Developing a Carbon Cycle Learning Progression for K-12[1]

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Table of Contents

Abstract: Developing a Carbon Cycle Learning Progression for K-12

This paper discusses students' conceptions of carbon pools, fluxes and cycles at different levels of ecological systems, and the coupling of natural and human energy systems. The paper is based on research with students informed by a literature review. We assessed elementary, middle, and high school students' knowledge of the role of carbon in human and natural systems. The analyses indicate that most students face challenges in acquiring an adequate understanding of carbon cycle processes. These challenges include 1) connecting scientific accounts at different levels of scale (e.g., connecting photosynthesis and global warming) and connecting living and non-living systems by tracing matter (e.g., decomposition) 2) tracing matter and energy though processes (e.g., photosynthesis, cellular respiration, and combustion), 3) using accounts explain and predict (e.g., providing explanations versus namedropping), 4) using scientific reasoning to inform decisions about environmental issues (e.g., understanding mechanisms and substances related to global warming), and 5) transitioning from narrative to model-based reasoning (e.g., reasoning about processes in systems versus actors, events, and locations). We discuss implications for developing a learning progression for the ecological carbon cycle and students' progress toward developing environmentally science literate practices.

Developing a Carbon Cycle Learning Progression for K-12

Understanding the ecological carbon cycle is critical to our view of *environmental science literacy*—the capacity to understand and participate in evidence-based discussions of the effects of human actions on environmental systems. Environmental science literate citizens need to understand relationships between seemingly disparate events such as how sea ice available to polar bears in the Arctic is connected to processes inside leaf cells in the Amazon rain forest and to American consumers' choices about what car to buy. Traditional science curriculum obscures rather than reveals these connections. Students do not learn to see the key processes that tie systems together—in this case the production and consumption of carbon dioxide and its effect on global climate. In this paper, we explore students' understanding of the key processes that connect complex systems and how students use fundamental principles as resources to support their explanations.

The Importance of Carbon

The global climate is changing and with this change comes increasing awareness that actions of human populations are altering processes that occur in natural ecosystems. The "carbon cycle" is no longer a cycle, on either local or global scales; most environmental systems—especially those altered by humans—are net producers or net consumers of organic carbon. Similarly, humans have altered the global system so that there is now a net flow of carbon from forests and fossil fuels to atmospheric carbon dioxide. Thus previous beliefs in the "balance of nature" and the basic stability of earth systems have been replaced by an understanding of environmental systems as dynamic in nature and changing in ways that human populations need to understand (see, for example, Weart, 2003). Recent evidence has confirmed that humans are influencing the ecological carbon cycle in unprecedented ways:

- Global climate change is happening, caused by rapidly increasingly atmospheric carbon dioxide levels, with inevitable consequences for sea levels, frequency and severity of storms, natural ecosystems, and human agriculture. (Keeling & Whorf, 2005).
- Up to 40% of net photosynthetic output of terrestrial ecosystems is now appropriated for human use (Vitousek, Ehrlich, Ehrlich, & Matson, 1986)

These changes are caused by the individual and collective actions of humans. In a democratic society like the United States, those actions will change only with the consent and active participation of our citizens. These circumstances put a special burden on science educators. We must try to develop education systems that will prepare all of our citizens to participate knowledgeably and responsibly in environmental systems. We have chosen carbon as a focus of our research because carbon-transforming processes are uniquely important in the global environment and understanding those processes is essential for citizens' participation in environmental decision-making.

Carbon-transforming processes are uniquely important. All living things are made of carbon compounds; living organisms grow and store food by transforming carbon compounds and obtain and use energy by oxidizing carbon compounds. Carbon compounds are equally important to human societies because we depend on biomass and fossil fuels for most of our food, energy, transportation, and shelter. The primary product of our activities—carbon dioxide—regulates global temperatures, atmospheric circulation, and precipitation. Thus an understanding of the many processes that transform carbon compounds is central to understanding environmental processes and systems in general.

Understanding carbon-transforming processes is essential to citizens' participation in environmental decision-making. As a society we face a wide range of environmental issues that involve how we use or regulate carbon-transforming processes: Global climate change, prices and uses of fossil fuels and alternative energy sources, deforestation, soil fertility, hypoxic conditions in lakes and oceans, and so forth. As a nation, we need citizens who can understand and respond to these issues. We argue below that citizens' lack of understanding has a profound effect on our political culture. Most citizens lack the conceptual tools and practices that they need to reconcile their personal actions and the policies that they support with their environmental values, or to understand debates among experts.

The evidence is strong that most citizens do not understand biogeochemical systems in ways that will enable them to make well-informed decisions. A video widely circulated by the Private Universe project shows Harvard and MIT graduates failing to understand that the mass of a tree comes largely from carbon dioxide in the air. Andersson and Wallin (2000) found that many Swedish students confused global warming with ozone depletion. In our own research at the college level, we found that most prospective science teachers—senior biology majors—said that when people lose weight their fat is "burned up" or "used for energy"—even when we offered a better option (the mass leaves the body as carbon dioxide and water). Other studies (e.g., Anderson, Sheldon, & Dubay, 1990, 1990; Songer &, Mintzes, 1994; Zoller, 1990; Fisher, et al., 1984) document troubling gaps in adults' understandings of carbon-transforming processes, but they do not address the implications for these limited understandings.

We discuss the implications of these studies by looking in some depth at a study that investigated the relationships between adults' environmental values, their scientific understanding, their practices as consumers, and the policies that they advocated as citizens. Kempton, Boster, and Hartley (1995) conducted in-depth interviews with a sample of American adults, ranging from members of Earth First! and the Sierra Club to Oregon loggers whose jobs were endangered by environmental regulations. A first key finding of their study was that virtually all the informants were deeply concerned about the environment and convinced that we should be doing more to preserve and protect it. They believed that we should be changing our lifestyles now to protect the environment, either for the sake of natural systems themselves or for the sake of future human generations, including their own children and grandchildren. Kempton and his colleagues also found, however, that most informants engaged in practices as consumers or advocated policies that were inconsistent with their espoused values.

Focusing on global warming as a key issue, they found informants did not understand key aspects of the science. A fair number of them confused global warming with ozone depletion or attributed global warming to chlorofluorocarbons or other pollutants. Planting more forests and pollution controls were both ranked higher by survey respondents than reducing carbon dioxide emissions as steps we could take to reduce global warming. Thus the sources of their confusion about the scientific debate included (a) difficulties with understanding *processes or mechanisms*—the processes that lead to global warming, (b) difficulties with understanding *substances*—the chemical nature of key greenhouse gases, and (c) difficulties with understanding *quantities*—for example, the relative amounts of carbon dioxide released by burning of fossil fuels and absorbed by growing forests.

Environmental Science Literacy Framework

We recognize that much of the science phenomena and fundamental processes of the ecological carbon cycle are currently addressed by state and national science standards and included in science curriculum. The last decade has seen widespread support for standards-based reform in science education. Although the reform efforts have generally been well received, much of the current science curriculum has not met the ambitious goals of national science standards. Furthermore, the standards documents underplay the interconnectedness of human and natural systems and the interdisciplinary nature of scientific research. A traditional organized school curriculum obscures rather than reveals the connections between the science disciplines, teaching students science content in seemingly disconnected ways. The burden of making connections between sea ice, Amazon trees, and American car buying falls to the responsibility of the student. The sea ice in the Arctic might be analyzed in an earth science course as part of a weather and climate system. The leaf cells of Amazon plants might be analyzed in a life science course as part of a hierarchy of biological systems. American consumers' driving choices probably would not be discussed in a science course at all; they might be discussed in a social studies course as part of an economic system. The presentation of content in this way hinders students from *applying fundamental principles* to help explain *processes in complex coupled human natural systems.*

Environmental science literate students are capable of using fundamental principles in science as intellectual resources to inform their reasoning and decision making about complex environmental systems. Our research examines students' application of fundamental principles to both simple and complex systems. We propose that all environmental science literate students should engage in four key practices:

(1) Scientific inquiry: developing and evaluating scientific arguments from evidence,

(2) Scientific accounts: using scientific accounts of the material world,

(3) Application: using scientific accounts as tools to predict and explain, and

(4) Citizenship: using scientific reasoning for responsible citizenship.

This framework is used to organize our data analyses, particularly analysis of the second, third, and fourth practices. For a more complete explanation of the framework, see Anderson, Sharma, Mohan, Cho, Jin, Wilson, Lockhart, & Tsurusaki, (2006). The environmental science literacy framework will guide the presentation of results and discussion that follow, so we will explain each practice in more detail here.

Practice 1. Scientific Inquiry.

This practice refers broadly to the way that people learn from experiences and observations of the material world. In this practice students learn to develop arguments from evidence and learn to use personal or vicarious observations of data to identify patterns or develop explanations. It includes the transition from informal learning experiences to systematic and organized practices of science. Students learn to evaluate arguments using evidence, including evaluating multiple scientific models that explain similar phenomena. Students learn to make observations, measure and quantify data, and use these experiences to inform their arguments.

Practice 2 and 3. Provide and apply scientific accounts.

Scientific communities have developed very detailed accounts of the material world using data and patterns and creating models to help explain and predict complex environmental systems. It is critical for students to learn from authorities and use scientific accounts to help reason about environmental systems. *Applying fundamental principles to processes in coupled human and natural systems* is a key characteristic of environmental science literacy. In this practice students learn to reason about a hierarchy of systems and develop understanding of accounts at multiple levels of scale, from microscopic to macroscopic to large-scale accounts. Students also learn to trace matter and energy through processes in systems, particularly understanding the role of carbon in matter-transforming systems. They also become increasingly more aware of the interconnectedness of living and non-living systems, as well as connections to human engineered systems. Table 1 below summarizes the key principles of processes and systems that are critical to understanding the ecological carbon cycle.

Table 1: Scientific Accounts of Environmental Systems

Applying fundamental principles…		***…to processes in coupled human and natural systems***		
Type of Principle	**Fundamental principles**	**Earth systems: Earth, inorganic forms of carbon**	**Living systems: Producers, consumers, decomposers**	**Engineered sys-tems: Energy, transportation**
Structure: Hierarchy of Systems	Microscopic	Properties of atoms and molecules	Cell structure, biomolecules	Materials in engineered systems
	Macroscopic	Physical and chemical properties of materials	Multicellular organisms	Appliances, automobiles, factories
	Large scale	Matter pools	Populations, ecosystems	Large engineered systems
Constraints on Processes	Tracing Matter: Carbon	Geological carbon cycle, soil carbon, atmospheric CO_2	Ecological carbon cycling, growth, matter transformations	Fossil fuel systems, air quality, combustion
	Tracing Energy		Ecological energy flow, photosynthesis & respiration	Human energy systems; combustion

Practice 4. Use scientific reasoning to engage in responsible citizenship.

