in the context of interdisciplinary understanding. The concepts and interdisciplinarity were compared with those of CC-related topics in the U.S. Framework and Next Generation Science Standards. Most experts demonstrated a breadth of interdisciplinary knowledge based on their disciplinary backgrounds. The experts hold a wider set of ideas about CC than is present in the standards. Many topics not included in the standards could feasibly be added (e.g., the process of carbon sequestration into the ocean and rocks and CO₂ emissions by volcanic activity). This study generates concrete recommendations for science standards to guide the revision of existing curricula or to guide the development of new interdisciplinary approaches to teaching global CC.

Introduction

The global carbon cycle (CC) depicts the multiple pathways by which carbon (in the form of various compounds) moves through terrestrial systems, including the land, rocks, oceans, and atmosphere. The carbon cycle includes processes vital to life, such as photosynthesis and cellular respiration, fossil fuels as vital energy sources, and the greenhouse effect. Anthropogenic disruptions of the CC via the burning of fossil fuels and deforestation along with natural phenomena (volcanic eruptions, chemical weathering, etc.) contribute to wide-ranging environmental issues such as global warming, climate change, and ocean acidification. The carbon cycle is a critical consideration for designing sustainable development patterns that could reduce current ecological, economic, and societal threats. Science education must prepare students to understand how the carbon cycle's components and processes function, how these are related in a complex system, and how and why disruptions to the carbon cycle pose significant environmental challenges, so that, as scientists and citizens, they can take appropriate actions.

Because natural and socioscientific phenomena, including the carbon cycle, are intrinsically interdisciplinary, a single-discipline perspective may be insufficient for developing solutions to problems or models to better understand the phenomena (You et al., 2018). Understanding the carbon cycle requires interdisciplinary scientific knowledge, and interdisciplinary understanding in the context of carbon cycling is defined as the following:

Performance of students in integrating knowledge from different science disciplines to explain a scientific phenomenon or to develop an argument about a scientific problem that cannot be dealt with adequately by a single discipline, in the context of carbon cycling. (You et al., 2019, p. 9)

Interdisciplinary learning about the carbon cycle helps students develop an essential core of knowledge to determine the big picture and make explicit links among the individual science disciplines that inform this important topic. Interdisciplinary learning also aids students by providing the skills, practices, and knowledge associated with the relevant disciplines.

Both the carbon cycle and interdisciplinary learning have received growing attention in the United States, as reflected in the national K–12 standards for science education. Whereas the National Science Education Standards (National Research Council [NRC], 1996) mention *interdisciplinary learning* once and the *carbon cycle* twice, the more recent Next Generation Science Standards (NGSS Lead States, 2013) and the Framework (NRC, 2012), which guided the development of the NGSS, together mention *carbon cycling* over a dozen times and *interdisciplinarity* four times. However, there is little research regarding how science experts focus on interdisciplinary links to think about the carbon cycle.

Several studies have explored students' interdisciplinary knowledge about carbon cycling through an instrument called the Interdisciplinary Science Assessment for Carbon Cycling (You et al., 2018) and through students' model-based reasoning about carbon cycling in curricular interventions (Zangori et al., 2017). This study extends that work by analyzing, in depth, the interdisciplinary knowledge of 10 experts, contrasting it across experts and relating their knowledge to the concepts included in the U.S. standards. We thereby address the gap concerning expert knowledge in carbon cycling and its potentially interdisciplinary nature.

The study is guided by the following research questions:

- 1) What do experts in various scientific disciplines know about the carbon cycle?
- 2) How does interdisciplinary knowledge about the carbon cycle vary across science experts?
- 3) How does the experts' knowledge about the carbon cycle compare to the U.S. K–12 science standards?

To explore these questions, we conducted semistructured interviews with 10 science experts from various disciplines and analyzed their carbon cycling models. In the models, we identified the core components and then compared them among the experts and against the science standards (the NGSS and Framework).

Theoretical Background

Concepts Related to Carbon Cycling in the U.S. Standards

Disciplinary core ideas (DCIs) represent key concepts of a single discipline for understanding more complex

issues and ways to solve them. The DCIs, however, are often interdisciplinary and generate connections that are closely intertwined around the physical sciences (PS), earth and space sciences (ESS), and life sciences (LS). This study explored the DCIs for middle and high school students related to CC in the NGSS. For example, photosynthesis and cellular respiration are important concepts in the life sciences at both the middle and high school levels. The following excerpts from the NGSS include statements of what students should know and what they should do to learn about photosynthesis and cellular respiration. Middle-school and high-school DCIs are identified in parentheses:

- The chemical reaction by which plants produce complex food molecules (sugars) requires an energy input (i.e., from sunlight) to occur. In this reaction, carbon dioxide and water combine to form carbon-based organic molecules and release oxygen (MS-LS1-6).
- Cellular respiration in plants and animals involves chemical reactions with oxygen that release stored energy. In these processes, complex molecules containing carbon react with oxygen to produce carbon dioxide and other materials (MS-LS1-7).
- Photosynthesis and cellular respiration are important components of the carbon cycle, in which carbon is exchanged among the biosphere, atmosphere, oceans, and geosphere through chemical, physical, geological, and biological processes (HS-LS2-5).

