Overview of NARST Multiple Paper Set: Learning Progressions toward Environmental Literacy

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Abstract: Learning Progressions in Environmental Literacy

In this session we present data from a study of students' understanding of issues connected with *environmental science literacy*—the capacity to understand and participate in evidence-based discussions of the effects of human actions on environmental systems. Environmental science literate high school graduates should be able to engage in two practices that are essential for environmentally responsible citizenship. They should be able to understand and evaluate experts' arguments about environmental issues, and they should be able to decide on policies and personal actions that are consistent with their environmental values.

Environmental science literacy requires understanding of many aspects of science, including those addressed in this session: Chemical and physical change, carbon cycling, diversity and evolution by natural selection, and connecting human actions with environmental systems. 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. We argue that they can fit together as a coherent conceptual domain that all of our citizens need to understand. In particular, understanding in all of these domains requires *applying fundamental principles to processes in coupled human and natural systems.*

Working groups consisting of university-based researchers and K-12 teachers focused on each topic, reviewing relevant literature, developing assessments that revealed students' reasoning about the topic, and administering the assessments in the teachers' classrooms. The papers in this session present two products from the efforts of those working groups: (a) a research-based *learning progression* that includes a review of prior research, results of our research using data from pretests and posttests administered to elementary, middle, and high school students, and a possible series of steps that students could take toward understanding of the topic, and (b) assessment tests that can be used with elementary, middle, and high school students.

The results of the research indicate trends from elementary through high school that show increasing understanding of both fundamental principles and processes in environmental systems. For example, high school students are much more likely than elementary school students to be aware of atomic-molecular and large scale systems, to suggest mechanisms for processes, and to try to apply fundamental principles such as conservation of matter and energy. Even at the high school level, though, most students' understanding of coupled human and natural systems is disturbingly incomplete. Very few students were able to connect atomic-molecular, macroscopic, and large-scale processes. Important aspects of environmental systems, including gases, decomposers, and connections between human and natural systems, remained "invisible" to most students (and thus were unaccounted for in their explanations of processes in systems). Although many high school students invoked energy in their explanations, conservation of energy seems almost completely useless as an accounting tool for these students.

We conclude with a discussion of the implications of these results for the preparation of students as environmentally responsible citizens. Currently, few students are in a position to understand experts' arguments about the causes of environmental problems or about the effects of human actions; most students understand vaguely that some things are "good for the environment" and that other things are "bad." In part because their understanding is vague, most

students have little sense of personal agency or responsibility for the environmental impacts of their own actions.

Background: The Science Curriculum and Environmentally Responsible Citizenship

The last decade has seen a broad consensus in American science education around a program of standards-based reform. We have generally supported efforts to focus the curriculum on the largely overlapping content of the *National Science Education Standards* and *Benchmarks for Science Literacy* (AAAS, 1993; NRC, 1996). While this program still enjoys broad support, there are signs that that support is beginning to erode. Two lines of criticism have emerged, urging that the curriculum defined by the standards be changed in different directions.

The first line of criticism could be labeled a *traditionalist critique.* These critics are perhaps best exemplified the publications of the Fordham Institute and its director, Chester Finn (e.g., Gross, 2005a, 2005b). These critics claim that the current national standards, as well as state standards and assessments based on them, lack sufficient rigorous science content. They advocate a program of reform based on traditional disciplinary content. Although these critics have relatively little support in the science education community, they have a clear agenda that has attracted considerable attention among scientists and politicians.

The second line of criticism could be labeled a *science education research critique*. These critics focus on a number of limitations that are likely to keep the program of standards-based reform from achieving its ambitious goals (e.g., AAAS Project 2061, 2003; Anderson, 2004). Those concerns include the following:

- The reform agenda is more ambitious than our current resources and infrastructure can support.
- There are conceptual problems with the way standards conceive of relationships among knowledge, language, practice, and meta-level understandings about the nature of science.
- The standards advocate strategies that may not reduce achievement gaps among different groups of students.
- There are too many standards, more than students can learn with understanding in the time we have to teach science.
- The current standards are based on science content as of the early 1990’s, so there is a need to reconsider which science content is most current and most important.
- The current standards do not take full advantage of recent research on science teaching and learning.

While these concerns are widespread in the science education community, they have not led to clearly defined agendas that have wide support among science educators. This session is part of an effort to promote discussion that could lead toward such an agenda.

This paper set reports results from a long-term program of research that builds on developments in the natural sciences, where *interdisciplinary research on coupled human and natural systems* has become increasingly important. These changes in the natural science lead us to advocate changes in the science curriculum that refocus the curriculum on *environmental literacy and responsible citizenship.* Finally, our approach is influenced by developments in educational research, where *learning progressions* are emerging as a strategy for synthesizing research on science learning and applying that research to policy and practice.