In this practice students learn to reconcile experience, authority, and values to make informed decisions. Students learn to use fundamental science principles as resources for reasoning about complex environmental systems and use their scientific knowledge to inform their decisions and actions. This data in this paper specifically focuses on students' understanding of the influence of deforestation and fossil fuel burning on the global carbon cycling and their explanations for the actions that should be taken in response to these environmental issues.

The Role of Learning Progressions

This is a cross-age study, presenting data from assessments of elementary, middle, and high school students. We regard this study as a step toward the development of a *learning progression* leading to the development of environmental science literacy with respect to the role of carbon in environmental systems.

Learning progressions are descriptions of the successively more sophisticated ways of thinking about a topic as children learn about and investigate a topic over a broad span of time (Committee on Science Learning, 2007; Smith, Wiser, Anderson, & Krajcik, in press; Wilson & Bertenthal, 2005). They are anchored on one end by what we know about the concepts and reasoning of students entering school. On the other end, learning progressions are anchored by societal expectations (values) about what we want high school students to understand about science. Learning progressions propose the *intermediate* understandings between these anchor points that are reasonably coherent networks of ideas and practices and that contribute to building a more mature understanding. Learning progression can be useful to educators and educational researchers for three important reasons:

1. We can draw on and synthesize disparate studies to examine the development of big ideas. The available research is useful, but fragmented. Individual studies focus on students of different ages and cultures, different kinds of instruction, and different conceptual tools and practices. The framework for this study will enable us to make use of those studies in spite of their differences and use them as a starting point for our research. We will be able to investigate the interdependence of complex ideas and practices, successions or sequences of practices, and relationships among development, learning, and instruction. It is only through such synthetic work that we can study the development of complex and important Big Ideas in the natural sciences, such as the role of carbon in environmental systems.

2. We can use short-term studies to investigate long-term learning. It is virtually impossible to conduct studies that follow the development of understanding in individual students over periods of years. We can, however, develop models describing likely scenarios about the succession of children's ideas and reasoning strategies based on coordinated studies of diverse students of different ages.

3. Learning progressions can connect research, policy, and practice. Learning progressions organize and present research findings that make their applications to policy and practice clear. In the case of our study, for example, we will develop longitudinal descriptions of children's learning that can be directly compared to state and national standards, assessment resources that can be used for classroom or large-scale assessment, and teaching experiments that have implications for curriculum and instruction.

Research Methods

Participants

The participants in this study were members of a working group focused on the ecological carbon cycle. The carbon cycle working group consisted of seven K-12 science teachers and five science education researchers. The science teachers varied in grade levels, ranging from two third-grade teachers, one fourth-grade teacher, one sixth-grade teacher, one eighth-grade teacher, and two high school biology teachers. Participation in this project was associated with an ongoing partnership project between K-12 science teachers and an ecological research center located nearby. The carbon cycle working group met once during the research project to discuss preliminary findings from the assessments. In addition, some discussion occurred through email or written feedback between participating teachers and the researchers.

Data Sources

The teachers participating in the working group administered assessments to their students during the first few months of the school year. The results presented in this paper are based on the original versions of the assessments, although the assessments are being revised based on feedback from teachers. The researchers developed three versions of the assessment, one for elementary students, one for middle school students, and one for high school students. Initial drafts of the assessments were based on reviews of existing research on phenomena associated with the ecological carbon cycle and pilot data gathered during the previous school year. The assessment items were focused on the role of carbon in 1) producers, 2) consumers, 3) decomposers, 4) coupled human and natural systems and human energy systems, 5) physical and chemical changes, and 6) carbon reservoirs and fluxes. The assessment items were a combination of multiple choice or open response format. The elementary test included 13 items, the middle school test included 26 items, and the high school test included 28 items. Several of the items appeared on all three assessments.

Data Analysis

Analyses of assessment items were guided by working papers, written by the lead author, with rubrics for coding students' responses to the assessment items. The assessments, answer keys, and the working papers are available on the project website. The rubrics were designed to highlight patterns of students' responses relevant to the general theme of environmental science literacy and the specific trends in the succession of students' reasoning in the ecological carbon cycle. In order to ensure the rubrics were reliable, two researchers independently coded a sample of assessments and met to discuss their coding and any discrepancies that occurred. Initial reliability of the rubrics ranged from 65-100% agreement (See Appendix A for reliabilities of items presented in this paper). When there were discrepancies, the rubrics were revised until both researchers agreed completely. For most of the rubrics, two or more rounds of revision were needed before satisfactory reliability was achieved. Additional revisions were based on discussions among the working group leaders, as we developed our ideas about connecting ideas and themes.

The results presented in the paper are based on a sample of assessments across the elementary, middle, and high school data. The researchers analyzed 120 assessments, which included 40 students each from three elementary classrooms, 40 students from two middle school classrooms, and 40 students from two high school classrooms. Although we purposefully selected assessments that would represent all the participating classrooms, the selection within each class was random. The data received from assessment items was so rich and complex that the researchers involved in the working group deliberately narrowed the analysis of questions presented in this paper, selecting questions that were most representative of the emerging themes.

The Environmental Science Literacy Framework presented above guided the analysis of assessments and helped organize the results that follow. We did not assess students' understanding of *Practice 1: Scientific Inquiry* and therefore it is not included in the framework below. Our analysis focused on the following aspects of environmental science literacy:

- *Practice 2 and 3: Provide and apply accounts.* This practice is related to students' ability to apply fundamental principles to reason about the structure of systems and the processes within systems.
    - *Understanding structure of systems:* In this section we analyze students' ability to explain accounts at different levels of scale, especially microscopic and large scale accounts. We also analyze the way students explained the transformation of matter from organic to inorganic forms.
    - *Understand processes within systems:* In this section we were focus on how students trace matter and energy in systems, particularly their ability to trace gases through processes of photosynthesis, combustion, and cellular respiration. We also analyze students' explanations about physical and chemical changes of matter in simple and complex systems.
    - *Use scientific accounts to explain and predict*: In this section we look at students' ability to apply knowledge of fundamental principles (e.g., conservation of matter, gases have mass) on assessment items. We focused on students' explanation about processes and systems, looking at responses in which ideas are fully explained compared to responses that include namedropping of terms (e.g., cellular respiration, decomposition) without explanation of those terms.
- *Practice 4: Use scientific reasoning for responsible citizenship.* This practice generally refers to the scientific knowledge that students invoke to reason about environmental issues and actions that can be taken to solve those issues.
    - *Use scientific reasoning as resource for understanding complex environmental issues:* In this section we analyze students' use of scientific knowledge and practices as resources for reasoning about environmental issues. We focus on students' understanding of the order of magnitudes associated with environmental issues and how they explain the role of carbon compounds in complex environmental systems. We also specifically looked at students' explanations for the mechanisms causing global warming and their responses about the responsibility for reducing this problem.

Results

Understanding Structure of Systems

Hierarchy of Systems

Assessment data indicate that middle and high school students struggled with reasoning at different levels of scales, with particular difficulty using microscopic and large-scale scientific accounts. We asked questions that required the students to reason about microscopic parts of systems (e.g., What gas(es) do plants take in from their environment. Explain what happens to the gas(es) inside the plant.), as well as questions that required students to reason at the global level (e.g., What do you think are the main causes of global warming). Most questions required students to reason at multiple levels and make connections across microscopic, macroscopic, and large scale accounts.

We asked students, “Humans must eat and breathe in order to live and grow. Are eating and breathing related to each other?” Fifty-eight percent of middle school students responded ‘yes’. The number of students responding ‘yes’ increased to 83% among high school students. Of the students who responded ‘yes’ to the question, both middle and high school students provided similar explanations (see Table 2). Fifty-two percent of middle and high school students explained the connection between eating and breathing in terms of survival of the organism, rather than explaining the role of eating and breathing in the process of cellular respiration.

Table 2. Yes, eating and breathing are related

	Middle	High
Both breathing and eating are needed for cellular respiration.	0%	3%
Both processes give the body energy or nutrients	9%	9%
Both processes are needed to live, survive, or help humans grow	52%	52%
One process is dependent on the other process	22%	22%
Both processes occur in similar locations (mouth, throat)	13%	3%
Other	4%	9%
I Don’t Know	0%	3%

The remaining students answered that eating and breathing were not related with their explanations following three patterns, 1) the processes were different due to what the human was taking into the body (i.e., nutrients versus air), 2) the processes were different since they occur in different parts of the body (i.e., stomach versus lungs), and 3) the process were different due to the amount of time humans could live without one occurring (i.e., days without eating versus minutes without breathing) (see Table 3).

Table 3. No, eating and breathing are not related

	Middle	High
Eating gives humans nourishment and breathing gives humans air	17%	25%
Amount of time a human can live without them is different	17%	25%
Air goes into the lungs and food goes into the stomach	33%	25%
No explanation given	8%	0%
Other	25%	25%

We asked elementary, middle, and high school students, "Do you think that wood is a mixture of different things?" The responses from students were mixed at all three grade levels (see Table 4).

Table 4. Is wood a mixture?

	Yes	No	No Response
Elementary	50%	40%	10%
Middle	29%	46%	25%
High	67%	30%	3%

High school students responded 'yes' more often than elementary and middle school students and 35% of these students provided explanations that included multiple substances, such as water, cellulose, minerals, and carbon dioxide (see Table 5). The elementary and middle school students responding 'yes' relied on visible characteristics, such as insects, leaves, moss, bark, to explain their ideas. For example, one student responded, "there are spots in wood of different textures and color so I think it is a substance." Of the students that responded wood is *not* a mixture of different things, the majority of these responses from all three grade levels were either tautological or no explanation given.

Table 5. Explanations about wood

YES, it is a mixture	Elem.	Middle	High
Response includes several things that make up wood (water, cellulose)	0%	13%	35%
Response includes only one thing	15%	29%	15%
Macroscopic account of visible things that make up wood	30%	29%	5%
It is made into multiple things, such as paper and books	10%	0%	0%
Tautological response or no explanation given	15%	29%	30%
Other & Unintelligible	30%	0%	10%
NO, it is not a mixture			
Wood is just wood, its one thing	25%	27.5%	33.5
No explanation or I Don't Know	69%	72.5%	50%
Other & Unintelligible	6%	0%	17.5%

Note: Columns will not total to 100%. Students answered either 'yes' or 'no' to the question and percentages were then calculated for both types of responses.

