Environmental Literacy Learning Progressions

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Abstract

In this paper we describe an iterative process that leads to successive "drafts" of three interconnected learning progressions, all sharing the goal of *environmental science literacy*—the capacity to understand and participate in evidence-based discussions of socio-ecological systems (i.e., interacting human societies and ecosystems). This process involves three major components, each interdependent on the other two.

- *Defining the domain.* We define the domain in terms of (a) roles and practices associated with environmentally responsible citizenship, (b) processes involving changes at multiple scales in socio-ecological systems, and (c) identifying intellectual resources and habits of mind that support the practices of environmentally responsible citizenship.
- *Developing frameworks for data collection and analysis.* We want our learning progressions to describe student performances in this domain from upper elementary through high school. We have defined an "upper anchor" or target performances based on our reasoning about environmental science literacy and on student performance data. We have developed a framework for data analysis based on levels of student achievement and important practices.
- *Using data to identify trends and levels of student achievement.* Our analyses of student written assessment and interview data and our reading of relevant literature leads us to characterize the development of student performances in term of three general trends and seven levels of achievement. The trends include (a) becoming more aware of hidden mechanisms and larger systems, (b) developing better resources for measurement, classification, and description, and (c) learning to use scientific models and principles.

The primary purpose of our work so far has been to develop empirically grounded descriptions of trends and levels of student achievement. The papers presented at this conference report our progress. These papers also show how challenging it will be to develop a learning progression that leads to environmental science literacy. The current national standards are generally written about our Level 5 of student achievement. Level 5 falls short of fully functional environmental science literacy, yet virtually all the students in our samples fall short of Level 5.

Introduction

This paper describes our approach to developing three interconnected learning progressions, all sharing the goal of *environmental science literacy*—the capacity to understand and participate in evidence-based discussions of socio-ecological systems. Environmental science literate high school graduates should have the capacity to act as environmentally responsible citizens. For us that does not imply any particular political position, but it does mean two things:

- Environmental science literate citizens should be able to understand and evaluate experts' arguments about environmental issues.
- They should be able to recognize social or economic policies and personal actions that are consistent with their environmental values.

Environmental science literacy requires understanding of many aspects of science, including chemical and physical change, carbon cycling, water cycling, biodiversity and evolution by natural selection. These phenomena are currently addressed in many state and national standards documents and in school curricula, but typically they are addressed in disconnected ways—in different courses or in different units in the same course. A connected understanding of all of these topics involves *applying fundamental principles to processes in socio-ecological systems.*

The term *socio-ecological systems* comes from the Strategic Research Plan of the Long Term Environmental Research Network (LTER Planning Committee, 2007). It reflects the understanding of these scientists that cutting-edge ecological research can no longer be conducted without considering the interactions between ecosystems and the human communities that occupy and manage them. Similarly, responsible citizenship has traditionally involved respecting the rights and values of our fellow citizens. We desire freedom, opportunity, and justice for ourselves; we recognize that our actions affect others; and we are obliged to act in ways that benefit them as well as us. This definition of responsible citizenship is no longer sufficient. We must recognize that our actions affect the material world—the environmental systems on which we and our descendents depend—and find ways to use scientific knowledge as a vehicle for considering environmental consequences in the decisions we make as we engage in the various roles of citizens.

So these three learning progressions, focusing on carbon, water, and biodiversity in socio-ecological systems, reflect our thinking about a science curriculum that would produce high school graduates prepared for responsible citizenship in a world where the limits of the environmental resources available to support human societies are increasingly apparent. In this paper we describe the domain in terms of socio-ecological systems and our understanding of how those systems function and change. We then describe the frameworks and research approaches we have developed to study how we can support the development of that understanding in K-12 students.

The Domain: Understanding Processes in Socio-ecological Systems

The domain for our research includes three interconnected learning progressions, all sharing the goal of environmental science literacy—the capacity to understand and participate in evidence-based discussions of socio-ecological systems. This section includes descriptions of this domain in terms of (a) roles and practices, (b) phenomena defined as processes in socio-ecological systems, and (c) important ideas or intellectual resources and habits of mind, including importance of "completing the socio-ecological loop," using principles to connect and constrain models, connecting models at multiple scales, and making decisions in uncertain conditions.

Roles and Practices

We start with the idea that learners' and citizens' practices are always socially embedded. Practices are associated with identities-in-practice (Belenky, Clinchy, Goldberger, and Tarule, 1986; Cobb & Hodge, 2006; Holland, Skinner, William, & Cain, 2001; Tan & Barton, 2006) or social roles. We work with learners who are currently in student roles, but a critical function of universal education is to prepare students for multiple roles that we play as citizens - as learners, consumers, voters, workers, volunteers, and advocates. The ways that we carry out our roles as citizens affect our impact, as individuals and as a society, on the Earth's socio-ecological systems.

Here are some key roles and the ways that these roles affect socio-ecological systems.

- *Personal or private roles.* The first three roles can be considered personal or private; they involve choices we make for ourselves and the people immediately around us. The cumulative effects of these personal choices, though, can have large environmental impacts.
    - *Learners.* We are learners throughout our lives. After finishing school, what we learn depends in large measure on what we choose to pay attention to, in the media, in our personal experience, and in more formal educational settings. Our choices about what we learn and how affect our ability to make use of evidence about environmental systems in all of our actions as citizens.
    - *Consumers.* We are also consumers throughout our lives, making decisions about our lifestyles and about the goods and services that we use. The impacts of the decisions we make as individual consumers are small. The cumulative impact of many individual consumer decisions, though, is huge. The human systems with the greatest environmental impact have been constructed to satisfy consumer demand.[1]

[1] Our choices of goods and services as consumers always involve environmental systems that produce and transport those goods and services as well as systems that dispose of wastes. For example, a person consuming a hamburger indirectly makes use of

- *Workers.* Environmental systems are affected both by the jobs we choose and by how we choose to do them. Workers make decisions that have environmental impacts ranging from whether to recycle paper in an office, to how much fertilizer and pesticide to put on a farm field, to whether to build a new power plant. Some citizens will do work that influences our laws and policies or the practices and priorities of large corporations.

- *Public or social roles.* The last two roles are more public and social. They concern the actions that citizens take to influence public policy at local, state, or national levels.
  - *Voters.* As voters, we sometimes vote directly on measures that have environmental implications—votes on support for mass transit, or sewage treatment and other infrastructure, or land use decisions. Even votes that do not seem to be directly about the environment can have environmental implications. Voters choose elected officials who make decisions about environmental issues, and elected officials respond to voter concerns when they set policies or appoint people to regulatory agencies.
  - *Volunteers and advocates.* Citizens also have many other opportunities to influence the interactions between human populations and environmental systems. We can serve as members of boards or commissions or as advocates for particular causes. We can serve as "citizen scientists" who help to collect data and monitor environmental systems. We can decide what organizations to join or support with our donations. We can participate in political action at local, regional and global levels. We can serve in political office.

Playing these roles responsibly is complicated and difficult. In our work we focus specifically on the *scientific* knowledge and practices that citizens will need to play these roles responsibly. Our framework includes three key *practices* that are essential for responsible citizenship and that students can engage in as learners:

1. *Inquiry:* learning from experience, developing and evaluating arguments from evidence
2. *Scientific accounts:* understanding and producing model-based accounts of environmental systems; using scientific accounts to explain and predict observations
3. *Citizenship*: using scientific reasoning for responsible citizenship

Each of these practices is actually a complex domain, including many more detailed practices and performances. Our work to date has focused primarily on the second and third practices, accounts and citizenship.

Phenomena: Processes in Socio-ecological Systems

The phenomena we focus on are *processes in socio-ecological systems.* Figure 1 and Table 1, below, elaborate on the meaning of this phrase. Figure 1 is an adaptation of the "Loop Diagram" developed by the Long-Term Ecological Research (LTER) Network to describe their ongoing research agenda (LTER Planning Committee, 2007). The LTER Loop Diagram is more complex than Figure 1; it sets the agenda for cutting-edge ecological research. The underlying idea, though, is as applicable to K-12 education as it is to ecological research: We need to understand the relationships between our societies and economies and the environmental systems upon which we depend.

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production systems that created the ingredients, transportation systems that brought the ingredients together, energy systems for food preparation, waste disposal systems, and so forth.