Additionally, the ESS3 DCI from the NGSS framework includes an important topic: human activities in carbon cycling. Knowledge of human activities helps students formulate answers to questions such as the following: “How do human activities affect Earth systems and their living organisms, and how does the release of excess CO₂ from burning fossil fuels impact the global climate?” In the ESS3 performance expectations, students are expected to demonstrate their understanding of one of the core ideas in carbon cycling by constructing an explanation and engaging in an argument:

- Human activities have significantly altered the biosphere, sometimes damaging or destroying natural habitats and causing the extinction of other species. However, changes to Earth’s environments can have different impacts (negative and positive) for different living things (MS-ESS3-3).
- Human activities, such as the release of greenhouse gases from burning fossil fuels, are major factors in the current rise in Earth’s mean surface temperature (leading to global warming). Reducing the level of climate change and reducing human vulnerability to whatever climate changes do occur depends on our understanding of climate science, of engineering capabilities, of human behavior, and on our wise application of that knowledge in decisions and activities (MS-ESS3-5).
- Changes in environmental conditions (e.g., deforestation and global warming) may result in (a) increases in the number of individuals of some species, (b) the emergence of new species over time, and (c) the extinction of other species (HS-LS4-5).

Another important subcore idea in carbon cycling is “matter cycles and energy flow” in living organisms. The performance expectations in LS2, PS3, and ESS2 from the NGSS show that students must develop qualitative ideas on the matter cycles and energy transfer process. Students develop their understanding of important qualitative ideas about the concept of energy transfer from one object or system of objects to another. Students are also expected to understand the movement of matter among plants, animals, and decomposers through the

food chain or food web—where carbon is an important element in matter cycles:

- Food webs are models that demonstrate how matter and energy are transferred among producers, consumers, and decomposers, particularly as the three groups interact within an ecosystem. The transfer of matter into and out of the physical environment occurs at every level. Decomposers recycle nutrients from dead plant or animal matter back to the soil in terrestrial environments or to the water in aquatic environments (MS-LS2-3).
- Plants or algae form the lowest level of the food web. At each link upward in a food web, only a small fraction of the matter consumed at the lower level is transferred upward to produce growth and to release energy in cellular respiration at the higher level. Given this inefficiency, there are generally fewer organisms at higher levels of a food web. Some matter reacts in a way that releases energy for life functions; some matter is stored in newly made structures; and much is discarded. The chemical elements that make up the molecules of organisms pass through food webs and into and out of the atmosphere and soil, and they are combined and recombined in different ways. At each link in an ecosystem, matter and energy are conserved (HS-LS2-4).
- Energy cannot be created or destroyed, but it can be transported from one place to another and transferred among systems (HS-PS3-1 and HS-PS3-4).
- All Earth processes are the result of energy flowing and matter cycling within and among the planet's systems. This energy is derived from the sun and the hot interior of the earth. Flowing energy and cycling matter produce chemical and physical changes in Earth's materials and living organisms (MS-ESS2-1).

Interdisciplinary Expert Understanding

The need for and importance of the interdisciplinary perspective in science education have been recognized in the Framework (NRC, 2012) and in the NGSS. The Framework recognizes that “we acknowledge the multiple connections among domains. Indeed, more and more frequently, scientists work in interdisciplinary teams that blur traditional boundaries” (NRC, 2012, p. 31). The NGSS takes a step forward in supporting interdisciplinary teaching and learning by listing connections from each DCI to other DCIs in the same grade band, some of which are in other disciplines and, thus, are interdisciplinary. Another way in which the current U.S. standards address interdisciplinarity is through “crosscutting concepts” (CCC) such as “scale, proportion, and quantity,” “patterns,” “cause and effect,” and “stability and change.” CCCs are posited to “bridge disciplinary boundaries” (NGSS Lead States, 2013, p. 1), uniting core ideas throughout the fields of science and engineering. Their purpose is to help students deepen their understanding of the core disciplinary ideas and develop a coherent and scientifically based view of the world (NRC, 2012). The first type of interdisciplinary connection—links across DCIs—is more explicit and specific than the second type—CCCs. Yet the actual nature of experts' interdisciplinary understanding of complex phenomena is an open empirical question, particularly regarding the carbon cycle.

Experts possess more extensive and organized knowledge and are better than novices at perceiving meaningful patterns among relevant concepts (Bransford et al., 2000; Chi, 1988). Kozma and Russell (1997) provided a key expert knowledge principle regarding interdisciplinary understanding: “The knowledge of experts consists of a

large number of interconnected elements that are stored and recalled as time and information as extended, coherent chunks of information organized around underlying principles in specific domains” (p. 2). Accordingly, experts have identified core concepts from various disciplines to understand the relationship of their own disciplines to other disciplines (Kline, 1995), which can help them envision the big picture of knowledge connections to explain phenomena. It is thus important to study how experts organize the knowledge that reveals their interdisciplinary understanding, and which provides insight into interdisciplinary education.