Interestingly, the high school students that responded 'yes' to this question demonstrated limited understanding of appropriate classification of chemicals in different scales such as atomic-molecular and cellular distinctions. For example, students provided responses like, "wood is made of water, minerals, and cells," or "carbon, water, and proteins." High school students also relied on their knowledge of elements more than middle or elementary students (e.g., "wood is not an element, so it must be a mixture."), with ten percent of high school students referring to elements in their answers compared to none from the middle and elementary responses.

We asked high school students the following question in order to see how students at this level connected accounts at different scales, from the microscopic scale (e.g., photosynthesis) to macroscopic scale (e.g., driving cars) to large scale (e.g., global warming and climate change):

> On March 10, 2004, National Public Radio reported that "forests in a remote part of the Amazon are suddenly growing like teenagers in a growth spurt." Though, the radio report added, "This shouldn't be happening in old, mature forests." Scientists have speculated that our actions may have caused this phenomenon. What do you think could be the scientific basis behind such a speculation?

The assessment data indicate that high school students have limited knowledge about the connections between large scale accounts of global warming and the microscopic process of photosynthesis, specifically with respect to the role of carbon dioxide. The data for high school students is presented in Table 6. The most common pattern of response from students was that humans were directly influencing the growth of trees (e.g., "someone put fertilizer on them."), which provides evidence that students are unaware that human actions could indirectly influence plant growth. Students also answered that natural influences, such as high amounts of water or nutrients, might be responsible. These students are focused on the microscopic or macroscopic accounts of plant growth, but do not make the connection to global level phenomena. Interestingly, several students provided very sophisticated responses about plant growth, but did not understand that the plant growth could be influenced by a distant source. For example, one student responded, "Naturally, trees would not suddenly have grown an incredibly drastic amount in just a year, so by deduction you must believe that man-made influences caused it. Possibilities are controlled burns, soil that has been removed or changed to stimulate crop rotation, or even particles in rainwater or chemical substances." In our sample, not one student mentioned carbon dioxide in their response, providing evidence that students do not see the connection between human actions of burning fossil fuels and the carbon dioxide plants need for photosynthesis.

Table 6: Tree growth in Amazon

	High
Trees grow due to elevated levels of CO_2 in the air	0%
The temperatures are warmer causing the trees to grow	5%
Natural influence on growth (e.g., high amounts of water, nutrients)	25%
Humans are directly influencing growth	30%
Lack of pollution or lack of human interference	7.5%
Deforestation is leading to more space for growth	7.5%
Other	7.5%
I Don't Know or No Response	17.5%

Connection between Systems

Several of the assessment items required students to make connection between systems, for example, between living and non-living systems or between human-energy and natural systems. We also asked students to make connections in living systems at different scales, for instance to make connections between decomposers to other living systems. Elementary and middle school students were asked, "Explain how the following living things connect with each other: grass, cows, human beings, decomposing bacteria" (see Table 7). The purpose of this question was to understand the connections students draw between four living things and their understanding of the flow of matter between organisms in an ecosystem. The most common responses from elementary students included 32.5% of students explaining that all living organisms live and/or grow and 37.5% not providing explanations at all. The elementary students focused their explanations on categorizing the four living things by their needs for life or growth. Similarly, 32.5% of middle school students also said that the organisms were connected by common characteristics, however, 52.5% of responses at this age level demonstrated construction of food chains. Students at the elementary level were less likely to construct food chains. The majority of responses from middle school students provided narrative stories (i.e., sequence of events) that connected the four living things. Only one middle school student attempted to trace energy in the ecosystem answering, "the grass is eaten by the cow and becomes energy and the cows is eaten by humans and all these things die and are decomposed which mean we all make a connection with all these things."

Table 7: Connection between living organisms

	Elementary	Middle
Interdependence among living things, may trace flow of matter or energy.	0%	2.5%
Food chain for grass, cows, and humans; bacteria related differently	7.5%	20%
Food chain including all 4 living organisms	2.5%	20%
Incomplete food chain	12.5%	12.5%
Living things have things in common (e.g., live, grow, have cells)	32.5%	32.5%
Other or Unintelligible	7.5%	5%
I Don't Know or No response	37.5%	7.5%

We asked high school students to make connections across living and non-living systems in the following question:

> Years ago farmers found that corn plants grew better if decaying fish were buried near by. What did the decaying fish probably supply to the plants to improve their growth? Circle ALL correct answers.
> A. energy
> B. minerals
> C. protein
> D. oxygen
> E. water
> Explain your answer. How did the things you circled get from the fish to the plant?

The main idea of this question is that animals, like plants, supply organic matter to the soil system and that decomposers consume this organic matter and convert it to inorganic nutrients in the soil. These nutrients can then be absorbed through plant root and used for the production of organic compounds. The assessment data indicate that students are confused about the role of minerals and proteins in plant nutrition. Ninety percent of students correctly circled ‘minerals’, yet 95% also circled ‘proteins’. High school students explained that decaying fish released minerals and proteins into the soil, which are then absorbed by plant roots. Rarely did students mention the process of decomposition, rather students relied on general descriptions, such as “the fish decay” or “the fish goes into the ground.” Some students were able to name mechanisms by which the minerals would reach the plant (e.g., groundwater), but no students explained how the minerals would improve plant growth beyond absorption in the roots. The data from this question indicate that students do not understand the process of decomposition, limiting their ability to trace matter from organic to inorganic forms (see Table 8).

Table 8: Decaying fish and plant growth

	High
What happens to the fish?	
Mention the role of decomposers	0%
Fish decay and release minerals/ matter/other; fish decay or rot	37.5%
Fish are source of protein (i.e., nutritional value)	12.5%
Other answer	15%
Does not mention the fish	35%
How do the minerals get to the plant?	
They travel by groundwater or rainwater	12.5%
They go into the ground or soil	47.5%
They travel by insects or air	15%
Does not mention how it travels	27.5%
What happens in the plant?	
Mention absorption though roots	35%
Mention stuff getting to the plant but not absorption or roots	20%
Other answer	12.5%
Does not mention the plant	32.5%

Note: Column will not total to 100%. The student responses were coded using three rubrics so each response is represented three times in the table above.

Understanding of the Processes in Systems

Matter in Systems

We asked students a series of questions about the role of gases in plant and human processes. The purpose of the questions was to determine students' understanding of photosynthesis and cellular respiration, and most importantly, whether they traced matter through these processes (see Table 9). We asked students:

> Which gas(es) do plants take in from their environments? (you may circle more than one)
> oxygen carbon dioxide other
> Explain what happens to the gases once they are inside the plant.

We found that 27.5% of middle school students and 20% of high school students answered correctly about gas exchange in plants (i.e., that oxygen is required for plant respiration and plants take in carbon dioxide for photosynthesis). Carbon dioxide was circled more often than oxygen indicating that students may be more aware of photosynthesis than respiration. Specifically, we found that 22.5% of middle school students and 15% of high school students said that plants use only oxygen, whereas 45% of middle school students and 57.5% of high school students said that plants take in carbon dioxide from the environment.

Table 9: Gases in plants

	Middle	High
CO_2 and O_2	27.5%	20%
CO_2 only	45%	57.5%
O_2 only	22.5%	15%

The idea that respiration and photosynthesis are the processes involving gas exchange in plants appeared very difficult for students to understand. We looked to see if students could identify 1) the process, 2) provide the gas and/or food products of the process, and 3) trace energy. In general, middle school students did not provide explanations about the process, the gas or food products, or trace energy during the process of respiration. They provided more general responses, such as oxygen being a necessity for life or growth or provided a response that plants provide air for humans. Only 2.5% of middle school students and 7.5% of high school students explained the processes of respiration or photosynthesis, but their explanations focused exclusively on one process or the other (i.e., student did not explain both photosynthesis and cellular respiration in plants). One high school student traced gas products correctly for both processes. One middle school student and one high school student thought energy was produced in photosynthesis instead of using energy. The data also indicate that students have a better understanding of the role of gases in photosynthesis compared to respiration; however, they tend to focus solely on the idea that plants absorbed CO_2 and give off O_2 without explanation of the other reactants and products in the process.

In order to explore students' understanding of plant food production, we asked elementary, middle, and high school students the following question:

A small acorn grows into a large oak tree. Which of the following is FOOD for plants (circle ALL correct answers)?
Soil Air Sunlight Fertilizer Water
Minerals in soil *Sugar that plants make*

We found that all students circled several choices, with a particularly high number of students circling water (see Table 10). The data indicates that students become increasingly more aware that plants make sugar, however, they still believe that conditions for growth, such as sunlight, water, and minerals, are also food for the plant. Even though most students circled multiple factors, the number of students that circled 'air' remained relatively low and actually decreased for high school students.

Table 10: Plant growth

	Elem	Middle	High
Soil	60%	55%	35%
Air	47.5%	42.5%	25%
Sunlight	60%	80%	62.5%
Fertilizer	62.5%	35%	55%
Water	80%	87.5%	77.5%
Minerals in soil	42.5%	72.5%	82.5%
Sugar that plants make	**12.5%**	**25%**	**50%**

Note: Columns will not total to 100% as students were allowed to circle multiple choices.

We also asked students to explain, "Where do you think the plant's increase in weight comes from?"(see Table 11). Students' explanations for this question focused on water and/or minerals from the ground. Students also listed multiple sources for the weight gain, including that the weight comes from water, air, and sunlight. The students focused on visible aspects of plant growth (e.g., water), with responses excluding the primary contributor to the plant weight, which is carbon dioxide gas. We found that only 3 students (one from each grade level) out of the sample of 120 assessments included 'air' to explain the plant's weight gain. It appeared that students have limited understanding about the mechanism of plant growth--they traced water and nutrients from soil as the critical source of plant weight than food made from carbon dioxide and water through photosynthesis.

Table 11: Plant weight

	Elem	Middle	High
CO_2 in air and H_2O from roots	0%	0%	0%
From food or glucose	15%	15%	12.5%
From air, sun, water, minerals and/or soil	12.5%	7.5%	25%
H_2O from roots	15%	25%	10%

Air	2.5%	0%	0%
From the ground or roots	12.5%	17.5%	5%
Natural growth	7.5%	12.5%	7.5%
Other or Unintelligible	10%	17.5%	32.5%
I don't know or no response	25%	5%	7.5%

In order to explore students' understanding of the role of gases in human processes, we asked a series of questions related to human respiration. The purpose of these questions was to see if the students traced the gases through cellular respiration and could explain this process and the products resulting from the process. We asked elementary and middle school students, "Explain what happens to the air that we breathe when it's inside our bodies." (see Table 12).