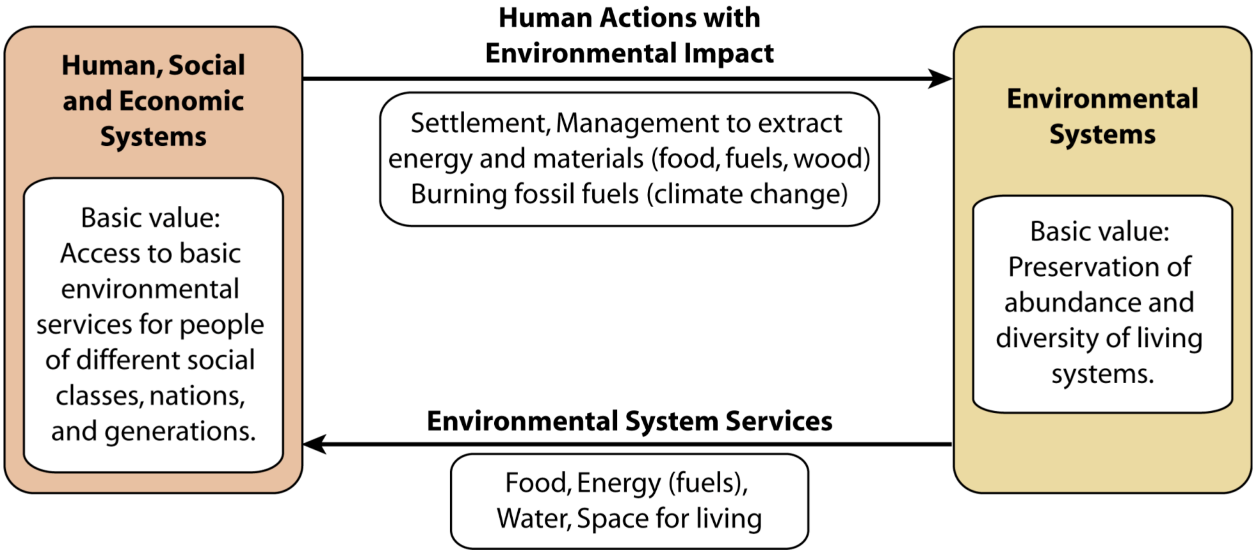

Figure 1: Structures and Processes of Socio-ecological Systems (Loop Diagram)

Figure 1 depicts the key relationships in terms of two boxes, representing human and environmental systems, and two arrows, representing the environmental impacts of our actions and the environmental services upon which we depend. We see this diagram as having three key implications for the science curriculum and the definition of our domain:

- Whenever you think about any of these issues, you need to think about the whole loop. For example, if we want to preserve biodiversity in environmental systems (the right-hand box), we need to consider how our management affects biodiversity (the human actions impact) and how we will get the food and living space we now get by reducing biodiversity (the environmental system services arrow).
- The current science curriculum (e.g., National Research Council, 1996; NAEP Framework, 2006) is mostly inside the environmental systems box. Our domain includes the environmental impact and ecosystem services arrows. (We also believe that the social studies curriculum should teach students about human social and economic systems in ways that enable them to connect those systems to the arrows, but we do not include those systems in the domain for these learning progressions.)
- We need to teach what's inside the environmental systems box in a way that helps students connect environmental systems to the arrows.

We have organized our learning progressions around three strands, each associated with a key characteristic of environmental systems (carbon cycling, water cycling, biodiversity) and each associated with a key environmental system service (fuel, water, food). These strands are the columns in Table 1, below. The rows of Table 1 go "around the loop" for each strand, starting with the environmental system services arrow and ending with key characteristics of environmental systems: structures, processes, and changes over time. The last two rows of Table 1 suggests "citizenship scenarios:" private and social choices that affect environmental systems for that strand.

Table 1: Loop Diagrams for Carbon, Water, and Biodiversity

Part of Loop	*Carbon*	*Water*	*Biodiversity*
Environmental System Service (Bottom Arrow)	Fossil fuels, Food	Fresh water	Food, Land for living
Human Economic System (Left Box)	Fossil fuel distribution and consumption: energy and transportation systems	Water distribution and use for homes, industry, agriculture	Food distribution and consumption Land ownership and use
Environmental Impact (Top Arrow)	Carbon emissions and deforestation	Management of watersheds and ground water systems	Land use: Management for agriculture Settlement in cities, suburbs, exurbs
Large-scale Structures (Environmental Systems Box) (Note that each large-scale structure is associated with macroscopic and cellular/atomic-molecular structures.)	Trophic levels in ecosystems Fossil fuel production systems	Watersheds (surface water systems) Ground water systems Human engineered water systems	Natural and agricultural populations (more and less diverse in genetics, age, environmental effects on individuals) Natural and agricultural communities (more and less diverse in species, size of populations
Large-scale Processes (Environmental Systems Box) (These are usually fairly well balanced between creation and destruction in natural ecosystems) (Note that each large-scale process is associated with macroscopic and cellular/atomic molecular processes.)	**Processes that generate organic carbon:** photosynthesis **Processes that transform and move organic carbon:** food webs, digestion, biosynthesis, (human organic chemistry: plastics, etc.); carbon sequestration **Processes the oxidize organic carbon:** cellular respiration in producers, consumers, decomposers; combustion of biomass and fossil fuels	**Processes that move & re-distribute water** run-off, infiltration, transpiration evaporation, condensation, precipitation, groundwater pumping, water diversions, etc. **Processes that alter water composition** Adding materials: erosion, dissolution, point & non-point source pollution Removing materials filtration, wetlands chemistry, water treatment processes	**Processes that create biodiversity:** Population: Mutation, sexual recombination, (genetic engineering) Community: Colonization by new species (e.g., weeds, succession) **Processes that sustain biodiversity:** Population: life cycles, reproduction, relationships among individuals Community: relationships among populations with different niches, habitats, survival strategies **Processes that reduce biodiversity:** Populations: natural selection, human selection (deliberate and unintended) Communities: reduction of niches and habitats by human management, invasive species
Changes over Time (Environmental Systems Box) (due to imbalanced processes*)*	Global climate change	Reduction in quantity and/or quality of available fresh water	Reduction of genetic diversity in populations and species Reduction of species diversity in communities (including extinction)
Personal (Consumer/Owner) Citizenship Scenarios[2]	Personal carbon footprint Carbon footprint of consumer products	Personal water use Water use of consumer products	Personal food consumption (e.g., strawberry interview) Personal land use (e.g., home ownership)
Social (Voter/Advocate) Citizenship Scenarios	Wedge game: options for reducing imbalance between generation and oxidation of organic carbon	Water use scenarios (e.g., Ice Mountain interview) Land use policies affecting water quality & quantity	Food supply systems and policies Land use policies

[2] Citizenship scenarios involve asking students to "complete the loop" when they are playing public or private citizen roles. That is, they need to connect personal and social decisions they make to our dependence on environmental system services and to the effects of our actions on environmental systems.

Ideas: Intellectual Resources and Habits of Mind

We define our domain primarily in terms of the roles and practices of environmentally responsible citizens. In particular, we believe this means that as they make personal and social choices in their roles as citizens, students should be prepared to complete to socio-ecological loop—to connect their actions and uses of environmental system services to changes in environmental systems.

Environmentally responsible practices clearly require a lot of knowledge—intellectual resources and habits of mind. We remain somewhat agnostic about the nature of that knowledge; our empirical research is in part aimed uncovering and organizing the intellectual resources of people who successfully engage in environmentally responsible practices. Here, though, are some of the key ideas about students' intellectual resources that inform our current work.

Models and principles. Figure 1 and Table 1 are ambiguous in what they depict. On the one hand, they can be interpreted as listing phenomena in our domain—the systems and processes of the human and material worlds that we intend students to investigate and explain. On the other hand, Figure 1 and Table 1 are not just lists; they represent a particular way of organizing and conceiving of those systems and processes. Figure 1 and Table 1 represent *models* of systems and processes that are constrained and connected by *principles.* Three principles are central to our thinking:

- *Tracing matter.* All of the processes in our domain (Figure 1 and Table 1) involve physical and chemical changes that neither create nor destroy atoms. This is a powerful idea, because it means that we can understand socio-ecological systems and processes more deeply by tracing elements and substances (e.g., carbon, water, materials carried by water) through them. Tracing Matter is a key Progress Variable[3] in our Carbon and Water strands.
- *Tracing energy.* Energy is also conserved in the systems and processes of our domain, so another powerful tool for understanding socio-ecological systems and processes is tracing energy as it is converted from one form to another and ultimately degrades into heat. Tracing Energy is a key Progress Variable in the Carbon strand.
- *Tracing information.* This principle requires a little more explanation, since it is not normally stated as a law. A key characteristic of living systems is that they maintain continuity in structure and function even as their subsystems disappear and are replaced. For example, individual humans' structures and metabolic processes are sustained even though virtually every atom in a baby has been replaced by the time the baby becomes an adult. Similarly, populations maintain continuity as individuals live and die, and ecosystems maintain continuity as populations change size or are replaced. We label the principles of genetics and other disciplines that explain how structure and function of living systems are sustained and how they change "Tracing Information."