Drawing-Based Modeling

Model-based approaches and modeling are currently considered key practices for scientific literacy. The Framework and NGSS state the importance of understanding their roles in science education. Modeling is defined as the cognitive process of making and using conceptual models (Hestenes, 1996); thus, modeling can be a powerful tool to guide explanation, interpretation, understanding, and the discovery of complex phenomena (Gilbert et al., 1998; Quillin & Thomas, 2015). Specifically, models using graphical representations help scientists and students express and process their understanding of scientific phenomena, making abstract ideas visible. In this study, we focus on the use of drawing as a tool for visualizing phenomena, as well as the processes involved. Engaging the experts in the construction of models provides opportunities for us to explore and identify their key concepts and the interdisciplinary nature of the relevant relationships among the concepts. Furthermore, constructing the models may help with better portraying the experts’ reasoning and their causal explanations of the mechanisms that underlie phenomena.

Modeling to explain scientific phenomena has been extensively used in science education. Zangori et al. (2017) developed a curriculum unit about carbon cycling and climate change in the context of a socioscientific issue (SSI) for a high school biology class. In the 2-week unit, students developed, evaluated, and revised their carbon cycle models for use as interpretive tools. The authors examined how students’ model-based explanations changed over time during the SSI unit. They used models as explanatory tools for supporting students in understanding carbon cycling and engaging in modeling-based reasoning. Heijnes et al. (2018) applied drawing-based modeling to the domain of evolution. Students in lower secondary education participated in creating an evolutionary model over four iterations. After each iteration, detailed scaffolding and instructions were provided based on students’ comments and the teachers’ observations. Van Joolingen et al. (2015) asked elementary students to create solar system models in drawings, with the intent of explaining solar and lunar eclipses using the models; the drawings were then turned into simulations. Their findings showed that the quality of the students’ drawings and their attitudes toward the simulation tool contributed to learning gain. Although modeling approaches based on a drawing are used to support students’ understanding and reasoning in diverse science topics, very few studies have applied modeling to examine science experts’ conceptual understanding.

Method

Recruitment of Participants

For the purpose of this study, faculty members with a science background and high school science teachers were

eligible to participate. A purposive sampling technique provided a more homogeneous population to better understand and describe the participants' knowledge of CC. We contacted all possible participants via direct emails and in-person meetings, asking if they would like to participate in this study. Once experts expressed interest in participating in the study, the third author arranged a time to meet with the potential participants. During this meeting, we explained the study's goal and answered any questions from the potential participants. Participation in the study was strictly voluntary. Participants who agreed to be involved in the study read and signed informed consent forms to indicate their agreement to include their responses.

Participants

A total of 10 science experts were recruited in this study. The participants included seven university instructors at a public university and three science teachers from the same high school. Before the interviews, the experts filled out a short questionnaire to provide demographic information such as gender, race, subjects taught, and years of teaching experience. Five were women and five were men, and their teaching experience ranged from 3 to 23 years in K–16. Seven of the instructors were White, and three were Asian. Each participant in the study received a pseudonym to be used for data analysis and reporting. Table 1 provides the summarized demographic characteristics for each of the experts.

Table 1. Characteristics of Participants

Name	Rank	Gender	Race/ Ethnicity	Yrs in Teaching	Subject Taught
Ryan	Assistant Professor	Male	White	9	Physical Geology
Abbey	Assistant Professor	Female	White	23	Plant Biology
Jamie	Professor	Female	White	38	Biology and Science Education
David	Assistant Professor	Male	White	10	Paleontology
Emily	Assistant Professor	Female	Asian	8	Organic and Biochemistry
Taylor	Assistant Professor	Female	Asian	3	Intro Physical Science, General Physics
Carl	Visiting Professor	Male	Asian	10	General Physics
Mark	Science Teacher	Male	White	15	Secondary Biology
Amber	Science Teacher	Female	White	4	Secondary Environmental Science
Chase	Science Teacher	Male	White	12	Secondary Biology

Data Collection Procedure

In this study, we employed a semistructured interview with guided questions, and each participant individually met with the first and third author for the face-to-face interview. Each interview lasted approximately 30 min. The interview began with a general explanation of the purpose of the study and the participants' role in it. Then, we asked broad and open-ended questions regarding their educational or professional backgrounds, with the goal of elucidating the influence of the discipline on the participants' thoughts and their ability to explain CC. They were then interviewed using the semistructured protocol. The initial questions, such as, "What comes to

mind when you hear the phrase, “global carbon cycling?” were designed to elicit their thoughts about global CC. Follow-up questions such as, “Do you think interdisciplinary knowledge or understanding information by multiple science disciplines is necessary to understand carbon cycling?” were used to capture their ideas of the interdisciplinarity of CC. The next questions were about the participants’ disciplinary knowledge of CC in relation to their science backgrounds and about the interdisciplinary relationships within their knowledge of global CC.