Table 12: What happens to air that we breathe

	Elementary	Middle
O_2 is used in cellular respiration to produce CO_2 and energy	0%	5%
Mention O_2/air providing energy	0%	7.5%
Mention O_2/air helping organs to function	7.5%	7.5%
Trace molecular exchange of O_2 into CO_2 through body system.	2.5%	15%
Air/ O_2 in the lungs	20%	25%
Generic response about breathing	10%	15%
Air is necessary for life	5%	7.5%
Gas exchange between human and plants	2.5%	2.5%
Unintelligible	30%	7.5%
No Response or I Don't Know	22.5%	2.5%

More than half of the elementary students (52.5%) could not explain respiration. The majority of their descriptions focused on air or oxygen entering and remaining in the lungs. A few of the elementary students mentioned the molecular exchange between oxygen and carbon dioxide. The most common response from middle school students was also that air or oxygen entered the lungs, however, the assessments showed that more middle school students explained their ideas by tracing gases beyond the lungs compared to elementary students.

We asked high school students a similar set of questions in order to see if they had a more sophisticated understanding of gas exchange during human respiration:

Humans get oxygen from the air they breathe.

A. Where in the body does the oxygen get used?

B. How does the oxygen get used?

When humans breathe, they exhale carbon dioxide. How is the carbon dioxide produced in the body?

The data showed that even high school students rarely explained the usage of oxygen in terms of cellular respiration. Only 10% of high school students traced the oxygen used in cellular respiration to the cells of the body. Most of the answers (57.5%) only traced oxygen as far as the vital organs, such as the lungs, heart, or brain and the bloodstream as a transporting system.

In the second question about exhaling carbon dioxide, 47.5% of high school students could not specify how carbon dioxide is produced in the human body. Over 20% of high school students explained their ideas at the molecular exchange of oxygen and carbon dioxide in human body, but did name the process or explain the mechanism. Only 7.5% of high school students attributed carbon dioxide production to the process of cellular respiration.

Overall, the assessment data indicate that students at all levels struggled with tracing gases through plant and human processes. Students tended to have better understanding of the process of photosynthesis in plants and less developed ideas about cellular respiration in plants or humans. We found that older students were more likely to explain their ideas at the molecular level, although they were still limited in their understanding of the processes of gas exchange. Very few students mentioned energy during their explanations and focused primarily on tracing carbon dioxide or oxygen gas.

Matter to Energy Conversions

Students struggled to trace matter through complex processes, such as tracing matter through metabolism of fat tissue. We asked elementary, middle, and high school students the question:

> When a person loses weight, what happens to some of the fat in the person's body?
> (a) The fat leaves the person's body as water and gas.
> (b) The fat is converted into energy
> (c) The fat is used up providing energy for the person's body functions
> (d) The fat leaves the person's body as feces
>
> Explain your answer to the previous question. Why do you think this happens to the fat?

In examining the explanations to this question (see Table 13), we found that only 10% elementary students mentioned energy, while about half of the middle and high school students demonstrated some awareness of energy. Middle and high school students also showed a commitment to the law of conservation: Only 15% middle school students and 5% high school students responded that the fat disappeared. Many of the middle and high school students used expedient ways to make their explanations fit the law of matter conservation. They replied that fat is converted into energy (middle 35%; high 37.5%), fat is released in forms of feces (middle 12.5%; high 10%), or that fat is energy used up by body (middle 12.5%; high 2.5%). The middle and high school students are more aware of energy in systems, but do not correctly trace matter or energy in these systems.

There were some students who selected the correct choice that fat leaves the body as carbon dioxide gas and water. In their explanations, most of these students mentioned that fat changes into sweat, but did not mention account for carbon dioxide as another product of cellular respiration. It is likely that across the grade levels, very few students understand gases as reactants or products in cellular respiration. Explanations reflected that students tend to focus on a single substance, rather than the process, which involves the interaction between several substances. In this case, students focused on the end product of weight loss rather than respiration as a process of chemical reaction, during which fat reacts with oxygen and, as a result, water and carbon dioxide are produced.

Table 13: Tracing matter in weight loss

	Elem.	Middle	High
Fat is broken down to water and carbon dioxide in cells	0%	0%	5%
Fat is changed into water/sweat (Do not mention gas as product)	0%	17.5%	10%
Fat is converted into energy for body function or doing work.	10%	35%	37.5%
Fat is energy stored in body (used for body function or doing work)	0%	12.5%	2.5%
Fat is released in forms of feces	2.5%	5%	10%
Fat burns out or disappears	5%	15%	5%
I don't know/No response/Unintelligible	82.5%	15%	25%
Students who mentioned energy in explanation	***10%***	***48%***	***50%***

Note: Columns will not total to 100%. The last row shows a percentage across all patterns of responses.

Physical and Chemical Changes

We explored students' understanding of chemical and physical changes involving gases in order to see how students traced matter through these processes. We asked students, "What happens to the wood of a match as the match burns? Why does the match lose weight as it burns?" The intended purpose of this question was to explore whether students understand the chemical change occurring and to see whether they conserved matter by tracing the gas products from the process (see Table 14). We found that 47.5% of middle and 27.5% of elementary students said the process of burning makes matter disappear. None of the elementary or middle school students and only 10% of high school students explained the process of wood turning into carbon dioxide and water. Ten percent of middle and 5% of high school students traced matter transformation into gaseous form even though they did not specify the gases as carbon dioxide and water vapor.

Despite several years of experience, students do not appear to understand several aspects of chemical change, particularly when the change involves transformation of matter into or out of gases. Students focused on visible changes in the match, such as describing the match turning into smaller pieces of wood or the length of the match becoming shorter (elementary 10%, middle 20%, high 20%). Half of the elementary students had difficulty giving a specific description of what happens to the match when it burns.

Table 14: Burning match

	Elem.	Middle	High
Account for matter (CO_2 and H_2O)	0%	0%	10%
Match turns to gases, do not specify gases	0%	10%	5%
Account for matter as visible products (smoke and ash)	12.5%	15%	12.5%
Matter is transformed to energy	0%	0%	5%

Matter disappears, evaporates, disintegrates	27.5%	47.5%	17.5%
Physical "visible" changes (e.g., turns to smaller pieces)	10%	20%	20%
I don't know or No response	50%	7.5%	30%

We also explored students' ideas about the mass of gases during physical change in closed systems. We asked students:

A sample of solid carbon dioxide (dry ice) is placed in a tube and the tube is sealed after all of the air is removed. The tube and the solid carbon dioxide together weigh 27 grams.

The tube is then heated until all of the dry ice evaporates and the tube is filled with carbon dioxide gas. The weight after heating will be:

(a) less than 26 grams.
(b) 26 grams.
(c) between 26 and 27 grams.
(d) 27 grams.
(e) more than 27 grams.

Explain the reason for your answer to the previous question.

The data indicate that many students struggled with understanding the mass of gases during physical changes (see Tables 15). We found that a majority of middle and high school students responded that carbon dioxide gas weighs less than carbon dioxide solid. We also found a small number of students who answered that the carbon dioxide gas would weigh more after the change. Very few students, even at the high school level responded that the weight would remain the same. .

Table 15: Conserving mass during physical change

	Mid	High
Weight is less after sublimation	57.5%	60%
Weight is the same after sublimation	5%	27.5%
Weight is more after sublimation	25%	7.5%
No response	12.5%	5%

Among the 27.5% of high school students who answered carbon dioxide gas weighs the same as dry ice solid, only two-third of the students provided explanations for conserving mass. A little over one-third of the students provided explanations conservation of mass in terms physical change from solid to gas (see Table 16). The majority of students who answered correctly on the multiple-choice portion did not provide adequate explanation to demonstrate a robust understanding of conservation of mass. We did not ask the middle school students to explain their reasoning for the multiple-choice portion.

Table 16: Explaining physical change- answer choice D for high school

	High
Conserve mass: CO_2 is in a different form	36.3%
Conserve mass: Nothing escapes the system	27.3%
Conserve mass: Repeat law of conservation of mass	18.2%
Tautological	9.1%
No response or no explanation provided	9.1%

Note: The percentages presented in this table reflect only the students answering choice D on the multiple choice question and do not account for all the high school students' explanations.

Process of Decomposition

In general, students showed limited reasoning about microscopic processes, especially the process of decomposition. We asked students, "When an apple is left outside for a long time, it rots. What causes the apple to rot? Explain what happens to the weight of an apple as it rots." The purpose of this question was to uncover to what extent students traced the movement of matter in decomposition processes.

Elementary students made predictions based on their everyday experience (e.g., what they visible observe when they see food rotting). Although 84% of elementary students made a correct prediction that the weight of apple will decrease, they did explain why the weight decreases. They also focused their analysis on a single organism: 40% elementary students replied that apple can rot by itself, while middle and high school students were much more aware that rotting happens with an interaction between the apple and other organisms.

The assessment data indicate that decomposition is invisible to most students across grade levels (see Table 17). Students tended to think that rotting is a physical change that occurs, citing observations of the apple shrinking or drying up due to sunlight, wind, or other external factors (Elementary 30% Middle 55%, High 35%). Students also thought that the apple rots because it is deprived of necessary living conditions (Elementary 2.5%; Middle 12.5%; High 25%). More students mentioned bacteria, oxygen, or decomposition in higher-grade levels giving evidence for the students' reasoning at the microscopic level. Some middle and high school students mentioned oxygen as the reason for rotting, but thought that the apple absorbed oxygen. These students may have likened the process of decomposition to that of oxidation. Several students mentioned bacteria in their explanations and tended to think that the bacteria 'eats up' the apple or that the apple goes into the ground after it is broken down by bacteria. The data indicates that some middle and high school students tried to reason about decomposition at the microscopic level maybe in effort to conserve matter. However, the explanations focused on a single factor, either oxygen or bacteria, and show limited understanding of the process of decomposition in matter cycling.

Table 17: The process of decomposition

	Elem.	Middle	High

Apple is decomposed by microbes/bacteria and turned into gas (carbon dioxide), water, and minerals.	0%	0%	0%
Microbes/bacteria eat apple	0%	7.5%	12.5%
Mentioned decomposition/bacteria but could not explain	10%	7.5%	7.5%
Rotting is a physical change caused by weather, heat, air, wind, etc.	30%	55%	35%
Oxygen is the only reason for rotting.	0%	10%	7.5%
Apple is deprived of living necessities (sunlight, water, earth, etc.)	2.5%	12.5%	25%
Rotting happened from inside the apple	40%	5%	0%
Apple is decomposed into parts and into ground	0%	0%	5%
Other response, such as apple is eaten up by worms	12.5%	2.5%	7.5%
Mechanism for decomposition is suggested (use the word decomposition or bacteria)	***10%***	***15%***	***24.5%***

Note: Columns will not total to 100%. The last row was a percentage across all the patterns of responses.