Interdisciplinary Scientific Research on Coupled Human and Natural Systems

In the natural sciences, traditionally separate fields are increasingly integrated. For example, modern ecology has focused on *linked human and natural systems* (see, for example, AC-ERE, 2003). Human populations survive by altering natural ecosystems and the processes in them, taking materials we need out of those systems and putting our wastes back into them. Thus ecological research has focused increasingly on environmental systems that have been substantially altered by humans, such as farms and cities, as well as the supply chains and waste disposal chains that connect human economic and technological systems with both relatively pristine and altered ecosystems.

These changes in the natural sciences are driven in part by increasing awareness among scientists of how human populations are changing local and global environments. For example, the "carbon cycle" is no longer a cycle, on either local or global scales; most environmental systems—especially those altered by humans—are net producers or net consumers of organic carbon. Similarly, humans have altered the global system so that there is now a net flow of carbon from forests and fossil fuels to atmospheric carbon dioxide. Thus previous beliefs in the "balance of nature" and the basic stability of earth systems have been replaced by an understanding of environmental systems as dynamic in nature and changing in ways that we need to understand (see, for example, Weart, 2003).

It is now generally accepted that human populations and the technological systems that support us have grown to the point where we are fundamentally altering the natural environmental systems that sustain all life on Earth. Human influences are changing environmental systems in new ways, at unprecedented rates, and with potentially grievous consequences to humans and other life forms. Evidence of the scale of human effects on environmental systems abounds:

- Global climate change is happening; average carbon dioxide levels have risen by almost 20% in the last 40 years. This process will have inevitable (though not completely understood) consequences for sea levels, frequency and severity of storms, natural ecosystems, and human agriculture (Keeling and Whorf, 2005).
- Around 50% of net photosynthetic output of terrestrial ecosystems is now appropriated for human use (Vitousek, Ehrlich, Ehrlich, & Pamela Matson, 1986).
- Species are becoming extinct at 1000 times the long-term average rate (Wilson, 2001).

These developments in environmental science research have implications for all of us. The natural environment cannot continue to support human societies in their present organization and technologies. As we continue to live beyond the resources means that ecosystems can provide, the consequences of this environmental deficit will fall inequitably across the people on this globe. Those who live in environmentally marginal areas, in impoverished economies, and in politically unstable countries will suffer first and most.

Responsible Citizenship and Environmental Science Literacy

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.

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. The scientific developments outlined above make clear that 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.

We cannot anticipate the environmental issues that our children will face during their lifetimes, or the courses of actions that will be wisest. Thus the role of science education is not primarily to advocate for particular actions or policies. *Scientific knowledge and practices should provide communal resources that all citizens can draw on.* Individual scientists can and should advocate for particular policies and practices based on their personal values and opportunities, but the resources of scientific reasoning should be available to all citizens, respected by all citizens, and all citizens should understand their nature and limitations.

Thus it is incumbent upon our education system to provide citizens with the knowledge and practices that will enable them to be environmentally responsible decisions. Historically, our schools have not done an adequate job of preparing citizens to make environmentally responsible decisions. Specifically, our current science curriculum does not reflect scientific understanding of coupled nature of human and natural systems. Furthermore, the practices necessary for responsible environmental decision-making, including the appreciation for the importance of arguments based on scientific evidence, are rarely nurtured in our schools today. The consequences are visible in studies of how adults reason about environmental issues (e.g., Coyle, 2005; Kempton, Boster, and Hartley, 1995). Most adults have difficulty using scientific evidence in environmental arguments or judging the quality of evidence-based arguments.

These circumstances put a special burden on science educators. We must develop education systems that will prepare all of our citizens to play their roles knowledgeably and responsibly. Thus in this session we address the question: *What scientific knowledge and practices should all students learn that will give them the capacity to be environmentally responsible citizens?*

Theoretical Framework: Key Practices of Environmental Science Literacy

Environmentally responsible students are capable of using scientific reasoning as a resource for personal and social decision making. This means that students need to engage in four key practices of environmental science literacy:

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

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

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

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

Our data analyses are organized around these practices, so we discuss each in more detail below.

1. Inquiry: Learning from experience

Practice 1 we label scientific inquiry. It refers broadly to the various ways that people learn from personal or vicarious observations of the material world. There are important differences between scientific arguments from evidence and the moral, political, and legal arguments that we also engage in as citizens. The other types of argument concern relationships among people, and we give people the ultimate authority for deciding them, through democratic processes, the rule of authority, or the rule of law.

