Answer Keys for Carbon Cycle Assessments
Introduction

"Answer key" may not be quite the right word to describe the documents we have developed, since the environmental literacy assessments are not primarily about right and wrong answers. We have developed the assessments because we are trying to create *learning progressions for environmental science literacy:* Learning progressions are "descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time (e.g., six to eight years)" (NRC, 2007).

We are developing assessments for three strands (carbon, water, and biodiversity) at three levels (upper elementary, middle, and high school). The answer keys explain our thinking about levels of achievement for the carbon strand in environmental literacy. In this introduction, we briefly describe (a) the *upper anchor,* our ideas about what environmentally literate high school graduates should understand, (b) the *lower anchor,* our hypotheses about informal thinking that we would like to explore, and (c) *levels of achievement,* our hypotheses about connections between the upper and lower anchors.

The upper anchor: Goals for environmentally literate high school graduates. One way that we represent our upper anchor is with a *loop diagram* that shows the relationships between environmental systems and human social and economic systems. The loop diagram for carbon cycling is on the following page.

We think of environmental literacy as being able to "complete the loop," connecting events in one part of their loop with their implications for all the other parts. Environmental *science* literacy focuses on the ***environmental systems*** box, and to a lesser extent the arrows going into and out of the box. Students need to understand environmental systems in ways that enable them to make connections with the arrows and with human needs and activities.

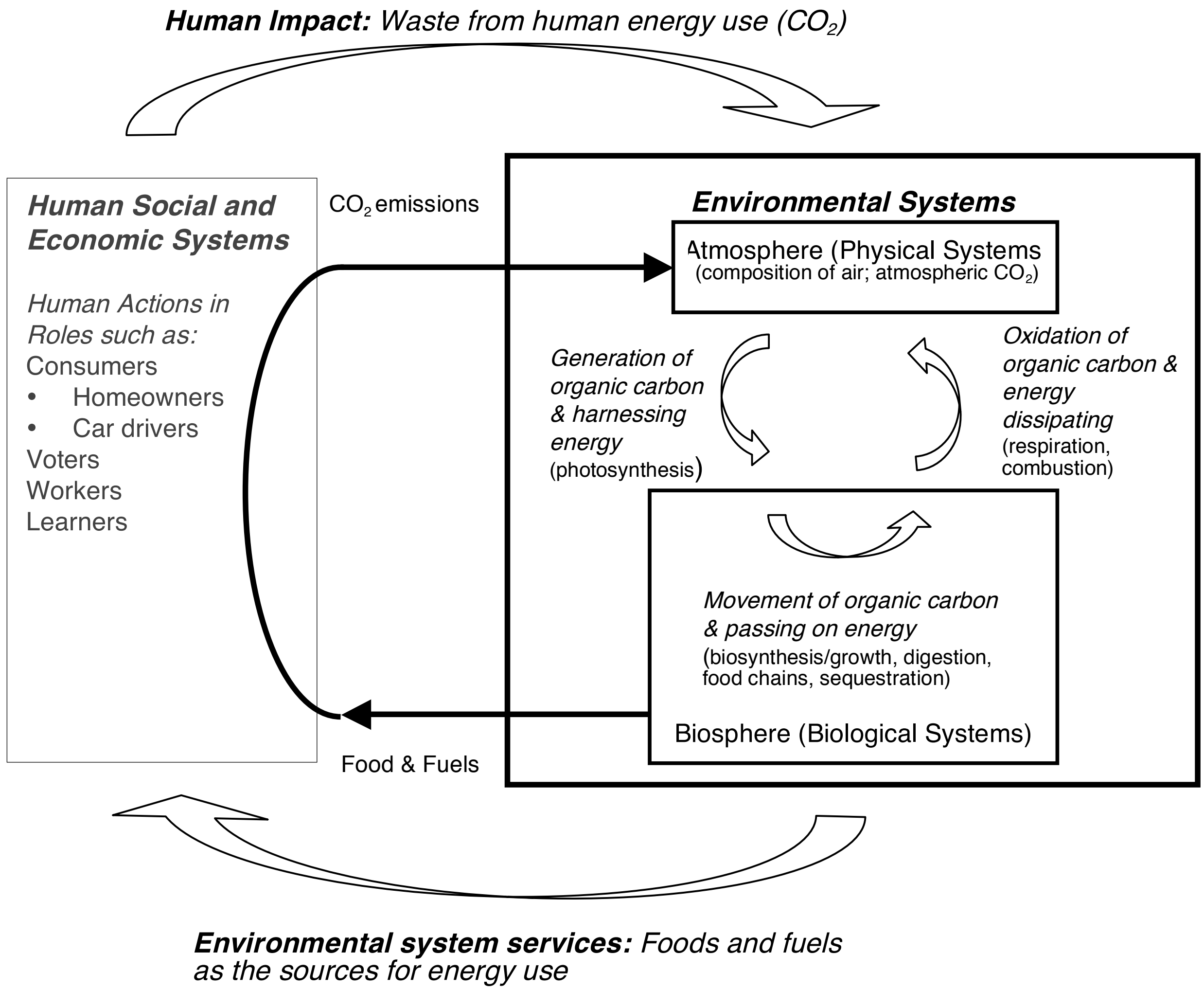
For the carbon strand we feel that students especially need to understand matter and energy aspects of environmental systems. In particular, they need to understand three kinds of processes in the environmental systems box of the loop diagram.