Synthesis: Using Accounts to Explain and Predict

Our assessment items often required students to apply their scientific understanding to a specific process or phenomena. This section synthesizes the results reported above, specifically looking at the characteristics and types of explanations provided across multiple items. We analyzed multiple assessment items to explore whether students seemed capable of applying fundamental principles (e.g., tracing matter in systems) to specific phenomena, both simple phenomena (e.g., physical changes in closed systems) and more complex phenomena (e.g., fossil fuel burning and tree growth in Amazon). This section presents patterns across multiple items (see Table 18). We found that both middle and high school students struggled with applying fundamental ideas to questions that required them to make connections. High school students were able to apply their understanding of physical change more often compared to other items. Both middle and high school students particularly struggled with understanding the metabolism of fat. We also found that high school students were able to apply their understanding of chemical change more often than middle school students when asked about the burning of a match.

Table 18: Applying fundamental principles

High School Questions	Yes	No	No response or Don't Know
Decaying fish and corn plants question	7.5%	**92.5%**	0%
Growth of trees in Amazon question	2.5%	**90%**	7.5%
Growth of acorn into a large tree question	2.5%	**97.5%**	0%
Weight loss question	0%	**100%**	0%
Burning match question	17.5%	**72.5%**	5%

Weight loss of burning match	7.5%	**85%**	2.5%
Sublimation of dry ice question	**32.5%**	**65%**	2.5%
Middle School Questions			
Growth of acorn into a large tree question	2.5%	**82.5%**	12.5%
Weight loss question	0%	**90%**	5%
Burning match question	2.5%	**90%**	7.5%
Breathing air question	2.5%	**52.5%**	**42.5%**

We also explored our data to understand students use of 'namedropping' on assessment items, that is how did students use terms, such as photosynthesis, respiration, conservation of mass, phase change, decomposition, decay, etc, in their explanations. We were particularly concerned with whether students used terms without explaining them (i.e., namedropping) or whether they included explanations of the terms when the terms were used. Explanations were coded as 'namedropping' if students wrote the name of a process without explaining the process (e.g., "conservation of mass") or as 'explain' when students included scientific terms and also attempted to explain the terms (see Table 19). We found that high school students attempted to explain their ideas most often on the items that asked about decaying fish. For many of the remaining items, we found that close to half of the middle and high school students use scientific terms without providing explanations of their idea. This is a particularly interesting trend because it indicates that students may be acquiring the vocabulary and language of science, but not necessarily understanding the meaning and application of terms.

Table 19: Namedropping

High School Questions	Namedrop	Explain	No response or Don't Know
Decaying fish and corn plants question	17.5%	**72.5%**	5%
Growth of trees in Amazon question	**52.5%**	20%	17.5%
Growth of acorn into a large tree question	**45%**	**45%**	10%
Weight loss question	15%	**62.5%**	20%
Burning match question	**42.5%**	**32.5%**	20%
Weight loss of burning match	**32.5%**	**37.5%**	25%
Sublimation of dry ice question	7.5%	**55%**	**32.5%**
Middle School Questions			
Growth of acorn into a large tree question	**85%**	0%	2.5%
Weight loss question	**45%**	**45%**	2.5%
Burning match question	**45%**	**45%**	10%
Breathing air question	**45%**	27.5%	10%

Understanding of mechanisms

The assessment data suggest that students have some experiences with environmental issues, particularly middle and high school students showed more awareness of these issues compared to elementary students. We asked the students to respond to several items about preservation of forests and global warming, in which they needed to apply fundamental principles of science (e.g., the role of gases in plants, conserving matter) in order to reason about the question being asked. We found four interesting trends in student responses, 1) unidirectional connection between human and natural systems, in which nature provides good things for humans, 2) limited understanding of the substances involved in environmental issues, 3) generalizations of good and bad, and 4) reliance on media and personal experiences.

We asked elementary and middle school students, "Explain why it might be important to preserve our forests?" The purpose of this question was to see students' understanding of the role of plants in cycling carbon dioxide and whether students viewed forest preservation as important for diversity and protection of animals (see Table 20). We found that 25% of elementary students responded that forest should be preserved to protect animal's habitat, but not diversity (e.g., So we wouldn't destroy animals' homes.'). We also found that 25% of elementary students recognized a connection between the air that plants give off and the air that humans breathe, with several of the elementary students using the term oxygen in their explanation. A few students also mentioned that forests were important for both animals and humans. It is important to note that one-third of elementary students did not explain or respond to the question. Interestingly the middle school students also cited animal habitats and humans' need for oxygen as the primary reasons for preserving forests. However, the middle school students tended to focus more on humans than animals. Fifty-eight percent of the middle school students mentioned that forests are needed for human uses, such as oxygen, recreation, or materials. Only twenty-five percent mentioned that preservation of forest is necessary for protection of animal's habitats. No elementary students and very few middle school students mentioned that plants are related to the cycling of carbon dioxide. One middle school student explained, "The trees not only shelter animals, but transfer our carbon dioxide to oxygen." This student is aware that plants take in carbon dioxide, which is an important concept to understanding the role of plants in the carbon cycle, however the student also showed that s/he is only aware of 'our' carbon dioxide rather than other sources of carbon dioxide in the air. The most interesting pattern from this question was that both elementary and middle school students see natural environments as providing resources for humans (i.e., unidirectional relationship) and sheltering animals.

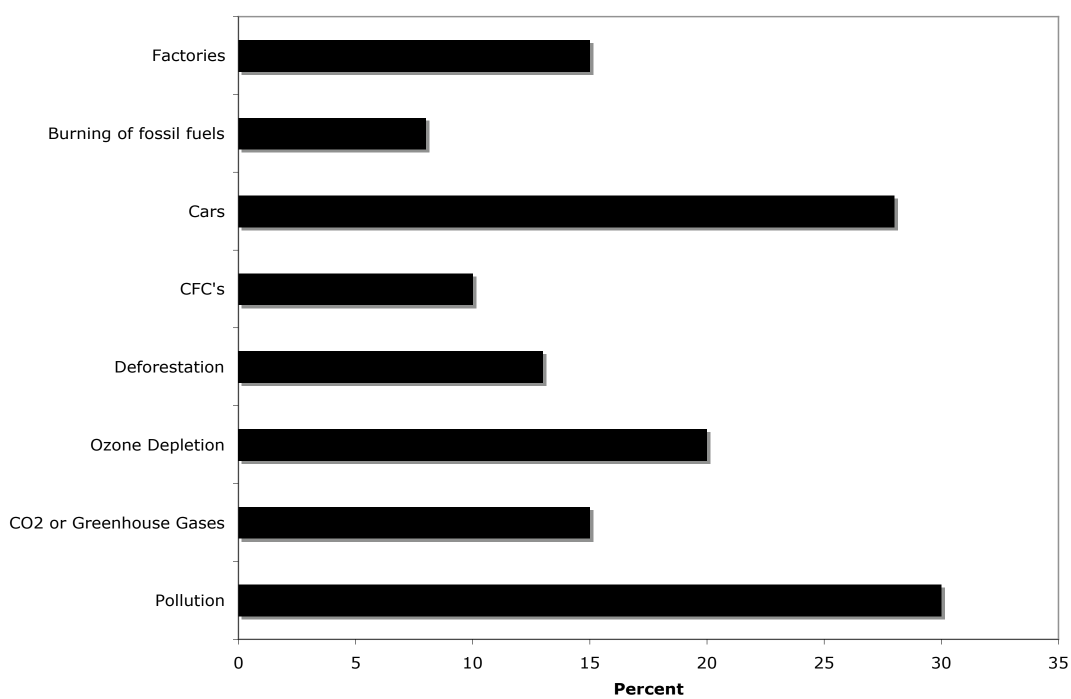
Table 20: Preserving forests

	Elementary	Middle
Trees absorb CO_2 from the atmosphere	0%	5%
To give humans oxygen and protect animals	5%	15%
To supply humans with oxygen/air	25%	35%
To protect animals	25%	10%

For recreational purposes or to supply materials (paper, books)	2.5%	7.5%
Other	10%	15%
I Don't Know or No response	32.5%	12.5%

We asked the high school level students a series of questions about the causes of global warming and ways to reduce global warming. The purpose of these questions was to see if students have knowledge of multiple factors influencing global warming, specifically if they understand that carbon dioxide emissions from the burning of fossil fuels is hugely influential to global warming. We found that high school students named several potential causes for global warming (see Figure 1). The most common cause mentioned was 'pollution.' Explanations from students provided clear evidence that pollution was bad for the environment, although the students did not explain what substances were considered 'pollution.' There was also a trend in responses that students could identify the sources of the 'pollution', such as cars and factories, but did not explain the substances that was causing global warming. For example, one student said, "coal plants, power plants, vehicles, and humans, because it's a fact." This response clearly indicated that the student understands that the burning of fossil fuels is related to global warming, although the student does not mention fossil fuels or carbon dioxide in the response, suggesting that he/she has not gone beyond the fact level to grasp the matter at a conceptual level. Students demonstrated confusion between the word 'pollution' and other substances that may be responsible for global warming (e.g., carbon dioxide makes the atmosphere thicker and so does pollution).

Figure 1: What are the causes of global warming



Several students mentioned that deforestation is a cause of global warming, explaining that trees are 'good' for the environment. This pattern suggests that students view trees as 'good' for the environment and pollution as 'bad', but students gave little explanation about the reasons for these judgments. Some students explained that deforestation was influencing our air supply (e.g., chopping trees lessen our oxygen supply), which in congruous with patterns we observed from elementary and middle school students when asked about forest preservation. Another interesting trend was that several students mentioned media-related evidence in their explanation (e.g., "scientists say that cars are the #1 cause of global warming and followed by factories.").

Almost one-third of the high school students confused global warming with ozone depletion and more general effects of greenhouse gases with specific effects of chlorofluorocarbons. One student linked ozone depletion with fossil fuels responding, "If we didn't use fossil fuels then there wouldn't be as big of ozone hole. Cars use fossil fuels. The hole in the ozone is caused by fossil fuels. Plants use CO_2 in the process of photosynthesis and would reduce CO_2 levels." This response is very sophisticated in that the student recognizes the link between the burning of fossil fuels, carbon dioxide levels, and plants' use of carbon dioxide, however, the student also linked all the factors to ozone depletion.

Understanding quantities and order of magnitude

Our data suggest that students have some understanding of the magnitude of factors influencing environmental issues, particularly factors influencing global warming. We asked students to answer two multiple choice questions about the amount of carbon dioxide emitted by a small car and the number of trees that would be needed to absorb the carbon dioxide from the small car (see Table 21 and 22).