Connecting models at multiple scales. Figure 1 and Table 1 refer to the *large-scale* systems and processes in our domain. These large-scale systems are near the top of a hierarchy of living and non-living systems. Students who have a basic understanding of socio-ecological systems must be able to connect systems and processes at three different scales:

- *Large scale.* Changes in large-scale systems and processes are a central concern for environmental science literacy. As Table 1 shows, these large-scale systems and processes include the carbon cycle in ecosystems, fossil fuel production and distribution systems, the water cycle, watersheds, groundwater systems, human water systems, populations, biological communities, and agricultural production systems.
- *Macroscopic scale.* Students are most aware of the systems and processes that they can see around them, from roughly a millimeter to roughly a kilometer in size. These systems and processes include growth, weight loss, and decay of plants and animals, flames, automobiles and

[3] Progress Variables are explained in the Framework for Describing Change in Knowledge and Practice, below.

appliances, precipitation, lakes and rivers, wells, water pipes and faucets, and the characteristics and life cycles of individual organisms.

- *Cellular and atomic-molecular scale.* We explain the macroscopic systems and processes that we see using models of systems and processes that are too small to see, at the cellular and atomic-molecular scales. These systems and processes include photosynthesis, digestion and biosynthesis, cellular respiration, combustion, changes of state of water, solutions and suspensions.[4]

Understanding processes leading to change over time. Sustainability—limiting harmful and irreversible change over time in environmental systems—is a fundamental concern for learning progressions focusing on environmental literacy. Students need to understand how environmental systems are changing in response to human actions and how those changes can affect their ability to continue providing essential environmental system services. Change processes, however, are even more complex than the structures and functions of the systems themselves. Changes in environmental systems usually have multiple causes, and they may involve feedback loops. In this domain we focus primarily on changes that arise from imbalances among processes that create and destroy essential environmental resources, including the following:

- *Global climate change.* In the pre-industrial era there was a rough balance between the one process that creates organic carbon materials—photosynthesis—and two processes that oxidize organic carbon—cellular respiration in plants, animals, and decomposers and combustion of biomass and fossil fuels. Our reliance on combustion of fossil fuels for energy is the primary process leading to the buildup of greenhouse gases.
- *Reduced quantity and quality of fresh water.* Most humans and most terrestrial ecosystems depend on fresh water that falls on land through precipitation. Climate change can change the amount and timing of precipitation, and many human actions—diversion of water from watersheds or ground water, changing vegetation or the permeability of soils, water pollution—can reduce the quality or quantity of fresh water that is available for human and environmental systems.
- *Loss of biodiversity.* In the pre-industrial era there was usually a rough balance between the processes that increase genetic variability in populations—mutation and sexual recombination—and the processes that reduce genetic diversity—natural and artificial selection. Similarly successional processes that increased species diversity in ecosystems were roughly balanced with disturbances that led to reductions in population sizes or local extinctions. Human agricultural and settlement practices, however, vastly increase the rate of selection processes that reduce genetic variability and species diversity. We manage land to get rid of unwanted species (pests, weeds); we reduce genetic variability in populations of domesticated plants and animals through selective breeding; and we destroy populations of other species in unintended ways such as loss of habitat and invasive species.

Heuristics for making decisions and dealing with uncertainty. Citizens' choices about environmental issues commonly hinge not just on question about *how* environmental systems will change over time, but on *how much* they will change or *how likely* a particular change is. However, projections or predictions of change in complex systems are uncertain for many reasons: We may not be looking at the best sources of information; we may not fully understand what the experts are telling us; the experts themselves may be unable to agree; the systems themselves may be inherently unpredictable, etc. We need heuristics that help to reduce uncertainty and make decisions that balance risks and benefits. We don't claim to know yet what heuristics to recommend. We do know from our own investigations (Covitt, Tsurusaki, & Anderson, 2007) and from other research (Arvai, Campbell, Baird, and Rivers, 2004; Belenky, et al., 1986; Perry, 1970; Petty & Wegener, 1999) that people use a wide variety of strategies for making decisions in

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[4] Genetic cellular and atomic-molecular models explain how phenotypic traits of organisms are inherited and how genetic traits become apparent in organisms' macroscopic structures and processes. These models, though, are not included in our learning progressions.

uncertain circumstances. These strategies vary in the assumptions they make about role and agency, in their intellectual demands, and in their effectiveness. We are organizing our investigations around students engagement with and understanding of three questions:

- *Who do you trust?* (Reasoning about SOURCES of information) Citizens often have access to multiple sources of information that make different and sometimes contradictory claims about environmental issues. We are studying how students make judgments about claims from different sources.
- *What's the argument?* (Reasoning about ARGUMENTS and supporting evidence) Citizens also have access to arguments that use scientific evidence and other knowledge claims. We are studying what kinds of evidence engage students' interest and attention, how they interpret the evidence and understand arguments from evidence, and how they evaluate the credibility of evidence and arguments.
- *What should you do?* (Reasoning about what course of action or POSITION to take) Ultimately citizens choose (sometimes unconsciously) among possible courses of action or positions to adopt. We are studying the attention and care that students take in making these choices, what students understand about different choices and their possible consequences, and how they assess the desirability of different choices.

Frameworks and Methods for Empirical Work

Developing learning progressions is an iterative process. We define a domain of phenomena, knowledge, and practice that we consider to be important; this definition provides a basis for initial data collection on students' actual knowledge and practice in the domain; these data lead us to redefine the domain and to develop initial hypotheses about levels of student achievement; these hypotheses inform further data collection, and so forth. So the domain defined above in part framed our data collection and in part resulted from our data collection.

This section describes other aspects of that iterative process: How we chose learners to work with; how we used our domain definition and initial empirical data to define an "upper anchor" or target performances for high school students; and how we developed a framework that enables us to trace students' knowledge and practice from on level to another.

Identifying Learners

We intend our learning progressions to be situated in required science courses taken by virtually all students—roughly the domain of current state and national standards documents (e.g., AAAS, 1993; NRC; 1996; NAEP Framework, 2006; Michigan Department of Education, 2006). We are not studying the knowledge and practices of the youngest students at the present, so our data collection focuses on students in fourth grade through high school, with an emphasis on students who are taking required science courses. To date, we have administered over 2000 paper-and-pencil assessments, conducted over 40 clinical interviews, and observed several classrooms where teachers were using materials that we have developed.

Describing Target Performances: The "Upper Anchor"

Our target performances or upper anchor are in part a declaration of our values: We believe that the practices of environmentally responsible citizenship are important and worthy of investment of our educational resources. We develop the upper anchor, though, through a dialogue between values and data. In particular, we are using data to address two important empirical questions:

- *What's reasonable to expect of high school students?* While we don't want to be tied down by the limitations of the current science curriculum, data on student performances also help us to appreciate the difficulty of some of the practices that we would like students to master and the nature of the intellectual resources that those practices demand. These data help us to separate goals that are realistically achievable from goals that we can merely wish for.

- *What's essential for responsible citizenship?* We take the idea of environmental science *literacy* seriously. We want to prepare students to use information that is available in the media, on the Internet, on product labels, etc., so we want to identify the knowledge that students need to use that information appropriately.

Our current answers to these empirical questions explain why, although we identify seven levels of achievement below, we think of Level 5 as our target—our upper anchor.

Developing a Framework for Describing Change in Knowledge and Practice

Our goal in developing learning progressions is to trace the development of the practices of environmental science literacy (discussed in Roles and Practices, above) from fourth grade through high school. This is a challenge because the practices and intellectual resources of naïve fourth-graders and relatively sophisticated high school students are in many ways incommensurable—they just see the world in different ways.

Yet in order to do our research we have to find the points of commonality among the practices and intellectual resources of all the different students we are working with—what we call *Progress Variables* (Wilson ref) that we can use to systematically compare and contrast the performances of different learners. Our approach to this problem has been in part theoretical (i.e., based on our ideas about the organization of the domain and the nature of student cognition), in part empirical (i.e., based on our attempts to find patterns in student responses), and in part pragmatic (i.e., based on the interests of different staff members in research questions that they would like to pursue.

Conceptually, we can think of our framework as consisting of Rows and Columns. The Rows are levels of student achievement, discussed below. The Columns use different aspects of our domain definition to identify characteristics of student practices—Progress Variables—that we can study systematically in learners at all levels. Our current organization of columns is outlined in Figure 2, below. The references are to posters and papers presented at this conference. There is also one poster in the set (Draney and Wilson, 2007) that addresses methodological issues in developing and validating progress variables.