Although the participants described important concepts and the relationships among these concepts based on their science disciplines, we asked each one to draw a concept map of the CC to visually confirm, in depth, the concepts and their interdisciplinary relationships. Before asking the participants to draw concept maps, the third author explained how to draw one and showed a snapshot of an example to ensure that participants were familiar with concept mapping. The participants were provided with unlimited time, but all finished within 40 min. Note that the broad concepts of expert knowledge mentioned in the research questions were further defined by asking the experts about the themes and concepts inherent in carbon cycling. We expected each expert to have their own personal ideas about the key attributes and concepts of the carbon cycle.

Data Analysis

Semistructured Interview

This study drew from the in-depth interviews with each of the 10 science experts to capture their disciplinary and interdisciplinary understanding of global carbon cycling. We audio recorded and transcribed all the interviews and imported the transcripts into the qualitative data analysis software program NVivo 12 (QSR International, 2020). We read and reread the transcripts to familiarize ourselves with the interview data. To address the first research question, we used line-by-line open coding to generate the initial codes for the CC concepts. We also used a constant comparison method to compare emerging codes and themes across all participants to eliminate bias during the analysis (Glaser & Strauss, 1967). The second step of the coding was axial coding, in which we grouped the initial codes into categories and subcategories to generate the overarching categories. This process involved using a triangulation method to increase the study’s reliability and allow consistent investigation. We then reexamined the entire data set and determined that each of these codes fit into the overarching categories of CC (e.g., reservoirs and flux, human activities, socio-scientific issues). One science educator and one undergraduate student who was a geology major then used peer review to triangulate the results to ensure the codes were appropriately coded and to check for any inconsistencies. If alternative codes popped up in different views, we conferred to address the differences in meetings.

Drawing-Based Models

For our qualitative analysis of each model, we started by extracting the experts’ disciplinary and interdisciplinary knowledge from the models. After evaluating the experts’ articulated models, we focused on the variations among the experts’ interdisciplinary conceptualizations of CC.

Comparing Models with the Framework

This last step involved identifying disciplinary core ideas and crosscutting concepts from the Framework that were present in the experts' work, as well as identifying expert-level ideas that were not present. The first author searched through the Framework using keyword searches corresponding to each proposition. For instance, the term *carbon sequestering* from one of the experts' models is not present in the Framework. In fact, the Framework includes a "boundary" statement at the end of grade 12, stating that "photosynthesis and respiration are important components of the carbon cycling" (NRC, 2012, p. 154) but provides no details about how carbon can be captured in photosynthesis and how it can mitigate or defer global warming. Information about other processes by which atmospheric carbon can be stored were not included. In contrast, some concepts were easily mapped onto the Framework's multiple DCIs. For example, the concept that plants carry out photosynthesis, present in most maps, appeared in multiple DCIs, including all three NGSS disciplines (PS3.D, p. 129; LS1.B, p. 146; LS1.C, p. 147; ESS2.D, p. 186; and ESS2.E, p. 189).

Results

RQ1) What do Experts Know About the Carbon Cycle?

The experts' emergent disciplinary or interdisciplinary concepts extracted from each interview transcript and model yielded five key components—carbon reservoirs and flux, energy and carbon movement, geological activity, human activity, and socio-scientific issues—that are essential for understanding carbon cycling and that could serve as tools for interdisciplinary learning.

Carbon Reservoirs and Flux

Most experts demonstrated their knowledge of different reservoirs in the Earth system. These reservoirs include the atmosphere, biosphere, geosphere, and hydrosphere. The experts described how the reservoirs are interconnected with each other and explained the carbon exchange between them. For example, David (a geology professor) provided this description:

the movement of carbon between the various spheres in the earth, primarily from the atmosphere into the hydrosphere, into the biosphere and into the geosphere and the interactions between those spheres and how carbon is moved between them.

Ryan (also a geology professor) demonstrated his knowledge of various forms of carbon among different reservoirs in the Earth system. For example, he mentioned that

it is so important that we start off with a reservoir of CO₂ in our atmosphere and that is put into the atmosphere through volcanoes. All right? Volcanoes emit CO₂ into the air and then those molecules can combine with seawater to make a whole new chemical called bicarbonate. That's HCO₃⁻, so that's now just in essence, a different molecule, but CO₂ is still in there.

Amber (a science teacher) stated that carbon remains for some time and that CO₂ moves from one area to

another, referring to

our [manufacturing] plants that run on non-renewables generating carbon into the atmosphere and how that also is part of that atmosphere carbon, that cycles with the oceans and is burning ancient carbon and adding that to the atmosphere.

Another science teacher (Mark) specifically described ocean and atmospheric carbon reservoirs and how they take up the carbon:

You're thinking about how these carbons are going to circulate. The oceans are taking up carbon, right, so that can have an effect on that. They're taking up a lot of the carbon but starting to get saturated in the amount that they can take up out of our atmosphere, and that's going to change the characteristics of the water environment, aquatic environments, that sort of thing.