Table 21: A small car on average uses 400 gallons of gasoline a year. About how many pounds of carbon dioxide do you think the car emits from burning the 400 gallons of gasoline?

	Middle	High
(a) close to 0 lbs of carbon dioxide as gases weigh almost nothing.	12.5%	10%
(b) close to 80 lbs of carbon dioxide	7.5%	17.5%
(c) close to 800 lbs of carbon dioxide	30%	22.5%
(d) close to 8000 lbs of carbon dioxide	22.5%	35%
(e) close to 80,000 lbs of carbon dioxide	10%	15%
No response	17.5%	0%

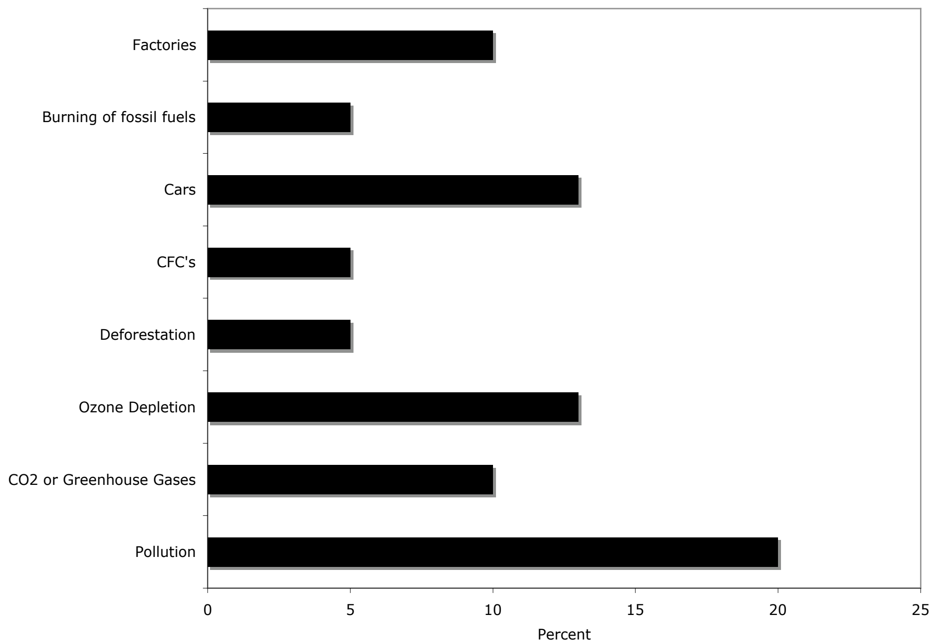
Table 22: About how many trees would you have to grow to absorb the amount of carbon dioxide emitted per year by the small car mentioned in the previous example?

	Middle	High
(a) about 2000	17.5%	57.5%
(b) about 200	50%	25%
(c) about 20	10%	15%
(d) about 2	5%	0%
No response	17.5%	2.5%

The correct answer to the car emissions question is answer choice ‘d’. The majority of middle and high school students answered either ‘c’ or ‘d’ suggesting that most students understand that gases have mass. Interestingly, 12.5% of middle school students and 10% of high school students answered choice ‘a’. These students did not think that gases have mass, a critical concept for students to understand in order to engage in tracing matter. One-fifth of the middle school students did not respond to this question indicating they might not understand this concept. The correct answer to the second question is choice ‘b’. Fifty percent of the middle school students selected this choice. In high school, we found that the students tended to overestimate the number of trees required with 57.5% selecting answer choice ‘a’. Most of the students understood that more than 20 trees are required to absorb the carbon dioxide from the small car. Data from these two items demonstrate that students may have basic ideas about the magnitude of carbon dioxide from burning fossil fuels and the number of trees needed to offset the carbon dioxide, however, responses to other assessment items regarding global warming provided little evidence that students understood the mechanisms related to these phenomena.

We asked the high school students to rank order the causes of global warming. The purpose of this question was to find out if students understood the magnitude of contributing factors (see Figure 2). We found that students generally responded that ‘pollution’ was the single largest cause of global warming, with 20% of students ranking this as first on their list. Twenty-eight percent of the students ranked cars, factories, or burning fossils fuels as the number one cause. The students that responded ‘cars’ or ‘factories’ placed responsibility on a single source compared to students who mentioned ‘burning of fossil fuels’, which encompassed multiple sources. Five percent of students ranked ‘deforestation’ as the leading cause, which clearly suggests that these students are confused about the magnitude of the contributing factors. Ten percent mentioned carbon dioxide or greenhouse gases in their response, which provided evidence that the students understood the substances that are involved. One student ranked, ‘greenhouse gases from cars and factories’ as the leading cause and explained that s/he would rank the two by, “which ones created more carbon dioxide.” Another interesting answer compared the amounts of pollution emitted by factories to the amounts of forests we need to uptake that ‘pollution’ (“There is a lot more pollutes in the environment than plants. If we had very little pollution from factories then we wouldn’t need many forests.”) The student clearly understood that trees are related to pollution, although it is less clear whether the students sees this connection by tracing carbon dioxide.

Figure 2: Rank order causes of global warming: First rank results



We also asked students to choose the best way to reduce global warming, selecting from four options:

> The BEST way to reduce global warming would be: (HIGH school)
> (a) To reduce air pollution from factories and power plants.
> (b) To plant more forests and grow more trees.
> (c) To use public transportation rather than personal cars.
> (d) Any other (mention): ______________________________
> Why do you think your choice on the previous question is the BEST way to reduce global warming?

The purpose of this question was to see if students had a sense of the magnitude of causes of global warming which influenced their decisions to reduce global warming. Fifty percent of students selected choice 'a', 10% selected choice 'b', and 15% selected choice 'c'. Several students selected more than one choice, with 7.5% circling at least 2 options and 10% circling all three of the choice. We asked students to explain their selection. The most common explanations we received were tautological (choice A, 52%; choice B, 63%; choice C, 50%). Of the students circling the first answer choice, 16% explained that pollution destroyed the ozone (e.g., "it has a direct contact with global warming and the atmosphere diminishing"). It is interesting that 10% of the students answered that planting more trees is the best way to reduce global warming. These students may understand the role plants play in the carbon cycle, but do not understand the magnitude of factors involved. The students that responded to answer choice C often relied on information from media in their explanations, such as driving hydrogen-fueled cars, hybrid cars, or just driving cars less.

A notable pattern we observed across the series of global warming questions was a tendency for students at all levels to focus on activities (e.g., burning fossil fuels and driving cars, deforestation) and locations (e.g., factories) rather than substances in the atmosphere. Many of the students who identified substances focused on a less important substance (e.g., CFC's) or referred to 'pollution' as a general substance. It could also be the case that students answering 'pollution' were referring a human activity rather than a mixture of substances.

Limited individual agency or responsibility

One interesting finding that emerged from the questions on forest preservation and global warming was that students communicated varying degrees of individual responsibility and agency. Most often students seemed to place responsibility for environmental issues on a distant source or cause. For example, one student said, "pollutants from power plants is outrageous, the saving of money and greed is a side effect of capitalism." Although not all responses connected environmental issues to economics as this one did, there was a definite trend that placed blame on power plants, factories, or people who drive their cars too much. When asked what is the best way to reduce global warming, only 10% of students mentioned that the responsibility lies with 'everyone' or a collective 'we' in their response. All of these responses included something about the burning of fossil fuels in cars. For example, one student explained, "burning of fossil fuels is something everybody does, whether driving a car or taking a bus." Another student said, "we need to use hydrogen versus oil fuel." These responses suggest that the students have some understanding of the actions of consumers that are influencing global warming.

Transition from narrative to model-based reasoning

The results presented above show that students are rarely able to apply fundamental principles to processes in systems in a rigorous, consistent way that involves scientific, model-based reasoning. These difficulties are due in part to their incomplete understanding of the principles and the systems. The results suggest to us, however, that perhaps more fundamental factors having to do with the genres of students' explanation are at work. We explored students' use of model-based reasoning compared to narrative reasoning on a select set of assessment items. We contrasted a model-based way of understanding phenomena as *processes in systems* with a narrative way of understanding guided by common nonscientific metaphors. We coded the assessment items with the following contrasts in mind and also included a coding category that combined the two types of reasoning.

Narrative Reasoning:

- Common nonscientific metaphors. The students applied common nonscientific metaphors to explain or predict processes. These metaphors, explanations, and predictions portrayed processes mostly as sequences of events that did not have to obey any mass or energy conservation constraints. Students grouped systems and processes according to superficial similarities, and used analogical informal reasoning to transpose explanations from one domain to another. For instance, since both animals and plants require nutrition, plants were considered to eat and grow just like humans. Also, in many contexts students explained or predicted the occurrence of an event or a phenomenon in tautological terms often by referring to its immediate observable causes or associated observable effects. Thus, events or phenomena were not explained or predicted in terms of underlying causal mechanisms.

Model-based Reasoning

- Connected qualitative models. Students connected systems and processes at different scales or in different domains (earth, living, engineered systems) using scientific models and theories. The explanations and predictions obeyed constraints imposed by conservation laws, and matter and energy were traced qualitatively across systems and processes. Students demonstrated ability to analyze events as processes within systems, and paid attention to underlying mechanisms in explaining and predicting events and phenomena.
- Connected quantitative models (only addressed by a few assessment items). Students quantified matter and energy. Students showed understanding that all processes associated with the carbon cycle are subject to constraints imposed by fundamental laws of nature, such as conservation of mass and energy, and the fact that physical and chemical changes do not create or destroy atoms. The student used *substance tracing* as a basic way of understanding processes at many different scales.

Our assessment data indicate that students rely heavily on their narrative stories and informal reasoning when responding to the assessment items. We also found a trend that students begin to reason about processes in systems more as they get older. We also found evidence that students used both types of reasoning when responding to certain types of questions. Table 23 summarizes data across multiple items from the assessment.