I. Accounts: Practices of developing accounts (e.g., narratives, models, principles) and using them to explain and predict phenomena in the domain)
    A. Carbon: Accounts of processes that create, transform, and oxidize organic carbon compounds in socio-ecological systems
        1. Tracing matter: Accounting for what happens to the "stuff" in these processes (Mohan, Chen, & Anderson, 2007)
        2. Tracing energy: Accounting for what makes things happen—or not happen (Jin & Anderson, 2007)
    B. Water: Accounts of processes that produce, move, and consume fresh water—and materials carried by fresh water (Gunckel, Covitt, Abdel-Kareem, Dudek, & Anderson, 2007)
    C. Biodiversity: Accounts of processes that create, modify, and reduce genetic diversity in populations and species diversity in communities (Wilson, Zesaguli, Tsurusaki, Wilke, & Anderson, 2007)

II. Citizenship: Practices of making decisions about human actions that use environmental system services or have environmental impact.
    A. Knowledge: Connecting human actions with environmental systems (Tsurusaki & Anderson, 2007; Tsurusaki, Covitt,& Anderson, 2007)
    B. Practice: Making decisions about human actions (Tsurusaki, Covitt,& Anderson, 2007)

Figure 2: Framework for Organizing Student Practices

The organization of Figure 2 does not fully reflect our long-term intentions. We intend to embed citizenship knowledge and practices in the three content-oriented strands: carbon, water, and biodiversity. Because we do not understand citizenship practices as well as accounts, however, we are for now conducting separate investigations of how students arrive at decisions about their actions. The individual papers have another level of detail below the level shown in Figure 2. For example, the Tracing Matter paper (Mohan, Chen, & Anderson, 2007) organizes student data into separate columns for photosynthesis, processes that transform organic matter, cellular respiration, and combustion (see Table 3 in the Appendix).

Using Data to Identify Trends and Levels of Student Achievement

The framework in Figure 2 organizes our data collection and analysis. In this section we describe some findings from our empirical work to date. We note again, though, that development of the trends and levels discussed in this section. The trends and levels are based both on our empirical work and our reading of the relevant literature, and we use our data about trends and levels to modify the domain and framework.

This section includes two parts. In the first part we describe general trends that we expect to see in student learning from elementary through high school level, based on current and previous research. In the second part we describe four levels of achievement that can be used to track students progress in these trends.

In describing trends and levels we focus primarily on describing student performances, particularly their language as they explain and predict the phenomena in Table 1. This contrasts with more traditional science education descriptions of misconceptions—strongly held beliefs that are in opposition to scientific knowledge. Our focus on performance arises in part from a desire to describe student learning in terms that can readily generate assessment items and in part because misconceptions are not the primary form of misunderstanding in this domain. Instead we see students piecing together gradually more coherent, model-based ways of understanding systems and processes—and building their model-based explanations and predictions on earlier narrative understandings.

General Trends in the Learning Progression

As students move through environmental systems, their accounts of environmental systems grow more sophisticated in several ways. Moving through the learning progression means that learners' horizons expand in part because they gain access to personal knowledge, but even more as they gain the ability to access and use critically the many information resources that are available to them. Three general trends are summarized below.

Awareness of Systems and Processes: From Invisible to Visible

Parts or aspects of the phenomena in Table 1 that are invisible to younger children enter the awareness of more advanced learners. This general trend has multiple dimensions, including increasing awareness of microscopic and atomic-molecular scale parts of systems, invisible mechanisms, and the roles of gases in physical and chemical change. Smith, Wiser, Anderson, and Krajcik (2006) and Inagaki and Hatano (2002) discuss aspects of this trend.

- *Microscopic and atomic-molecular scale systems:* Younger children sometimes learn to recite facts about cells or about atoms and molecules, but they are unlikely to use those facts when they try to explain phenomena that they can see at a macroscopic scale. Older learners are increasingly aware of smaller parts of systems, first at a barely visible or microscopic scale (bits of sawdust, cells), then at an atomic-molecular scale. In general their narrative performances—their ability to tell stories about smaller systems—precedes their model-based performances—their ability to use these systems to explain macroscopic scale phenomena (see below).
- *Large-scale systems:* Large-scale systems are also generally invisible to younger children. They see plants and animals but not ecosystems, lakes and rivers but not watersheds, differences among individuals but not variability in populations. Older learners are increasingly aware of the ways in which the macroscopic systems and processes that they observe are connected in larger systems.
- *Invisible mechanisms:* Younger children are aware of cause-effect relationships, but they rarely are able to suggest mechanisms by which one event causes another. These mechanisms often

involve parts of systems that are hidden or too small to see—body organs, cells, bacteria in the soil, movement of molecules, ground water, etc. Older learners are increasingly aware of hidden mechanisms and able to use those mechanisms in their predictions and explanations.

- *Gases:* Younger children often exclude gases entirely from their explanations of events, taking "evaporate" as a synonym for "disappear," for example. Older learners' awareness of gases often begins with accounts that treat gases as conditions (e.g., fires need oxygen but don't necessarily combine it with fuels) or as bystanders to other processes (e.g., the "oxygen-carbon dioxide cycle" is not connected with plant growth or animal metabolism). The most mature learners recognize gases as forms of matter that are reactants or products in chemical and physical changes.

Precision in Measurement and Description: From Impressions to Data

Younger children rely primarily on their senses and on informal or metaphorical descriptions of phenomena. More mature learners master practices and learn to use tools that enable them to (a) describe systems and phenomena with greater precision and accuracy, (b) find patterns in data, and (c) understand and communicate with others. These practices and tools include increasing use of instruments to extend the reach and accuracy of our senses, precision in measurement and data representation, and use of scientific terms and classification systems. Smith, et al. (2006) discuss these trends.

- *Trust in instruments and procedures rather than personal experience and "seeing is believing:"* Younger children must rely primarily on their senses for information about the world around them. Older learners gain skill in using instruments to measure more precisely and perceive systems or phenomena that would otherwise be invisible. Furthermore, they recognize that appropriate instruments and standardized procedures can be superior to sense impressions for many purposes, and that data collected by others can extend our access to phenomena that we do not witness ourselves.
- *Precision in description, measurement, and data representation.* Younger children rely extensively on metaphorical or analogical description and on sense-based perceptions of "amount of matter." At higher levels students move toward attribute-value description, with the attributes (variables) increasingly differentiated and precise (e.g., shifting from "amount" to "weight and volume" at to "mass, volume, and density").[5] Accompanying this increasing sophistication in description are practices that represent data in ways that communicate with other people and make patterns visible, such as graphs and tables.
- *Use of scientific descriptive terms and categories:* Younger children rely on categories related to appearance or relationship to humans. For example, they may classify plants as trees, bushes, and flowers, or animals as pets and enemies. Younger children may also have trouble distinguishing objects from the materials of which they are made or distinguishing matter from non-matter (e.g., they classify gases with other "ephemera" or conditions such as heat, light, and temperature; they may also have trouble tracing matter into and out of living organisms). Older learners increasingly recognize classifications that rely on hidden attributes or processes, such as phylogenetic classification of organisms or classification by trophic levels. Only students who have mastered atomic-molecular models can reliably distinguish between substances and mixtures and trace matter through chemical changes.

[5] We note an intermediate stage in the development of attribute-value approaches to description where students use different words for different attributes, but as alternatives rather than in a coordinated way. For example, children describing how much material is in an object use separate words for amount (more, less), weight (heavier, lighter), and volume (bigger, smaller). However they tend to have difficulty using those words in a coordinated way. Similarly, students' explanations of differences among individuals in a population can attribute those differences to genetics, age, or environmental conditions, but rarely to those factors in combination.

Nature of Accounts: From Stories and Procedures to Models Constrained by Principles

The final trend is the most complex and perhaps the most important. As students grow in awareness of hidden systems and processes and master instruments and procedures for describing and finding patterns in phenomena, they also need to undergo a shift in their fundamental approach to explaining and making predictions about the phenomena in Table 1, from *narrative* to *model-based* reasoning. These are two different approaches[6] to understanding and explaining the world. This trend is discussed extensively in the literature, for example by Bazerman (1988), Bruner (1985), Egan (1985, 1987, 1998), and Pozo and Gomez-Crespo (2005).

Model-based reasoning[7] is what we normally think of as scientific reasoning. Model-based reasoning uses patterns in observations of phenomena (i.e., laws) and models or theories to explain and make predictions. Model-based reasoning puts widely applicable laws, models, and theories in the foreground and seeks to understand the details of particular phenomena through their application. Science education standards documents (e.g., AAAS, 1993; NRC, 1996; NAEP Framework, 2006; Michigan Department of Education, 2006).