Energy and Carbon Movement

Abbey (a biology professor) brought up ideas about how nutrients in an environment are cycled in the metabolism to derive energy and matter out of foods and mentioned the concepts of the conservation of matter and transformation of energy:

Like if we talk about the carbon cycle and we talk about ecology and the cycling of nutrients in an environment and so I bring around the carbon cycle all the time. Because we talk a lot about energy movement through the ecosystem and that sort of thing. So, the metabolism component is, is what's our primary link in that.

All the experts agreed that the concepts of photosynthesis and cellular respiration are an essential part of carbon cycling. Mark pointed out the process of how photosynthesis and cellular respiration contribute to the movement of carbon:

Well, biologically a big part of that is the movement of carbon via photosynthesis and cellular respiration. Of course, that's moving carbon in and out of the atmosphere. So, you have carbon sequestering with photosynthesis, taking it from an inorganic to organic form and then returning that to its inorganic form through respiration.

Abbey emphasized the effect of atmospheric CO₂ produced by photosynthesis, stating that ~~the~~ photosynthetic process is the only known natural process that will remove carbon dioxide from the atmosphere." Davis (a geology professor) also mentioned that plants and animals pulled carbon out of the atmosphere via respiration.

Geological Activity

Some experts highlighted geological processes such as the rock cycle, volcanism, and subduction into the mantle. Ryan and Chase (a science teacher) stated that, as part of the loop of the rock cycle, carbon atoms can be part of the inorganic material in rocks, and Chase also mentioned one part of the rock cycle. Mark articulated the process of how volcanoes emit CO₂ into the air:

That sometimes can be outgassed through volcanic activity. So, through subduction, it gets deeper into the Earth's crust, and eventually it can be released through volcanic activity. I know in the form of methane, carbon dioxide, carbon monoxide would be the primary sources of it.

Human Activity

Several experts discussed how fossil fuels are formed and how they are related to human activities. Ryan stated that organisms consist of sugars or cellulose and explained that they can eventually form fossil fuels, which in turn can be burned, releasing CO₂ into the atmosphere. Amber emphasized human activities that involve the burning of fossil fuels, which causes imbalances in the natural carbon cycle:

It [carbon] changes when you're pulling fossil fuels out of the ground and you're combusting that ancient carbon. That's going to displace the carbon that would naturally be occurring, so that comes into that anthropogenic piece of the carbon cycle where we are altering it, because we are going in and pulling that carbon out that wouldn't naturally just be circulating in the modern carbon cycle.

Socioscientific Issues

Most of the experts mentioned socioscientific issues, including climate change, ocean acidification, coral bleaching, and deforestation. Abbey expressed concern about ocean acidification and about how the acidity affects the aquatic ecosystem:

The acidification of the oceans is a huge concern for me, more than the heating process, because think when it comes to the biological processes, enzymes and proteins and things that make us all tick start to not work so well when you change the acidity in the environment around them. . . And I specifically have studied algae and the microfauna of aquatic systems. And so, they are so ingrained, and they can't get out of that situation. So, they're just stuck there, and their situation is changing. And so that to me is wow, that's going to be something that's going to be a huge impact should it go past that tipping point of not so good and bad.

Ryan also stated that CO₂ is one of the greenhouse gases that hold heat in the air and cause global warming, and he showed his understanding of the physics of carbon in the atmosphere, and of how CO₂ acts as a greenhouse gas.

RQ2) How Does Interdisciplinary Knowledge about the Carbon Cycle Vary Across Science Experts?

Through the interviews, the experts shared their ideas about whether the knowledge of multiple science disciplines is necessary to understand CC. All participants agreed with using more than one science to understand how CC works.

Jamie (a biology professor) used a jigsaw puzzle metaphor to explain the perspective of interdisciplinarity: –Probably because each individually holds a piece of the puzzle, but you can't put the whole jigsaw puzzle

together until you understand how each piece fits in.” Ryan mentioned that the interdisciplinary perspective reflects “system thinking” because

The Earth is a system and you have to break out the different parts of the Earth’s system and then you have to see how those parts are related. So, that’s one part of system thinking. The other part of system thinking is how those parts are interrelated and if changing one of those can change other parts.

This study used drawing-based models from content experts to reveal what they considered to be the core concepts of CC. Although the experts’ ideas could have been elicited and revealed in many ways, drawing-based models provided a suitable means for generating ideas and their interconnections graphically. We examined the experts’ models and analyzed their perceptions to identify the key concepts of carbon cycling. Frequently used terms or phrases were assumed to be the key concepts.

Amber’s model emphasized biological processes such as photosynthesis, the cellular respiration of algae, and biomass, along with a concept from the physical sciences: the burning of fossil fuels as a primary source of CO₂ emissions, which reveals some interdisciplinarity. Socioscientific issues like global warming, ocean acidification, and air quality were not mentioned in the map (see Figure 1).