Table 23: Model-based and naïve reasoning

High School Questions	Model-Based	Narrative	Both	No response or Don't Know
Decaying fish and corn plants question	7.5%	12.5%	**70%**	5%
Growth of trees in Amazon question	7.5%	**45%**	20%	17.5%
Growth of acorn into a large tree question	2.5%	**50%**	**37.5%**	10%
Weight loss question	5%	**52.5%**	22.5%	20%
Burning match question	27.5%	**40%**	7.5%	20%
Weight loss of burning match	12.5%	**40%**	12.5%	12%
Sublimation of dry ice question	32.5%	**30%**	2.5%	12%
Middle School Questions				
Growth of acorn into a large tree question	2.5%	**55%**	25%	2.5%
Weight loss question	0%	**77.5%**	15%	0%
Burning match question	2.5%	**80%**	12.5%	5%
Breathing air question	25%	20%	**47.5%**	2.5%

We found that most middle and high school students relied on narrative reasoning when responding to the assessment items. If the context was largely unfamiliar or required tracing of matter in biological processes that are not given much emphasis in traditional science curriculum (e.g., metabolism of fat), most students relied on their default reasoning (i.e., naïve ideas to construct appropriate responses). Middle school students tended to use more model-based reasoning when responding to the question about human respiration and the growth of trees. The middle school students relied more on their narrative reasoning when responding to questions about chemical change (i.e., burning match) and metabolism of fat. Similarly, high school students also primarily used narrative reasoning to answer questions about chemical and physical changes and weight loss, although they used more model-based reasoning compared to middle school students. The weight loss question was particularly difficult for middle and high school students, with their responses often referring to, "burning the fat" or "fat melts away." High school students struggled with understanding what decaying fish supply to corn plants, often evoking a popular belief that "fish are a good source of protein." For example, one student responded, "I said minerals because they have minerals in their body from what they eat and the water they live in and when they break down that goes into the soil. I also said protein because fish is high in protein so when it breaks down that will go into the soil." Although not presented in the table above, we also found that students used narrative reasoning when responding to questions about global warming. One student responded, "the ozone layer is like sunblock for humans and when it breaks apart we get more sun and heat". Looking across multiple assessment items suggest that students' narratives are used often when responding about complex systems.

Discussion of Learning Progression

In this section we discuss major trends from our research and how these trends might inform the development of a learning progression for the ecological carbon cycle. What we present is an evolving and thus incomplete prototype of a learning progression. The discussion is organized around the practices of environmental science literacy, specifically practices two and three, *providing and applying scientific accounts*, and practice four, *using scientific reasoning for responsible citizenship*. Practice 1, *scientific inquiry,* is not discussed, as we did not collect data on this practice.

Practices 2 and 3: Providing and applying accounts

We see evidence of limited progress from elementary through high school with respect to three aspects of students' accounts: (a) understanding the structure of systems, and (b) tracing matter and energy in processes, and (c) using accounts to explain and predict.

Structure of Systems

Our data was analyzed with respect to two aspects of students' knowledge about the structure of systems. We first looked at students' awareness of a hierarchy of systems and their ability to reason at multiple scales about those systems. We found some evidence that students' progress from being aware primarily of macroscopic systems (i.e., organisms) toward seeing a hierarchy of systems of different scales. Younger students tend to focus on the visible, macroscopic accounts. Middle and high school students showed greater awareness of microscopic or atomic-molecular scale (e.g., gases in processes, such as photosynthesis, microbes involved in decomposition) and large-scale (e.g., global warming related to driving cars and 'pollution' from power plants), however, many of these students still were unable to use atomic-molecular reasoning to explain processes at the macroscopic level.

A second aspect we analyzed was the connections students make between living and non-living systems and to human-engineered systems. We found that younger students have some awareness of the connections between living organisms, but less evidence to suggest that they understand connections between living and non-living systems. Middle and high school students are also aware of connections between living organisms and demonstrate some understanding that matter can move from organic to inorganic forms. Their understanding of the processes by which this happens is less developed. Below we present key characteristics we observed about students' understanding of systems at the three age levels.

- *Elementary school students*: Younger students tended to focus on the 'visible' aspects of systems, usually explaining their ideas in terms of what is visible happening to the organisms or object, for example, explaining decomposition of an apple by focusing on tangible factors, such as heat and water. This reinforces findings by others who have studied this domain (Leach, Drive, Scott, & Wood-Robison, 1992; Smith & Anderson, 1986). Students make some connections between organisms, such as connecting the forests to animal habitats or plants providing humans with air. The connections are generally narrative or metaphorical rather than model-based; focusing, for example, on how plants and animals are similar or what conditions they need to survive rather than on ecological relationships or matter cycling (Driver, Rushworth, & Wood-Robinson, 1994; Smith & Anderson, 1986)
- *Middle school students*: Similarly to elementary students, middle school students still focused attention on macroscopic accounts. However, middle school students show an increasing awareness of the atomic-molecular scale of systems, such as the awareness of gases involved in photosynthesis. In this way, middle school students make connections between vitalistic accounts of living organisms and their new knowledge of molecules, such as oxygen and carbon dioxide (Inagaki & Hatano, 2002; Wandersee, 1983). According to Stavy, Eisen, & Yaakobi, 1987, middle school and high school students do not have a good understanding of the human body as a chemical system and are fairly unaware of the elements composing the living body. In fact, according to Smith and Anderson (1986), middle school students tend to think about organisms as being composed of very different types of matter compared to non-living, inorganic materials in the environment, such as soil and air. Middle school students also showed increasing awareness of the larger systems, such as constructing food chains involving multiple organisms compared to younger students that focus their explanations on categorizing all living things (see Driver, Squire, Rushworth, & Wood-Robinson, 1994, for review).
- *High school students:* Similar to middle school students, high school students showed awareness of atomic-molecular and large scale accounts, however, their explanations about photosynthesis or respiration were more detailed, for example, including some products and reactants during these processes. High school students also showed some awareness of global level issues when asked about global warming. Although we see that high school students have an increasing awareness of the hierarchy of systems, we found little evidence that they can move fluidly between different levels of scale or between living and non-living environments.

Learners face two kinds of challenges in making connections about the structure of systems. They need to account for connections among processes that occur at different scales within the hierarchy of environmental systems and subsystems, and they need to account for connections among processes that affect the same substances within a system, for example tracing a substance through decomposition. Most of these systems are either too large or too small for us to observe directly, so young children are not aware of their existence. Older children become more aware that processes take place at much smaller and much larger scales, but the students responding to our assessments generally did not connect the processes at multiple scales, a critical skill for understanding complex environmental processes.

Processes in systems: Tracing matter and energy

Our assessment data indicate that students have an increasing awareness of matter in systems, attempting to trace and conserve matter through processes and trying to explain the role of energy in systems. We found that students' understanding of matter is much more developed compared to their understanding of energy in systems. We describe key characteristics about tracing matter and energy observed in our data with respect to the three age levels:

- *Elementary school students.* We found that elementary students had a limited understanding of matter and energy involved in processes. Since students have little awareness of microscopic accounts, their understanding of matter through processes is limited to physical changes of visible objects. Students can explain the physical characteristics of an apple rotting or the connection between water and plant growth, but do not explain these processes in terms of matter or energy. Elementary students show some awareness that oxygen is involved in human breathing and that a product from plants is oxygen. Our data resonate with previous work by Carey (1985) who reported that lower elementary kids are generally clueless about what happens to air once it is inhaled, though upper elementary kids make an association of breathing with lungs and may know something about exchange of gases in lungs and that air travels around in the body. According to Leach et al., (1996), many students think that plants only give off oxygen. When asked to explain what happens to matter during the process of decomposition or combustion, students at this level may explain that the matter simply disappears (Leach et al., 1992; Smith & Anderson, 1986).
- *Middle school students.* Middle school students showed more awareness of matter in processes and show an increasing commitment to conservation of matter. The students' ability to trace matter is limited in that they often trace an incomplete set of reactants or products during processes, for example tracing oxygen as a reactant and carbon dioxide as a product during respiration without reference to water or glucose. When asked to explain what happens to matter during the process of decomposition or combustion, students at this level are less likely to say that matter disappears (Smith & Anderson, 1986). The students often tried to adhere to the law of conservation of matter, although we found that they do not understand the processes well enough to do this consistently. For this reason, students might default to an incorrect matter to energy conversion.
- *High school students.* Similarly to middle school students, students at this level also provided more detailed explanations of processes and a stronger commitment to the conservation of matter (as Leach, et al., 1992 found in their research). Some high students were able to explain the process of cellular respiration in consumers in more detail compared to middle school students, but the majority of students did not name all the reactants and products involved in this process. Interestingly, high school students had the same limited understanding of cellular respiration in plants as middle school students and tended to focus on plant photosynthesis in their explanations. Although students do have more commitment to conservation of matter, we found that almost two-thirds of students did not conserve

matter during a simple physical change (e.g., sublimation of dry ice in sealed test tube). Similarly to middle school students we also found that high school students make incorrect matter to energy conversions when trying to account for matter during processes.

Students' ability to trace matter and energy through systems is a major challenge. They must coordinate their representations of these systems at multiple scales and make connections between living organisms and non-living materials in order to trace substances and energy through these systems. In our recent research at the college level, for example, we see that college science majors generally fail to connect what they have learned about cellular metabolic processes such as photosynthesis and cellular respiration with questions about weight gain and weight loss in plants and animals.

Related conceptual change research on phenomena associated with the carbon cycle is documented in Reinders Duit's extensive bibliography (Duit, 2005) and reviewed by Driver, et al. (1994). Smith, et al. (2004) conducted a thorough review of the development of children's accounts of matter and changes in matter. The research on learners' conceptions of metabolism and matter transformations in living systems is also extensive. Some trends in this research are well established. For example, learners of all ages struggle to trace substances when asked questions that involve transformations between gases and solids or liquids (e.g., Where did the weight of a tree come from? What happens to the fat when a person loses weight? Where did the condensation on a cold cup come from?) Similarly, the concept of energy is more often confusing than helpful for learners of all ages, as when they say that "food is energy" or wood is "burned up to produce energy."

Using accounts to explain and predict

The assessment items we used required students to apply their scientific understanding to explain microscopic or large scale systems and processes within those systems. We looked across multiple items from the middle and high school assessment data to examine 1) students' application of fundamental principles that help explain or predict and 2) students' explanation of scientific terms used in their responses. We did not analyze elementary data with respect to these two factors and are limited to report only the key characteristics we observed from middle and high school students:

- *Middle school students*. We found that middle school students rarely apply fundamental principles to help explain scientific accounts. They are more aware of laws that can be used to govern the decisions they make (e.g., conservation of matter), but students do not seem to use the laws consistently or knowledgeably. Students struggled with using their understanding of conservation of mass in assessment items about photosynthesis, cellular respiration, and combustion. Middle school students were more likely to 'namedrop' scientific terms in questions about photosynthesis compared to cellular respiration or combustion, suggesting that students may be learning scientific terms without detailed knowledge of the concepts. In the questions about respiration or combustion, students more often tried to explain their ideas compared to simply using scientific terms without explanation.
- *High school students*. We found that high school students also struggled with applying fundamental principles during chemical change, however more students at this age level tended to use scientific principles more consistently especially when explaining physical changes in matter. We found that high school students were better at applying principles

to certain chemical change questions, such as describing the matter transformation during combustion, compared to other chemical change questions about cellular respiration. There was high use of 'namedropping' among high school students, where students tended to use scientific terms without explanation. The overall use of namedropping in high school assessments was less compared to middle school assessments.