Narrative reasoning plays a minor role in science education standards and research but a major role in how most people make sense of the world. Narrative reasoning explains and predicts phenomena by constructing stories that make intuitive sense. Stories are often connected to other stories by metaphors and analogies (e.g., growth of trees is sort of like growth of people). The meaning and sense of the stories does not rely on the application of general principles. Narrative reasoning often relies on cultural models[8] (Kempton, Boster, and Hartley, 1995) and on embodied experience (Pozo & Gomez Crespo, 2005; Warren, Ballenger, Ogonowski, Rosebery & Hudicourt-Barnes, 2001).

Thus narratives and model-based reasoning are alternative approaches to making sense of the world. Narratives put events in order; models function as flexible intellectual tools that can be systematically applied within their domains. As learners mature, they are able to use model-based reasoning more widely, they learn to use principles such as conservation of matter to constrain and connect models, and they learn to make distinctions among types of knowledge claims that are essential to model-based reasoning. In the examples below we describe general trends using example from one progress variable—Tracing Matter.

- *Changing balance between narrative and model-based reasoning.* Most children in elementary school are able to trace matter under some circumstances, such as understanding that water poured from one container to another is still the same amount of water with the same physical properties. They explain most changes in matter, though, as events with causes and outcomes through which they do not trace matter. (Their explanations of a fire, for example, focus on the origins of the flame and what the flame does to the wood rather than how the material of the wood is combining with oxygen.) As learners mature, the domains in which they are able to engage in model-based reasoning constitute growing "islands" in a narrative "sea;" they use models more widely, but still rely on narratives as a default sense-making strategy. Some learners, currently a small minority, eventually shift to model-based reasoning as a primary sense-making strategy; they use models to generate narratives rather than locating models within narratives.

[6] These notes omit another important aspect of students' reasoning about the material world: practical or craft reasoning based on direct experience with phenomena. It is difficult to construct verbal assessment items that assess students' practical reasoning. See, for example, Rath & Brown (1996) and Schauble, Klopfer, & Rhagavan (1991).

[7]. Modeling or model-based reasoning can have different meanings in different fields. In particular, developmental psychologists tend to use "modeling" or "model-based reasoning" much more broadly than we are using the term here, including a wide variety of ways in which children construct and use representations or models of the material world. Specialists in information technology commonly use "modeling" more narrowly, referring primarily to computer models of systems and processes.

[8] "Cultural models are everyday theories (i.e., storylines, images, schemas, metaphors, and models) about the world that tell people what is typical or normal, not universally, but from the perspective of a particular Discourse. (Gee, 2004 p. 40). From Gee, J. P. (2004). Discourse analysis: What makes it critical? From R. Rogers (Ed.) An Introduction to critical discourse analysis in education (pp.19-50). Mahwah, NJ: Lawrence Erlbaum Associates.

- *Using principles to constrain and connect models.* As noted in the domain description above, we have identified three general principles (conservation of matter, conservation of energy, and continuity in structure and function) as fundamental principles that constrain and connect the models we use to explain many different processes, including all the processes in Table 1. Learners who master these principles and their applications have important constraints on processes that enable them to assess their understanding. ("I must not really understand this process because I haven't accounted for all the carbon atoms.") They can also see deep connections among processes that narratives connect weakly and metaphorically. (Consider the difference between showing that the reactants and products of combustion and cellular respiration are chemically similar—a model based connection—and saying that exercise "burns off" fat—a metaphorical connection between narratives.)
- *Distinguishing models from observations and patterns.* Narratives put facts in order, without distinguishing among different kinds of facts. In contrast, model-based reasoning requires learners to distinguish between things that we can observe and measure (for example, the masses of reactants and products in a chemical reaction) and models or theories that we use to explain our observations (for example, atomic molecular theory). The science practices described in state and national standards documents depend on this distinction. Standards asking students to explain or predict phenomena require applying models to observations; scientific inquiry requires finding patterns in observations and/or developing models to explain those patterns (see Smith, et al., 2006; NRC, 2000; NAEP Framework, 2006; Michigan Department of Education, 2006).

Proposed Levels in the Learning Progressions

The general trends described in the previous section are reasonably well empirically validated through prior research and continuing research and development. Reporting students' progress, however, requires demarcation of specific levels or benchmarks along the trend lines. This has been a primary focus of our research.

Our ultimate goal is to develop empirically validated levels of student achievement for all of the practices and phenomena in our domain. We are still a long way from that goal. For example, Tracing Matter is the best-developed of our progress variables, but we find that processes differ greatly in the demands they make on students' intellectual resources. For simple physical changes such as pouring water from one container to another, students can trace matter without knowledge of the chemical composition of the water or how mass and volume are related to density. In contrast, tracing matter through biological processes such as cellular respiration requires a detailed understanding of how atoms are recombined into new molecules in complex biological systems. There are other limitations to the descriptions of levels in this section. These levels represent a simplification of a complex and changing reality. In order to create levels, we had to put boundaries within a generally continuous developmental process. These levels represent what we see in data from current American students, not a developmental trajectory that all learners will inevitably follow.

Table 2 below describes seven general levels of achievement for students' performance on questions that ask for accounts of phenomena in our domain (see Table 1). There are columns for each of the three strands: carbon, water, and biodiversity. We follow the conventions of the Berkeley assessment group (e.g., Briggs, Alonzo, , Schwab, & Wilson, 2004), putting the levels in descending order. Briefly, the levels are as follows:

- *Level 7: Quantitative reasoning about uncertainty.* Learners at Level 7 can understand the assumptions and procedures that lead to quantified measures of risk and uncertainty. Learners at this level can also identify hidden assumptions underlying risk assessments and projections of environmental change or other processes that should be taken into account in assessing the environmental impact of particular courses of action (e.g., costs of production and land use in switching from fossil fuels to biofuels). In general, expert reports such as those of the

Intergovernmental Panel on Climate Change (2007) or the Millenium Ecosystem Assessment (2005) are written at Level 7.

- *Level 6: Quantitative reasoning about processes and change over time.* Learners at Level 6 can use quantitative measures to relate processes at different levels (for example, figuring out how much carbon dioxide is absorbed when a tree gains 100 kg of biomass). They can compare rate measures of large-scale processes affecting carbon, water, and biodiversity to one another to assess rates of change over time (for example, comparing rates of processes that generate and absorb atmospheric carbon dioxide). In general, decisions based on quantitative understandings of rates of change over time require reasoning at Level 6.
- *Level 5: Successful qualitative model-based reasoning about processes in socio-ecological systems.* Students at Level 5 can use scientific models and principles to relate atomic-molecular, macroscopic, and large-scale processes for all of the processes in Table 1. They can trace matter and energy through systems, and they can explain evolutionary changes in populations and successional changes in ecosystems through processes of reproduction and selection. In general, high school standards in state and national standards documents require Level 5 reasoning.
- *Level 4: "School science" narratives of processes in systems.* Students at Level 4 can produce narrative accounts of systems and processes at atomic-molecular, cellular, macroscopic, and large scales. However, in responding to questions that require model-based reasoning across scales, they commonly fall back on cultural models and embodied experiences. They are generally successful in tracing matter through processes involving solids and liquids, but not gases. They are rarely successful at using principles of energy conservation to constrain processes. They use ideas about inheritance but not ideas about variability in populations to explain evolutionary change. In general middle school standards require Level 4 or Level 5 reasoning. Many high school assessment items require Level 4 reasoning.
- *Level 3: Events driven by hidden mechanisms.* Students at Level 3 generally explain the phenomena in Table 1 with stories about events rather than treating the phenomena as processes involving changes in matter, energy, and/or biodiversity. They understand that macroscopic systems have subsystems (e.g., body organs) and that there are relationships among organisms (e.g., food chains), but their awareness of systems that are too small (e.g., cells, molecules) or too large (e.g., watersheds, ecosystems) to see is generally limited to patchy narratives that they cannot connect to macroscopic objects and events. In general, elementary school standards require Level 3 or Level 4 reasoning.
- *Level 2: Sequences of events with little attention to hidden mechanisms.* Students at Level 2 explain the processes in Table 1 as sequences of events. They recognize that plants and animals have needs, but they do not generally distinguish among conditions (such as warmth), forms of energy (such as sunlight), and materials (such as food and water). They explain combustion as an event; they are likely to focus on the observable flame and heat rather than how matter is changing. Some assessment items based on elementary school standards can be successfully answered with Level 2 reasoning.
- *Level 1: Egocentric reasoning about events.* Students at Level 1 focus mostly on events in which they are personally involved and on how people make them happen (as opposed to independent causation). Plants and animals are generally both viewed as alive, though there may be some confusion about plants. There is no evidence of understanding of what goes on inside plants and animals, and they are described and classified with words that emphasize their relationships with humans (pets, flowers, weeds, wild animals). Descriptions of needs may also include human-centered conditions (e.g., "care"). The standards documents generally do not include performances requiring only Level 1 reasoning.