Scientific arguments are different. They are about the material world rather than relationships among people. Scientific communities have tried (often imperfectly) to develop methods and standards that give evidence from the material world the last word in deciding an argument. They have done this by developing an important set of distinctions among types of knowledge claims we can make about the material world and practices for assessing the validity of each type of knowledge claim.

These knowledge claims and practices are represented in Figure 1, below. The types of knowledge claims are represented by the levels of the triangle: *observations, patterns,* and *theoretical models.*[2] The arrows represent practices that relate different kinds of knowledge claims: *inquiry* and *application.*

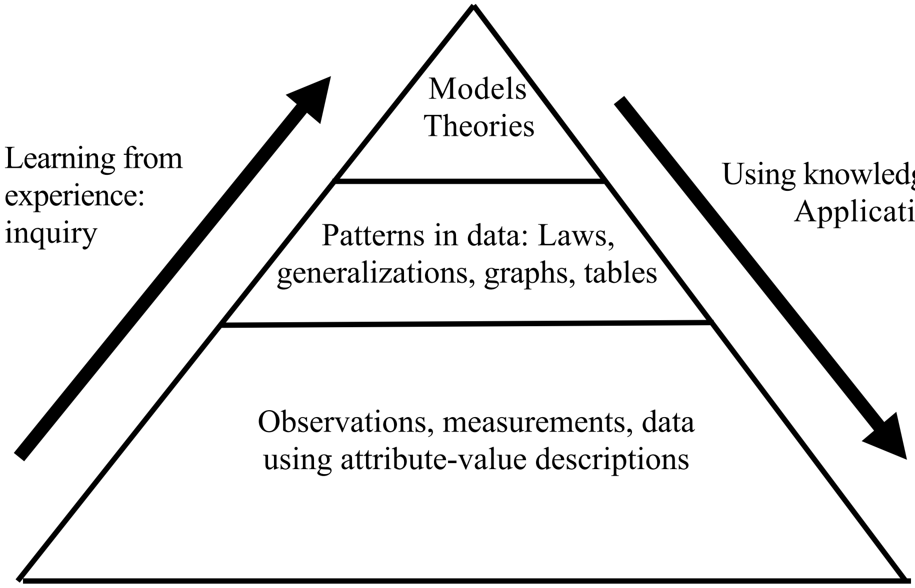

Figure 1: Scientific Knowledge and Practices

In this section we focus on the practices associated with scientific inquiry, so let's start from the bottom of Figure 1, considering the kinds of knowledge and the standards for validity in each part.

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[2] Notice that there is no mention of "facts" in this description of scientific reasoning. There is a reason for that. When scientists are speaking quickly they may use the word "fact" to indicate any sort of knowledge claim (observations, patterns, or theories) that is generally accepted by the scientific community. When they are being careful, though, as when they are writing research reports, they generally use more precise terms for the kinds of knowledge claims they are making. It is also important to note that "scientific facts" aren't always "true." Sometimes a law or theory that is accepted by one generation of scientists is rejected by the next.

- *Observations or data.* People can know the systems and phenomena of the world only through their interactions with them--through experience in the material world. Scientific arguments recognize only experiences that we can verify, reproduce, describe or measure precisely, record, and share. These experiences we *observations* or *data*. Descriptions of individual plants or animals, individual measurements denoted by points on a graph, weather reports, and readings from particle detectors in cyclotrons are all experiences that scientists would consider data. The standards by which we judge data are designed to assure that observations are tied as closely as possible to the *phenomena* (events) and *systems* of the material world. The broad base of Figure 1 indicates that scientific knowledge is based on *lots* of experience; most scientists spend a large part of their professional lives accumulating experience (i.e., collecting data) in some small portion of the material world and sharing their data with other scientists.
- *Patterns in data (laws, generalizations, graphs, tables).* Scientific laws and generalizations are statements about patterns that scientists see in their data. The gas laws, for example, represent patterns of relationships among the temperature, pressure, and volume of gases that encompass millions of individual measurements (observations) that scientists have made over the years. Thus *pattern finding* is an essential scientific practice, a key part of developing scientific arguments from evidence. *Graphs* and *data tables* are ways of presenting data (i.e., organizing experience) so that readers can see the patterns. These patterns in experience are the essential links between data and theories. In general, scientists do not accept patterns in data as valid unless they can be used to predict patterns in data not yet examined.
- *Scientific models and theories.* Scientific models and theories are designed to explain patterns in data. For example, biologists accept the theory of evolution because it explains many different patterns that scientists have observed in different ways—in the fossil record, in changes in populations observed by humans, in the biochemical makeup of different organisms, and so forth. The great scientific theories are beautiful in the elegant and parsimonious way that they explain a diversity of phenomena. Scientific models are simpler versions of theories that explain a smaller set of patterns. For example, a “billiard ball model” of a gas explains the patterns summarized in the gas laws pretty well, but not why gases sometimes condense into liquids. The small tip of Figure 1 indicates that the power of scientific theories and models lies in their parsimony—a few theories can explain many different patterns, each of which is based on thousands of observations. As with patterns, we use predictions about data not yet collected to test the validity of scientific models and theories.