Practice 4: Using scientific reasoning for responsible citizenship.

Our data assessing students' understanding of environmental issues reflect previous research on adults' understanding (Kempton et al., 1995). We found that students struggled with understanding the mechanisms causing environmental problems, specifically the substances involved and the tendency of students to generalize about good and bad influences. We found that students viewed human and natural systems as a unidirectional connection, where natural systems provide something for humans or animals to survive or that humans take something from the environment. We also found a wide range in students' explanations about the responsibility of environmental issues. We present key characteristics observed in our data with respect to the three age levels:

- *Elementary school students*. We collected limited data on younger students' understanding of environmental issues, however, we did find that students at this level make broad generalizations about "good" and "bad", where trees are good (e.g., humans need to help protect trees, trees clean our air) and pollution is bad. We also found that elementary students primarily focused on what trees provide for animals (e.g., habitat) or humans (e.g., air) (as observed in work by Roth & Anderson, 1985).
- *Middle school students*. We also collected limited data from middle school students regarding environmental issues. We found that students at this level made generalizations about "good" and "bad" similar to younger students. They also tend to focus the unidirectional connections between natural systems, such as trees, to what they provide for humans (e.g., oxygen). We also found that a few students at this level understood that preservation of forests is related to carbon dioxide, however, students tend to focus this relationship on the role of trees in "converting" carbon dioxide to oxygen for humans to breathe (Roth & Anderson, 1985).
- *High school students*. We included several assessment items at the high school level regarding global warming. A majority of high school students tend to make broad generalizations about "good" and "bad", for example explaining that pollution is bad for the environment, but not explaining why. We found that students often rely on the media in formulating their explanations, such as explaining that people need to drive hybrid or hydrogen-fueled cars, but not explaining why driving such vehicles would reduce global warming. Students provided various explanations about who is responsible for causing and reducing global warming, but a common pattern was to identify either factories or people driving cars. We found no students to make connections to their own actions (e.g., taking a hot shower, turning lights on at night) that might be related to global warming.

The data we synthesize above is incomplete and results in only a preliminary look at what students know about environmental issues. Our assessment data indicate that students at all levels have limited understanding of environmental problems and rarely use their scientific knowledge as resources for decision making. We found that students generally do not know the mechanisms related to environmental issues and provide general descriptions about actors, activities, and locations in their explanations rather than focusing on substances and processes. Our observations of the data noted that students rarely explained their ideas in regards to questions about the environment suggesting that students do not have the science knowledge to answer the question or do not know how to apply the knowledge they have to reason about more complex accounts. We offer this discussion as a preliminary look at students' reasoning in relationship to environmental science literacy.

Transition from narrative to model-based reasoning.

Underlying the trends described above we feel that there is a more general pattern associated with students' evolving understanding of the genre of scientific explanation. Our results with respect to this underlying trend are suggestive but far from definitive. We hope in our future research to explore further students' ideas about the nature and purpose of scientific explanations, and to document characteristics of different approaches to the genre.

Our data found that many students relied primarily on informal and tautological reasoning when responding to the assessment items. Informal reasoning is a natural starting point for students. However, using narrative reasoning may obscure connections between systems and focus explanations at the macroscopic scale. We found very few students used model-based reasoning, as indicated by explaining *processes in systems*, although high school students tended to explain processes more often than middle or elementary students. We found that a majority of students relied primarily on common nonscientific metaphors, with a few middle and high school students demonstrating some connected qualitative model-based reasoning, such as tracing matter through processes and attempting to account for energy.

We suggest that students going through a successful learning progression will accomplish three levels of sophistication in scientific reasoning: Common nonscientific metaphors (as in elementary and middle school students understanding of food chains as sequences of events), connected qualitative models (as in the understanding of plants and animals as matter-transforming systems), and connected quantitative models (as in the relative size of different carbon fluxes in environmental systems). Each of these levels of sophistication is associated with different ways of understanding the nature of scientific reasoning and the constraints (e.g., conservation of mass) on processes involving physical and chemical changes.

Limitations

At best, our attempt to construct a learning progression is incomplete. By focusing on accounts of phenomena, we ignore some environmental science literacy practices such as *Practice 1: Engaging in Inquiry* and only present preliminary evidence about *Practice 4: Using Reasoning for Responsible Citizenship*. Because we could not explore these practices fully, the learning progression that results is a series of snapshots rather than a dynamic account of learning. There are many gaps where needed empirical research is missing (or just unknown to us). In spite of these limitations, though, we are excited about the potential of this approach and eager to explore it further.

In addition, the research presented here mostly documents ways that school children do not reason scientifically, especially elementary age children. Driver et al., (1994) summarized research that distinct stages of reasoning in the conceptual development of any one child or group of children are not evident and a child may use different types of reasoning in different contexts. Further, according to Driver et al., (1994) there is not much evidence that pupils use science concepts learnt elsewhere in the curriculum to inform their understanding of ecological issues. While this is useful information, we aspire to a learning progression that does a better job of describing the key elements of children's reasoning on their own terms. This is especially important since some important elements of children's reasoning remain prominent in the reasoning of older students and adults. We believe that learning progressions can help us trace the developmental pathways leading to powerful scientific knowledge. We do not consider learning progressions to be a set of discrete and sequential steps in development, but rather that children have multiple developmental pathways that connect their naïve understandings with scientific theories. Without focused attention on the types of reasoning used by young students, a learning progression will not adequately describe the diverse means employed by learners in making sense of scientific accounts.

Conclusions

Environmental science literacy is the capacity to understand evidence-based arguments concerning the interactions among human populations and environmental systems and to participate knowledgeably in decisions based on those arguments. This definition focuses on environmental science literacy as informed action: We believe that schools should prepare citizens to participate in evidence-based reasoning about human actions and their environmental effects.

Our research indicates that students currently make limited progress from elementary through high school in understanding this one component of environmental systems and processes, with this progress far from adequate in preparing students to participate knowledgeably in environmental decision-making. Obviously, other components need to be understood to enable students to participate in their responsible role as citizens in a democratic society. Although students' knowledge of systems and processes does expand, high school students still struggle with connecting key ideas they have learned in their science coursework.

These findings lead us to a major challenge that we face as science educators. Our experience and our reading of the available research have convinced us that scientific reasoning about the carbon cycle is a major intellectual achievement, requiring mastery of complex practices and the ability to apply fundamental principles to complex systems. It is unlikely that most students will achieve this understanding without sustained, well-organized support from schools and science teaching that is effective in helping students develop the science knowledge and practices that are essential to understanding evidence-based arguments and participating knowledgeably in responsible citizenship.

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Appendix A: Initial Reliability Table

What happens to the wood of a match as the match burns? Why does the match lose weight as it burns?	81%
A sample of solid carbon dioxide (dry ice) is placed in a tube and the tube is sealed after all of the air is removed. The tube and the solid carbon dioxide together weigh 27 grams.	89%
When you open a bottle of soda, the soda starts to fizz. Does anything happen to the weight of the soda? (Circle One) *YES* NO Explain your answer to the previous question	86%
Which gas(es) do plants take in from their environments? (you may circle more than one) *oxygen* *carbon dioxide* other Explain what happens to the gases once they are inside the plant.	100% 65%
Which of the following is FOOD for plants (circle ALL correct answers)? Soil Air Sunlight Fertilizer Water Minerals in soil *Sugar that plants make* How does a plant change as it grows? ere do you think the plant's increase in weight comes from?	100% 90% 80%
ars ago farmers found that corn plants grew better if decaying fish were buried near by. What did the decaying fish probably supply to the plants to improve their growth? Circle ALL correct answers. A. energy *B. minerals* C. protein D. oxygen E. water Explain your answer to the previous question. How did the things you circled get from the fish to the plant?	100% 70%
Explain what happens to the air that we breathe when it's inside our bodies	100%
Humans get oxygen from the air they breathe. A. Where in the body does the oxygen get used? B. How does the oxygen get used?	90% 85%
When humans breathe, they exhale carbon dioxide. How is the carbon dioxide produced in the body?	75%
When a person loses weight, what happens to some of the fat in the person's body? *(a) The fat leaves the person's body as water and gas.* (b) The fat is converted into energy (c) The fat is used up providing energy for the person's body functions (d) The fat leaves the person's body as feces Explain your answer to the previous question. Why do you think this happens to the fat?	100% 70%
Humans must eat and breathe in order to live and grow. Are eating and breathing related to each other? (circle one) *YES* NO Explain why you circled your answer for the previous question.	85%
When an apple is left outside for a long time, it rots. a) What causes the apple to rot? (b) Explain what happens to the weight of an apple as it rots.	80% 80%
Explain how are the following living things connected with each other: (a) Grass. (b) Cows. (c) Human beings. (d) Decomposing bacteria.	70%
Explain why it might be important to preserve our forests?	90%

What do you think are the main causes of global warming? List them in order of significance. Explain your choice of order on the previous question, explaining how you decided which causes were more significant than other causes.	78% 65%
The BEST way to reduce global warming would be: (a) to reduce air pollution from factories and power plants. (b) To plant more forests and grow more trees. (c) To use public transportation rather than personal cars. (d) Any other (mention): ____________________ Why do you think your choice on the previous question is the BEST way to reduce global warming?	100% 65%
On March 10, 2004, National Public Radio reported that "forests in a remote part of the Amazon are suddenly growing like teenagers in a growth spurt." Though, the radio report added, "This shouldn't be happening in old, mature forests." Scientists have speculated that our actions may have caused this phenomenon. What do you think could be the scientific basis behind such a speculation?	68%
A small car on average uses 400 gallons of gasoline a year. About how many pounds of carbon dioxide do you think the car emits from burning the 400 gallons of gasoline? (a) close to 0 lbs of carbon dioxide as gases weigh almost nothing. (b) close to 80 lbs of carbon dioxide (c) close to 800 lbs of carbon dioxide *(d) close to 8000 lbs of carbon dioxide* (e) close to 80,000 lbs of carbon dioxide	100%
About how many trees would you have to grow to absorb the amount of carbon dioxide emitted per year by the small car mentioned in the previous example? (a) about 2000 *(b) about 200* (c) about 20 (d) about 2	100%
Do you think that wood is a mixture of different things? (Circle one) *YES* NO Please explain your ideas about what makes up wood.	78%