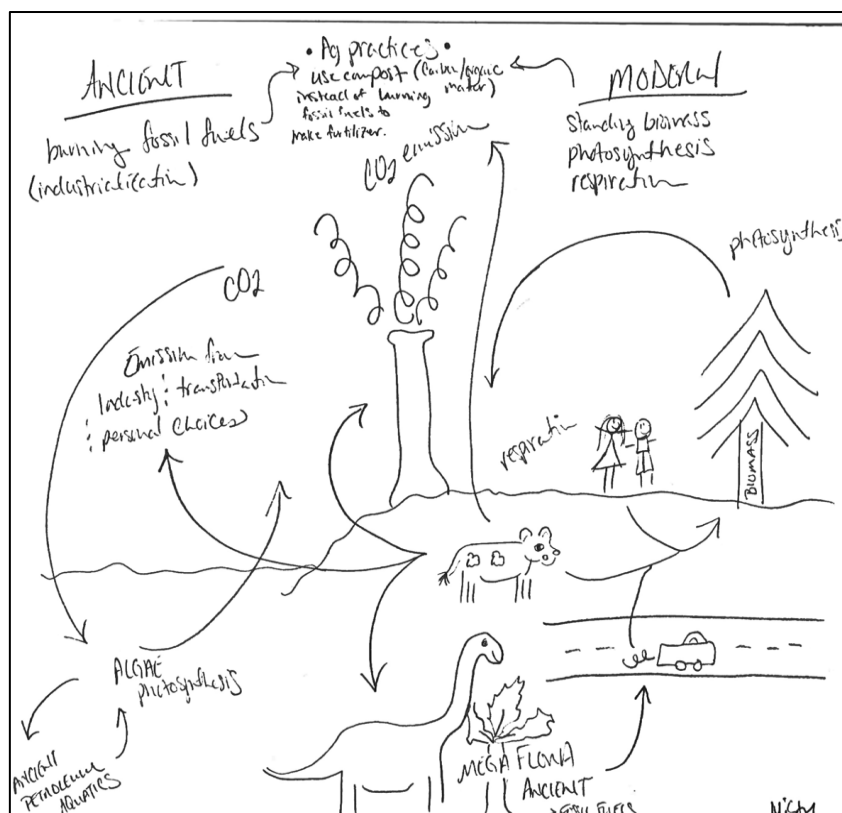


Figure 1. Amber’s Model about CC

In Jamie’s work, there was a strong biological emphasis compared with the other models; she explained photosynthesis and cellular respiration in detail, including the products and reagents of photosynthesis and energy release connected to cellular respiration. The model also included examples of carbon sinks such as

carbonate rocks, fossils, and water. Jamie did not express socioscientific issues such as global warming and ocean acidification, showing limited interdisciplinarity, although she mentioned the necessity of science literacy to address the problems derived from socioscientific issues.

David's model presented the four major reservoirs of carbon in the cycle and described the processes that occur in each sphere and the ways in which they interact (e.g., respiration and deforestation in the biosphere, global warming in the atmosphere, ocean acidification and coral bleaching in the hydrosphere, and carbon extraction and weathering in the geosphere). Increasing ocean sediment is related to both the geosphere and hydrosphere. He showed the connection between the hydrosphere and biosphere for coral bleaching and between the hydrosphere and atmosphere for increased evaporation resulting from global warming. Overall, all reservoirs in his model were connected to carbon (see Figure 2).