1. Photosynthesis: the only process that consumes carbon dioxide and produces organic carbon materials and oxygen on a large scale.
2. Digestion, biosynthesis (growth of plants and animals), and food webs: processes transform organic carbon compounds.
3. Cellular respiration and combustion: two processes that oxidize organic compounds and produce carbon dioxide.

When students explain these processes, they need to be able to engage with:

1. Principled reasoning about tracing matter- Students need to be able to use conservation of matter as a principle to explain *what happens to stuff* during changes in systems. All of the processes are chemical changes that rearrange carbon, oxygen, and hydrogen (and sometimes other) atoms into new molecules
2. Principled reasoning about tracing energy- Students need to be aware of energy sources and energy transformations that occur during processes that *harness, pass on, and dissipate energy*, and students need to distinguish between energy transformations and matter transformations. Students need to be able to use energy

transformation and degradation as principles to explain *what causes events to happen*.



The lower anchor: Hypotheses about students' informal thinking that we would like to explore. Our research has convinced us that "upper anchor" thinking about environmental systems is a hard-won intellectual achievement. When people—children and adults—think informally about the environmental systems and processes associated with carbon cycling, they think in very different terms. For example, here are some characteristics of lower-anchor reasoning that we have seen in our previous research and we would like to explore further.

1. *Hierarchy of Systems and Scale-* Students are familiar with many systems (plants, humans/animals/decomposers) and have stories to explain how those systems change. They may be able to describe changes in terms of materials, but their understanding of chemical identity of materials is limited. They may also have some familiarity with microscopic and atomic-molecular scale (cells, atoms) and large-scale (food chains, ecosystems), but cannot easily make connections between these scales (e.g., using a cellular process to explain a visible phenomena of growth).

2. *Causes: Need and Conditions-* Most students start to explain why events happen in terms of needs and conditions. For example, they know that living organisms need certain materials in order for the body to function and to do physical activities, but they cannot clearly distinguish forms of energy from conditions and matter. They know that energy is involved in events such as plants making foods and child running, but they tend to think that energy is used up to make events happen.
3. *Conservation: Gases are matter and energy is not-* While most students are aware of the conservation of matter and energy principles and recognize that gases are matter, they have difficulty conserving gases during chemical and physical changes, and still confuse matter transformations with energy transformations. (Examples: trace matter in terms of CO_2-O_2 cycles in plants and animals; trace materials that focus on solids and liquids, such as plant growth from water and decomposition making soil; tells stories that confuse matter and energy transformation, such as exercise converting fat into energy).

Transitional Levels: Connecting the anchors. If we are generally right about the upper and lower anchors, the next question is "how do we get from here to there?" If most students (and most adults) normally tend to think about environmental systems in informal terms, how can we help them learn to identify the occasions when more scientific "upper anchor" thinking is helpful and to reason using scientific concepts?