Table 2: Comparing Levels of Student Achievement for Carbon, Water, and Biodiversity Strands

Level	***Carbon***	***Water***	***Biodiversity***
Framing Questions	*What happens to "stuff?" (matter)* *What makes it happen? (energy)*	*Where does water come from and go to?(water)* *What is in water and how can that change? (materials in water)*	*How are individuals and eco-systems alike and different?* *How did they get that way?*
Level 7: Quantitative Reasoning about Uncertainty	Can explain sources and quantitative estimates of uncertainty associated with carbon fluxes and their influence on global warming. Can quantify uncertainty in projections of energy consumption's impact on global warming.	Can explain sources and quantitative estimates of uncertainty in projections of water supply or water quality associated with climate change or human management of watersheds and groundwater.	Can apply models of change that include quantification of probabilities (uncertainty) of events such as mutation rates, drift, birth and death rates and natural or human-caused disturbances.
Level 6: Quantitative Model-based Reasoning	Quantitatively traces matter within and between organisms and between living and non-living systems. Quantitatively traces energy in terms of bond energy (ΔH) and traces energy and matter through large-scale systems.	Quantitatively traces water and materials in water through systems at multiple scales. Relates quantitative measures of concentration of materials in water to measures of mass and effects of purification processes.	Quantitatively traces information across multiple scales. Quantifies the relative contribution of multiple sources of variation; rates of change; and variables associated with diversity at the ecosystem and population levels.
Level 5: Qualitative Model-based Reasoning	Qualitatively describes matter transformations during biogeochemical processes and conserves chemical substances. Qualitatively describes energy transformations, including tracing sources back to resources and degradation.	Uses models to trace water and materials in water along multiple pathways through systems at multiple scales. Relates atomic-molecular models of solutions and suspensions to water quality and macroscopic and large-scale processes.	Traces information through short and long term processes at both the population and ecosystem level. Considers multiple sources of variation, processes than maintain variation, and processes that reduce variation in natural and human-controlled systems.
Level 4: "School Science" Narratives	Recognizes matter transformations at the cellular and atomic-molecular level and attempts to conserve chemical substances. Identifies energy sources and recognizes energy transformations, but rarely gets transformations right.	Uses spatial visualization to trace matter through systems and explain mechanisms of flow. Associates water quality with dissolved or suspended materials, but not specific about chemical identity or atomic-molecular models.	Recognizes many of the appropriate systems and processes that explain change over time in natural and human-controlled systems, but fails to connect the systems and/or processes in a manner constrained by scientific principles.
Level 3: Events Driven by Hidden Mechanisms	Recognizes mechanisms for events at a hidden scale; conserves matter for visible physical changes. Recognizes energy sources such as foods, fuels, and sunlight, but does not distinguish between energy and other needed conditions or materials.	Recognizes that a mechanism is required to move or change water, but mechanisms provided do not account for limitations of processes or systems. Associates water quality with conditions or non-specific materials (e.g., "chemicals").	Recognizes connections between micro and macro, and macro and large scale systems, but the mechanisms connecting those systems are explained by cultural narratives or embodied experience. Diversity in systems not considered in explanations of processes or change.
Level 2: Sequences of Events	Describes observable changes in systems, but not attempt to conserve matter during those changes. Uses triggering events, conditions, and needs to explain why things happen.	Uses iconic visualizations and representations, usually about visible parts of systems, but does not recognize hidden mechanisms for events. Characterizes water quality in broad terms—good or bad.	Recognizes variation in systems where it is visible at the macroscopic scale. No connections made between small scale systems such as genes and large scale phenomena such as phenotypic variation.
Level 1: Egocentric Reasoning about Events	Explains why events involving changes in matter happen in terms of human needs and intentions.	Explains what happens to water and water quality in terms of human needs and agency.	Explain what happens to organisms, species or ecosystems in terms of humans needs or natural tendency.

In our current paper set (see Figure 2, above) we are trying to work out how these levels can be used to find patterns in student performances within and across strands. Table 2 presents some of the patterns we see in brief form. More detailed descriptions of these patterns, with supporting data, can be found in the papers and posters. The Appendix of this paper also has a more detailed description of patterns in student performances for one Progress Variable: Tracing Matter through processes involving the generation, transformation, and oxidation of organic carbon.

Conclusion

In this paper we describe an iterative process that leads to successive "drafts" of three interconnected learning progressions, all sharing the goal of *environmental science literacy*—the capacity to understand and participate in evidence-based discussions of socio-ecological systems. We conclude with very brief comments on three questions.

1. Why study the results of bad teaching? The primary purpose of our work so far has been to develop empirically grounded descriptions of trends and levels of student achievement. The papers presented at this conference report our progress. But how are the trends and levels that we *see* related to the trends and levels that we *want?* What can we learn without systematic teaching experiments that explore and demonstrate what is possible? I don't have a good answer to this question, but our experience so far leads me to be cautiously optimistic. It's interesting how much of the content school science does *not* appear in our students' interview and written responses. They write and talk about what makes sense to them; by doing this they help us identify what may be worth teaching.

2. Is this enough? We are interested in talking about how close the domain for these learning progressions (with the addition of some content on health and nutrition) could come to defining the entire required science curriculum. Students who reach Level 5 in these learning progressions would know more science, and be better prepared for the issues they face as citizens, than high school graduates today.

3. Is this too much? These papers also show how challenging it will be to develop a learning progression that leads to environmental science literacy. The current national standards are generally written about our Level 5 of student achievement. Level 5 falls short of fully functional environmental science literacy, yet virtually all the students in our samples fall short of Level 5.

We feel confident that these challenges will be enough to keep us occupied for many years to come!

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Appendix: Detailed Levels for One Progress Variable

Table 3: Tracing Matter through Processes that Generate, Transform, and Oxidize Organic Carbon

	Living Systems			Human Engineered Systems
Levels	**Generation-** photosynthesis	**Transformation-** food chain/web, biosynthesis	**Oxidation-** cellular respiration	**Oxidation-** combustion
Level 7: ***Quantified uncertainty and change*** Use quantitative, accounts at multiple scales to explain large-scale change over time and uncertainty associated with that change.	Quantifies uncertainties associated with specific processes and specific actions and is able to do risk assessment (e.g., can consider the likelihood/ uncertainty that certain actions, such as how using biofuels instead of fossil fuels, will influence the level of atmospheric greenhouse gas levels). Identifies hidden assumptions underlying risk assessments and projections of environmental change. Identifies other processes that should be taken into account in assessing the environmental impact of particular courses of action (e.g., costs of production and land use in switching from fossil fuels to biofuels). May require tools to find relevant information (e.g., searching on Google), but knows enough to access the correct information.			
Level 6: ***Quantitative model-based accounts across scales*** Use qualitative and quantitative descriptions of carbon movement through multiple processes in multiple scales.	Uses quantitative measurements of carbon fluxes through multiple processes in multiple scales. Explains accumulation of carbon dioxide in the atmosphere and global climate change in terms of imbalances among processes that generate and oxidize organic carbon compounds (biomass, foods, and fuels). Can use stoichiometirc calculations to connect atomic-molecular quantities with measures of mass or volume at macroscopic and large scales, but cannot quantify uncertainties of those calculations. (e.g. can calculate how much carbon dioxide a car produces in burning 100 L of gasoline; how much carbon dioxide a tree absorbs in making 100 kg of wood, but cannot use calculations to deal with the uncertainty such as how the making and using biofuels instead of using fossil fuels will influence the level of atmospheric greenhouse gas levels.) Relates measures of energy (megawatt-years) to measures of mass (e.g. gigatons of CO_2). May require tools to find relevant information (e.g., searching on Google), but knows enough to access the correct information.			