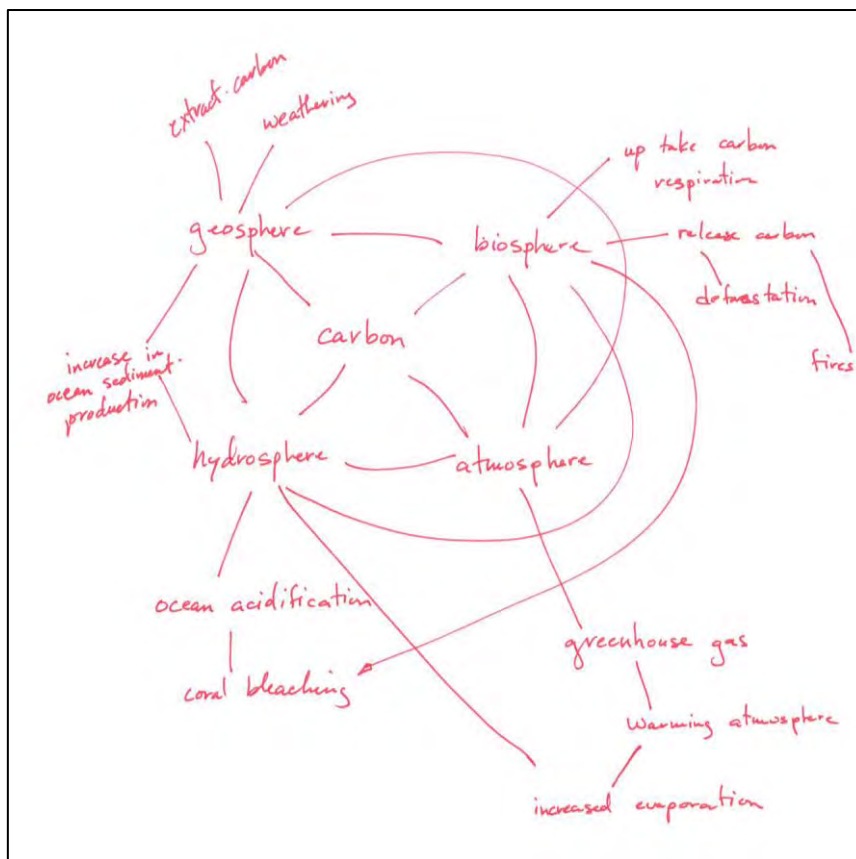


Figure 2. David's Model about CC

Abbey's model showed diverse interdisciplinary connections with content from biology and earth science (see Figure 3). The model included concepts from earth science (volcanos, rocks, and shells), biology (photosynthesis and cellular respiration of aquatic and terrestrial producers, plants eaten by animals, and decomposition), chemistry (fossil fuel combustion to form carbon dioxide), and human activity (fossil fuel burning).

used concepts contained in the DCIs, yet they all associated the DCI elements in different ways that reflected the experts' disciplinary backgrounds.

RQ3) Based on the Experts' Knowledge, What Are the Missing Parts of Carbon Cycling in the U.S. K-12 Science Standards?

Comparing the experts' knowledge to the standards allows for additional findings of important themes and concepts regarding CC. The concepts expressed in the experts' models and narratives from the interview were compared with the US Framework's DCIs to find ideas that were not included in the Framework and NGSS.

The experts with geology backgrounds focused mainly on concepts that were not included in the standards. They brought up the long-term carbon cycle, which operates over millions of years and involves the exchange of carbon between rocks and the Earth's surface (e.g., carbon buried in sedimentary rocks in the form of carbonate minerals and fossil fuels such as oil, natural gas, and coal). In contrast, the Framework focuses more on short-term links in the carbon cycle on the order of seconds or a few years, such as food chains, photosynthesis, and decomposition. One of the geology experts (David) stated that the lithosphere contains the largest amount of carbon in the Earth, but this information is missing in the standards. Furthermore, the Framework provided a limited picture of carbon movement, focusing on short-term biochemical processes between the atmosphere and the terrestrial biosphere (MS-LS-1-6 and MS-LS-1-7).

The models and expert interviews addressed different socioscientific issues such as global warming, ocean acidification, and deforestation, whereas the Framework shows only the connection between human activities, such as the release of greenhouse gases, and global warming (MS-ESS3-5). Scientific understanding of cause-and-effect processes might not be stated directly, even though the biosphere (land and ocean) is a significant sink for anthropogenic carbon. It might be useful to include other crucial human activities, such as deforestation and ocean acidification, which may have connections to more DCIs in the curriculum and instruction. For example, two of the experts went into detail about the interactions between CO₂ and water and the consequent problem of ocean acidification from carbonic acid, but this topic is not mentioned in the standards.

Another geology professor (Ryan) was the only expert who touched upon "systems thinking" about the Earth. He emphasized that the best way to think about the CC is to use systems thinking because the Earth is a complex dynamic system whose components interact with each other in such a way that alterations to one component change the others. He added, "that's getting into like feedback, positive versus negative feedback." However, feedback cycles or loops representing causes and effects that induce some initial change in the system to run through a series of secondary effects are not highlighted in the standards.

We also analyzed the experts' models and interview transcripts in terms of the CCCs, though there was little explicit mention of these. Specifically, Jamie mentioned the mechanisms that relate to the CCC of cause and effect. Ryan stated that the carbon cycle is considered a system, which relates to the CCC of systems and system models. Abbey also mentioned systems, and her references to the cycling of nutrients relates to the CCC of

energy and matter. Although David's map portrayed a system with a cyclical, highly interconnected nature, it did not mention any CCC.

Discussion

Although there is ample rationale for the interdisciplinary approach to science learning, no empirical studies have explored the interdisciplinary understanding of experts with different science backgrounds to inform the current science standards or curriculum. We recruited disciplinary experts to draw models and interviewed them to examine the principal themes and concepts inherent in the CC. Then, we analyzed inferences about the nature of expert knowledge and related the experts' knowledge to the current US standards to derive implications for future policy documents and instruction. Although all experts agreed with the need for interdisciplinary knowledge to understand global carbon cycling, they revealed diverse concepts from multiple science disciplines, and when comparing the experts' models and narratives, some differences clearly emerged. We discuss content that can be added to the standards and curricula below.