We have been working on this question, too, though we still have a *lot* of work to do. One result of our work is teaching materials about different aspects of carbon cycling (available on our website). Another result is the table on the following page, which describes a series of levels connecting the lower anchor (Levels 1 and 2) to the upper anchor (Level 5). This table points our key accomplishments and limitations that we have identified at each level.

We know that these Levels are still hypotheses. Your students' answers to the questions on this assessment should help us to come up with a better sequence of levels—and with assessments that are valid and reliable for assessing where students are in the sequence. Thank you for your help with this work!

Table 1: Summary of Tracing Matter & Energy Levels

Level	Accomplishments	Limitations
Level 5: Qualitative model-based accounts	Model-based accounts of all carbon transforming processes, which includes matter conservation and energy transformation and degradation as fundamental principles to constrain processes across scales. Understanding organic substances as being energy-rich in terms of chemical bonds (C-C and C-H bonds). Clear accounting for role of gases in carbon-transforming processes and distinction between matter and energy Qualitative understanding of global warming in terms of the relation among energy consumption, carbon emissions, and carbon sequestration.	Difficulty with quantitative reasoning that connects atomic-molecular with macroscopic and large-scale processes (e.g., stoichiometry, global carbon fluxes, energy consumption). Difficulty with quantitative reasoning about risk and probability. Difficulty with reasoning chemical reaction in terms of bond forming and breaking. (e.g., May hold the idea that energy is released when bonds break)
Level 4: "School science" narratives about processes	Stories of events at atomic-molecular, macroscopic, and large scales and attempts to conserve matter and energy at all levels. Gases clearly identified as forms of matter and reactants or products in carbon-transforming processes. Some knowledge of chemical identities of substances. Stories about chemical equations of processes, energy flow in food chains and energy pyramids, and energy conservation. Association of global warming with some "bad" human activities at macroscopic scale.	Mass of gases not consistently recognized. Incomplete understanding of chemical identities of substances and atomic-molecular models of chemical change. Energy-matter conversion and difficulty distinguishing between chemical potential energy and energy-rich materials (e.g., food is energy). Energy recycling without degradation in processes and systems. No connection between global warming and energy or matter transformations
Level 3: Causal sequences of events with hidden mechanis ms	Stories involving hidden mechanisms (e.g., body organs) and recognition of events at microscopic scale. Descriptions of properties of solid and liquid materials. Tracing matter through most physical changes Coherent stories of food chains. Using energy to reason why things happen Association of energy with some of its observable indicators.	Matter (especially gases) not clearly distinguished from conditions or forms of energy. O_2-CO_2 cycle separate from other events of carbon cycle (e.g., plant and animal growth, decay, food chains). Macroscopic events (e.g., growth, breathing) are associated with specific organs (e.g., stomach, lungs) rather than cellular processes. Energy as cause to make things happen and energy can be used up to make things happen. Confusion between energy, matter, and conditions.
Level 2: Event-based narratives about materials	Coherent stories that focus on causation outside of human agency (e.g., needs of plants and animals). Clear distinctions between objects and the materials of which they are made. Tracing matter through simple physical changes (e.g., pouring, flattening a ball of clay) Association of energy with some events (e.g. wearing heavy clothes, friction, etc.)	Focus on reasons or causes for events rather than mechanisms (e.g., "the wood burns because a spark lit it"). Vitalistic explanations for events involving plants and animals (e.g., "the tree needs sunlight to live and grow"). Using "triggering events", "needs of organisms", "functions", or "sequences of events" instead of energy to reason what make things happen. Energy can be created through certain events.
Level 1: Human-based narratives	Coherent stories about macroscopic events such as plant and animal growth, eating, and burning. Naming objects and materials Description of events using the word energy.	Focus on human agency and human analogies in stories and explanations. For example, plants and animals are classified by relationship to humans (pets, flowers, weeds) and given human needs and emotions. Human causes of events are emphasized (e.g., "The match burns because you strike it.") Energy as a common-language term (e.g. energy as desire, spirit, etc.)