	Generation- photosynthesis	**Transformation-** food chain/web, biosynthesis	**Oxidation-** cellular respiration	**Oxidation-** combustion
Level 5: ***Qualitative model-based accounts across scales*** Use qualitative descriptions of carbon movement through multiple processes in multiple scales.	Can use atomic molecular understanding of photosynthesis to explain macroscopic and large-scale phenomena (e.g., plant growth, plants as a carbon sink) and conserve matter and mass (including gases) at the atomic-molecular level in terms of rearrangement of atoms. Can name chemical identities of all products and reactants during photosynthesis, including gases and organic materials (i.e., glucose). Recognizes that molecules are the basic unit to keep substance's identity (e.g., glucose, CO_2). Recognize proteins, lipids, and carbohydrates as key molecules in plants, and know that these organic molecules are made primarily of atoms of carbon, hydrogen, and oxygen. *Correctly identifies that plant matter, such as wood is a heterogeneous mixture and names substances or kinds of molecules in this mixture that contain carbon (other than CO_2)- distinguishes mixture from compound and from elements.* *Common Errors:* • Cannot use stoichiometric calculations to calculate the amount of certain materials involved in photosynthesis. • Sub-processes, such as light-dependent (light) and light-independent (dark) reactions may still contain errors.	Recognizes that matter is being passed through the food chain/web and can conserve matter and mass (including gases) at the atomic-molecular level in terms of rearrangement of atoms through multiple sequences of changes. *Describes role of organisms in terms of trophic levels (producers, consumers, decomposers, etc) and can predict changes in one trophic level based on changes in another level.* Recognize proteins, lipids, and carbohydrates as key molecules that move within and between organisms, and know that these organic molecules are made primarily of atoms of carbon, hydrogen, and oxygen. Recognizes that molecules are the basic unit to keep substance's identity (e.g., glucose, CO_2). *Recognizes that plant growth occurs when plants transform simple sugars made through photosynthesis into complex sugars/starches or polysaccharides (e.g., cellulose, lignin, etc). May know some details of biosynthesis (e.g., enzymes, carbon fixation), but primarily can only name products.* *Recognizes that growth of humans/animals/decomposers occurs when organisms synthesize simple carbohydrates and amino acids into more complex molecules (lipids, proteins, etc). May know some details of biosynthesis, but primarily only name products.* *Common Errors:* • Details or sub-processes of biosynthesis may be incomplete or contain errors.	Can use atomic molecular understanding of respiration to explain macroscopic and large-scale phenomena (e.g., weight loss, soil respiration as a carbon source) and conserve matter and mass (including gases) at the atomic-molecular level in terms of rearrangement of atoms. Can compare/contrast cellular respiration to combustion in terms of characteristics of reactants and products. Can differentiate cellular respiration (aerobic) and fermentation (anaerobic) in terms of the role of O_2 as a reactant. Can name chemical identities of all products and reactants during respiration, including gases and organic materials (e.g., lipids, carbohydrates). Recognizes that molecules are the basic unit to keep substance's identity (e.g., glucose, CO_2). Recognize proteins, lipids, and carbohydrates as key molecules in, and know that these organic molecules are made primarily of atoms of carbon, hydrogen, and oxygen. *Common Errors:* • Cannot use stoichiometric calculations to calculate the amount of certain materials involved in respiration • Sub-processes in the Krebs cycle, such as the details of the glycolysis & pyruvate oxidation, may contain errors.	Can use atomic molecular understanding of combustion to explain macroscopic and large-scale phenomena (e.g., burning gasoline, carbon fluxes from fossil fuels use) and conserve matter and mass (including gases) at the atomic-molecular level in terms of rearrangement of atoms. Can compare/contrast combustion with cellular respiration. Can name chemical identities of all products and reactants, although may not know exact chemical identities of fossil fuels. Recognizes that molecules are the basic unit to keep substance's identity (e.g., molecule of butane, propane). Correctly identifies gasoline as a homogenous mixture and wood as a heterogeneous mixture and names substances or kinds of molecules in these mixtures that contain carbon. *Common Errors:* • Cannot use stoichiometric calculations to calculate the amount of certain materials involved in combustion. • The exact chemical identity of fuel sources, although the student does know it contains carbon.

	Generation- photosynthesis	**Transformation-** food chain/web, biosynthesis	**Oxidation-** cellular respiration	**Oxidation-** combustion
Level 4: ***School science narratives of processes*** Atomic-molecular narratives about cellular processes and large scale narratives about food chains can explain (to a limited degree) macroscopic events	Can reproduce formulas for photosynthesis (that may be balanced or not), but cannot explain this process in detail or use the formula to explain a macroscopic event (e.g., where does tree get its mass?). Recognize the need to conserve matter and mass in chemical changes and attempt to conserve matter at the atomic-molecular level. *Recognize that gases are matter and attempt to conserve these during chemical changes (e.g., say that CO_2 contributes to mass of tree), but may ignore some gas reactants or products.* Can name materials by their chemical identity, such as CO_2, O_2 and glucose when asked specifically about photosynthesis, but cannot identify the substances that make up common foods or plants. Neither can students use chemical information about those substances to develop explanations of how they were created. *Recognizes that the cell is the basic unit of both structure and function of plants and that plant cells contain organelles (e.g., chloroplasts) and are made of water and organic materials.* *Common Errors:* Details of photosynthesis may: • Be incomplete or contain errors such as matter-energy conversion (e.g., sunlight contributes mass) or gas-gas cycles (saying that photosynthesis converts O_2 to CO_2). • Focus on minor products or reactants or materials in the systems (e.g. water, minerals contribute to mass of tree). • Explain changes in plants using photosynthesis but not respiration (e.g., plant loses mass because it could not do photosynthesis).	Recognizes that matter/energy is being passed through food chain, but cannot consistently identify matter transformation and chemical identities of matter and may not distinguish matter from energy. *Describes role of organisms in terms of trophic levels (producers, consumers, decomposers, etc).* *Plant growth is explained at the atomic-molecular levels as the accumulations of simple sugars (e.g., glucose) or as the accumulation of carbon dioxide (e.g., compacted CO_2).* *Correctly identifies that wood is a heterogeneous mixture, but does not name substances or kinds of molecules that contain carbon other than CO_2 or focuses on minor constituents in mixtures (e.g., minerals).* *Human/animal/decomposer growth is explained at the atomic-molecular levels in terms of what cells do with the food/substances these organisms eat.* *Common Errors:* Details of food chains/webs may: • Use matter and energy interchangeably when explaining relationships within a food chain or web. • Contain detailed descriptions of one process in the food chain (e.g., photosynthesis) but not details about other processes. • Describe matter flow within a food chain/web in terms of a "general" materials and not specific substances (e.g., carbohydrates, lipids, proteins). • Cannot explain biosynthesis in terms of cellular processes that combine simpler molecules into more complex molecules (e.g., mass of plant comes of glucose or CO_2 or mass of humans comes from lipids in food we eat).	Can reproduce formula for cellular respiration (that may be balanced or not), but cannot explain this process in detail or use the formula to explain a macroscopic event (e.g., where does fat go when humans lose weight? What happens to the mass of a decomposing apple? What happens to the plant mass when they receive no light?). Recognize the need to conserve matter and mass in chemical changes and attempt to conserve matter at the atomic-molecular level. *Recognize that gases are matter and attempt to conserve these during chemical changes (e.g., say that fat leaves body on CO_2) but may ignore gas reactants and products or not be able to explain where gas products came from.* Can name materials by their chemical identity, such as CO_2, O_2 and glucose when asked specifically about respiration, but cannot identify the substances that make up the matter in animals. Neither can students use chemical information about those substances to develop explanations of how they were created. *Recognizes that the cell is the basic unit of both structure and function of all organisms and that cells contain organelles (e.g., mitochondria) and are made of water and organic materials. Recognize that animal cells are different from plant cells.* *Common Errors:* Details of respiration may: • Be incomplete or contain errors (matter-energy conversion such as saying that cellular respiration converts glucose to ATP). • Focus on minor products or reactants or materials (urine, feces) or focus only on the chemical identity of products, but not reactants (saying fat is converted to CO_2 and H_2O).	Can reproduce formula for combustion (that may be balanced or not), but cannot explain this process in detail or use the formula to explain a macroscopic event (e.g., what happens to mass of a match when it burns). Recognize the need to conserve matter and mass in chemical changes and attempt to conserve matter at the atomic-molecular level. *Recognize that gases are matter and attempt to conserve these during chemical changes (e.g., say that a burning match becomes smoke, gas), but may fail to recognize the primary gas products and fail to explain the role of O_2 as a reactant in combustion.* Can name products of combustion in terms of their chemical identities (CO_2 and H_2O) but cannot identify substances that make up fuels or use chemical information about those substances to develop explanations of how they created or what happens when they oxidized (may provide more explanation of the burning of wood compared to burning of fossil fuels) Recognizes homogenous mixtures (e.g., gasoline) but cannot name substances or molecules in the mixture that contain carbon. *Common Errors:* Details in combustion may: • Be incomplete or contain errors (matter-energy conversions). • Focus on minor products or reactants (e.g., ash) or do not recognize the role of key reactants (e.g., asserting that oxygen is needed for combustion but not describing fuel molecules as reacting with oxygen molecules).