The Slow Geological Process

Four of the experts incorporated aspects of the rock cycle, volcanism, and tectonic activity into their models and ideas about the carbon cycle. Although the Framework (NRC, 2012) refers to the rock cycle (ESS1.C, ESS2.A, ESS2.B, and ESS2.E) and to fossils used for establishing relative ages, there is no mention of how carbon compounds are involved except for the mention of fossil fuels. Given that the rock cycle is already included, and given that the largest amount of carbon on Earth is stored in sedimentary rocks, it would be feasible and useful to add the slow geological processes of carbon compounds to the K–12 standards and curricula. It is expected that students should understand how atmospheric carbon moves to the lithosphere and forms sedimentary rocks and fossils, and it is also expected that students should understand how carbon rocks transform and recycle through plate tectonics, weathering, and volcano eruptions. For example, the melting of rocks in plates can eventually result in the emission of CO₂ back into the atmosphere through volcanic eruptions, and atmospheric carbon dissolved in rainwater forms a weak acid—carbonic acid—that dissolves rocks, yielding bicarbonate and other ions, a process called chemical weathering (NASA Earth Observatory, 2011). However, the geological and geochemical processes over the long timescales of the CC, including the uplift and exposure of organic deposits, the dissolving of carbonate rocks, the subduction of these and subsequent release of carbon dioxide through volcanos, and the role of silicate rocks in fixing carbon are all absent from the Framework.

Interconnecting Cycles

The relationship between the rock cycle and the carbon cycle would be an excellent example of how large-scale cycles are not independent but interact with one another. Chase included the hydrogen, oxygen, and nitrogen cycles, all of which could be added to the K–12 curriculum and standards, which provide nonspecific guidance only: “students understand chemical cycles such as the carbon cycle” (NGSS Lead States, 2013, p. 71). The Framework emphasized that “Earth consists of a set of systems that are intricately interconnected having

different sources of energy and matter cycles within and among them in multiple ways and on various time scales” (NRC, 2012, p. 169). Although the process could be slow, even minor changes in one part of a system could have enormous consequences in other systems via cause-and-effect feedback. Thus, knowledge that provides the ability to see the big picture of interconnected cycles in multiple systems should be highlighted in the standards.

Acids, Bases, and Ocean Acidification

Ocean acidification is a major threat, imperiling food sources as well as affecting photosynthesis by oceanic plankton (National Oceanic and Atmospheric Administration [NOAA], 2020). This issue could be added to the standards and curriculum to bolster the meager emphasis on acids and bases currently in the Framework. Two experts described acidification and included it in their models. The idea of the thermodynamic equilibrium between atmospheric and oceanic carbon dioxide and carbonic acid—that, in the ocean, dissolved carbon dioxide and carbonic acid in surface layers interact quickly with the atmosphere, whereas carbon compounds in deep layers constitute a huge source of carbon that interacts on a timescale of centuries—was not present in either the Framework or the NGSS. Additionally, links among the direct effects of ocean acidification at the organism level, the indirect effects on the food web (on predator–prey interactions), and the functioning of the marine ecosystem are absent in the standards.

Connections across Disciplinary Core Ideas

The standards have two methods of showing interdisciplinarity: the crosscutting concepts mentioned in both the NGSS and the Framework, and the listed connections across performance expectations in the NGSS. In the experts’ concept maps, the connections among concepts related to DCIs were much more common than the crosscutting concepts, which were infrequently mentioned explicitly.

The connections across DCIs in the NGSS are incomplete; furthermore, even if the DCI connections across the physical sciences, earth and space sciences, and life sciences were comprehensive, a listing of all relevant connections would not provide sufficient support for teachers or curriculum developers (Delgado & You, 2018). Thus, additional work will be required to flesh out these connections in future iterations of the standards.

Recommended Next Steps for Standards

Deep interdisciplinary understanding can be developed in different individual disciplines, tapping learners’ cognitive processes (You, 2016). The integration of disciplines helps students develop an essential core of knowledge for seeing the big picture of knowledge connections (Kozma & Russell, 1997). A companion publication to the NGSS and Framework is recommended; it could contain comprehensive interdisciplinary connections for at least some central topics like the carbon cycle. Based on this study’s findings, science educators should determine which parts are necessary for learning about the CC, as well as how the necessary knowledge can be linked in the standards. This could support curriculum development (e.g., learning

progressions and literature syntheses), existing assessments, and teaching practices. This principled process would help realize the vision inherent in the standards of interdisciplinary knowledge for U.S. student environmental literacy.

Conclusion

To implement successful interdisciplinary science learning, coherent coordination among instruction, curriculum, and assessment is essential (Zhang & Shen, 2015). Coordination requires well-specified standards to guide development efforts. The results of this study provide concrete recommendations for standards to guide the revision of existing curricula or to develop new approaches to the teaching and learning of the carbon cycle, shifting the approach from disciplinary to interdisciplinary. Similar efforts will be required for other central K–12 science themes. Professional development for interdisciplinary teaching will also be required to help teachers learn to support students in organizing their disciplinary knowledge, in drawing meaningful interdisciplinary connections, and, eventually, in achieving desirable scientific literacy (You, 2016). The benefits of having a scientifically literate citizenry are essential for our society's future well-being and sustainability.


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