	Generation- photosynthesis	**Transformation-** food chain/web, biosynthesis	**Oxidation-** cellular respiration	**Oxidation-** combustion
Level 3: **Causal sequences of events with hidden mechanisms** Reasoning about materials indicating a hidden mechanism (at the barely visible, microscopic or large scale) responsible for changes at the macroscopic level.	Instead of a cellular process, the focus is on the materials that plants take inside them to help them grow (e.g., list air, water, sunlight, minerals, etc) but does not recognize molecular structure of materials, identify chemical identities of materials, or distinguish matter from light energy. Recognize that gases are matter, but no attempts to conserve these at the atomic molecular level. Gases in plants are explained as a gas-gas cycle that is opposite of breathing in humans (CO_2-O_2 cycle) and not associated with a cellular process, indicating only that they understand this happens at an invisible scale rather than as a cellular process. Recognizes that plants are made of cells, but does not know the role of the cell in photosynthesis. Recognizes heterogenous mixtures (e.g., wood is not a uniform compound) and attempts to identify barely visible parts of the mixtures (e.g., wood is made of air, water, minerals). *Common Errors:* • Does not distinguish molecular, cellular, and barely visible levels. • Focus on gas-gas cycles between plants and humans (e.g., plants make O_2 for humans).	Recognizes food chain as sequences of events. (e.g., rabbit eat grass and coyote eat rabbit) but does not pay attention to the underlying matter movements in those events. Identifies all organisms including decomposers in food chain or present in ecosystems, but not their role as producers, consumers and decomposers (e.g., may think fungi are producers like plants and visible decomposers, such as worms and insects are consumers). Recognizes plants are made of cells but does not recognize the role of the cell in plant growth. Describes growth as a general processes, which may be localized to parts of the plant. Recognizes heterogenous mixtures (e.g., wood is not a uniform compound) and attempts to identify barely visible parts of the mixtures (e.g., wood is made of air, water, minerals). Recognizes animals/humans are made of cells (not decomposers), but does not recognize the role of the cell in growth. Describes growth as a general process of incorporating food into the body and focuses on the materials that humans and animals take inside them, which may be localized to parts of the body (e.g., stomach digests food). *Common Errors:* • Explaining digestion and growth in terms of processes that are localized in the stomach and intestines. • Does not distinguish molecular, cellular, and barely visible levels.	Instead of a cellular process, the focus is on the materials that humans/animals take inside them to help them grow (e.g., food, water), but does not recognize molecular structure of materials, identify chemical identities of materials, or distinguish matter from energy. Describe weight loss as a general process that is associated with human/animals needs for energy but not with the cell or cellular processes. Recognize that gases are matter, but no attempts to conserve these at the atomic molecular level. Breathing is commonly explained as a gas-gas cycle (O_2-CO_2 cycle) and not associated with a cellular process, indicating only that they understand this happens at an invisible scale rather than as a cellular process. May know the name "decomposition" and can associate this with an accurate mechanism (e.g., bacteria), but not with a cellular process, indicating only that they understand this happens at an invisible scale rather than as a cellular process. Typically described as general processes, such as decompose, decay, rot, etc. May also explain decomposition/rotting/decay analogous to rusting or by evaporation of liquids. *Common Errors:* • Does not distinguish molecular, cellular, and barely visible levels. • Explaining breathing in terms of processes that are localized in the lungs (e.g., our lungs breathe in oxygen and breathe out carbon dioxide)	Focus on materials being burned, but does not recognize molecular structure of materials, identify chemical identities of materials, or distinguish matter from energy. Describe combustion as a general process of "burning" and focus mostly on macroscopic products and reactants. Recognize gases are matter, but do not use their knowledge to conserve matter involving solid to gas changes during combustion. Recognize that air is needed for combustion, but treat it as a condition rather than as the source of a substance (oxygen) that reacts with the material that is burning. Recognizes similarity among classes of materials such as foods and fuels (e.g., distinguish between substances that will burn (fuels) and substances that will not), but the distinction is based on experience rather than an ability to describe properties that all fuels share. *Common Errors:* • Does not distinguish molecular, cellular, and barely visible levels. •

	Generation- photosynthesis	**Transformation-** food chain/web, biosynthesis	**Oxidation-** cellular respiration	**Oxidation-** combustion
Level 2: ***Event-based narratives about materials*** Reasoning about materials at the macroscopic level is not extended to barely visible or microscopic scales and very limited large-scale reasoning.	Focus on observable changes in plants (e.g., plant growth) based on plant needs or vitalistic causality—idea of vital powers; need air, water, good to maintain vitality and health (e.g. plants need water to stay alive). Not understood in terms of smaller parts or hidden mechanisms or distinguished from conditions or forms of energy (e.g., sunlight gives plants its mass). Recognize materials such as air, water, and soil as fulfilling needs of plants, but do not distinguish between materials that plants need to make food and other things that plants need (e.g., space). Does not recognize heterogenous mixtures of wood or may describe heterogenous mixtures in terms of macroscopic parts. Does not recognize gases as matter and does not attempt to conserve these during plant processes. *Common Errors:* • Wood or plants are made of flowers, branches, and roots.	Uses **romantic narratives** to describe relationships and connections among organisms. (e.g., nature videos). Identify plants and animals in food chains, but not decomposers. Identify subclasses of organisms based on macroscopic experiences. Explain plant and animal growth in terms of a general process attributed to taking materials into the body that the body needs. *Common Errors:* • Does not identify decomposers in ecosystems or food chains. • Does not recognize growth in terms of internal mechanisms of plants and animals, but rather the materials that plants and animals need (e.g., mass of plants comes from water or dirt, but not gases).	Focus on observable changes in humans and animals (e.g., weight loss) bases on human/animal needs or vitalistic causality—idea of vital powers; need air, water, good to maintain vitality and health (e.g. human breathe to stay alive). Not understood in terms of smaller parts or hidden mechanisms or distinguished from conditions or forms of energy. Recognize materials such as food, air, and water, as fulfilling needs of humans/animals, but do not distinguish between materials that humans/animals need to for growth, living, and energy and other things that humans/animals need (e.g., shelter, exercise). Focus on observable changes in decomposing objects caused by visible or tangible mechanisms (e.g., weather, worms) or decomposing objects disappear or go away. Does not recognize gases as matter and does not attempt to conserve these during respiration/weight loss/ decomposition. *Common Errors:* • Decomposing materials disappear or turn into smaller visible objects (e.g., decomposing leaves go away or turn into soil). • Weight loss happens because the fat just disappears or goes away	Focus on observable changes in materials that are burned (e.g., wood, fossil fuels). Not understood in terms of smaller parts or hidden mechanisms or distinguished from conditions or forms of energy. Causes of burning of fuel sources may be related to essential characteristics of materials (e.g., the match burns because wood is flammable; gasoline tank is empty because it makes the engine run) and described in terms of what the fire/flame does to the materials being burned (e.g., fire consumed the match). Does not recognize heterogenous mixtures of homogenous mixtures comprising fuels sources. Does not recognize gases as matter and does not attempt to conserve these during burning/combustion. *Common Errors:* • Burning materials disappear or turn into smaller visible parts (e.g., burning match disappears or turns into little bits of wood).

	Generation- photosynthesis	**Transformation-** food chain/web, biosynthesis	**Oxidation-** cellular respiration	**Oxidation-** combustion
Level 1: ***Human-based narratives about objects*** Reasoning about objects at macroscopic level based on human analogies and personal experiences.	Focus on observable changes of plants, but use human analogy to explain how changes happened (e.g., plant died because it did not get love). Plants are characterized according to their relationships with humans and human uses—food, flowers, etc. *Common Errors:* • Plants need love and care to grow; plants need vitamins like humans. • Classify or explain plants in terms of their use for humans (e.g., grouping vegetables and fruits because humans eat them).	Uses **mythic narratives** to describe relationships and connections among organisms. (e.g. Lion king, Bambi). Explain plant and animals growth using "natural tendencies" (plants just grow because that's what they do). *Common Errors:* • Relationships among animals are cooperative in the sense of "good will" to fellow animals. • Relationships among animals are judged in terms of human emotions or characteristics: "mean fox" and "innocent bunny". • Plants and animals grow because that's the way it is.	Focus on observable changes in humans and animals (e.g., weight loss or gain), but use human analogy to explain why changes happen. Animals are characterized according to their relationships with humans—food, pets, etc.—or are understood in human terms (e.g., cartoon movies about animals with human traits and emotions). *Common Errors:* • Animals are associated with human personality and human intentions (e.g., stereotypes of animals from cartoon movies). • Weight loss attributed to effort (e.g., he tried hard to lose weight)	Focus on observable changes in fuel sources (e.g., wood, fossil fuels) and the causes of these changes center around human intentions and effects on humans (e.g., the match burns because someone struck the match). *Common Errors:* • Classify or explain fuels/materials in terms of their use for humans (e.g., gasoline helps cars run, wood is used for furniture, paper, and pencils).