In general, the practices of scientific inquiry are represented by the left-hand arrow of Figure 1. The practices of environmentally literate people who can successfully develop, use, and evaluate scientific arguments from evidence include the following:

1. Acquiring data that meet standards for precision, validity, and reproducibility.
2. Finding patterns in data
3. Scientific investigations: Developing explanations for patterns in data and comparing them with scientific accounts
4. Practical or applied investigations (e.g., product testing, land use decisions, “citizen science” monitoring of environmental systems): Using patterns in data and scientific patterns and models to predict the effects of different courses of action

5. Critiquing or evaluating reports of applied or scientific investigations

These practices and their predecessors, such as embodied reasoning in children and adults (see Keller, 1983; Warren, et al., 2001), are essential for environmentally responsible citizens because we often encounter situations in our roles as citizens where our knowledge is incomplete or where we encounter conflicting knowledge claims. We need to be able to learn from our own observations and to assess the quality of the arguments that we hear. We also need to understand the nature and limitations of "scientific facts" and "scientific proof." These practices are not a major focus of the papers in this session, simply because they are poorly addressed by our assessments.

2 and 3. Scientific Accounts: Learning and Applying Authoritative Scientific Knowledge

Scientific communities have used arguments from evidence to develop a marvelously detailed and complex set of accounts of the material world—interlocking data, patterns, and models that explain the workings of environmental systems and how they are changing. Understanding and using these accounts is an important aspect of environmental science literacy. In this section we briefly discuss some important characteristics of the accounts of environmental systems developed by scientific communities, and we describe some key practices that citizens who understand and use these accounts can engage in.

Environmental science literacy requires an understanding of key ideas from the life, earth, and physical sciences, but scientists who study environmental systems have found it necessary to move beyond traditional disciplinary boundaries. Environmentally literate citizens need to understand how the sea ice available to polar bears in the Arctic is connected to processes inside leaf cells in the Amazon rain forest and to American consumers' choices about what car to buy.

A traditionally organized school curriculum obscures rather than reveals these connections because we teach students to analyze the systems in different ways. The sea ice in the Arctic might be analyzed in an earth science course as part of a weather and climate system. The leaf cells of Amazon plants might be analyzed in a life science course as part of a hierarchy of biological systems, ranging from molecules to ecosystems. American consumers' driving choices probably would not be discussed in a science course at all; they might be discussed in a social studies course as part of an economic system.

The core problem is not that these systems are studied in different courses; it is that they are analyzed in ways that obscure their connections. The earth science course might emphasize atmospheric circulation and patterns of precipitation; the life science course might emphasize the role of chlorophyll in photosynthesis; the social studies course might emphasize the economics of automobile production and distribution. While all of these characteristics might be worthy of study, they do not help students see the *key processes that tie the systems together*—in this case the production and consumption of carbon dioxide and its effect on global climate.

This suggests to us that the school curriculum needs to emulate recent developments in science by emphasizing interdisciplinary accounts that use *fundamental principles* to reveal the linkages among *processes in coupled human and natural systems.* Table 2, below, summarizes the key principles, processes, and systems included in our framework. Those addressed in this paper set are highlighted in red.

Table 1: Details of Practice 2: Scientific Accounts of Environmental Systems

Applying fundamental principles…		*…to processes in coupled human and natural systems*		
Type of Principle	**Fundamental principles (Big Ideas)**	**Earth systems: Earth, water, air**	**Living systems: Producers, consumers, decomposers**	**Engineered systems: Food, water, shelter, energy, transportation**
Structure: Hierarchy of Systems	Microscopic (Atomic-molecular, cellular)	Properties of atoms and molecules	Cell structure, biomolecules	Materials in engineered systems
	Macroscopic	Physical and chemical properties of materials	Multicellular organisms	Appliances, automobiles, etc.
	Large scale	Matter pools	Populations, ecosystems	Large engineered systems
Constraints on Processes: Tracing Matter, Energy, and Information	Matter: Air	Wind, weather	Atmospheric CO_2	Air quality
	Matter: Water	Water cycle	Transpiration	Human water systems
	Matter: Carbon	Geological carbon cycle	Ecological carbon cycling, growth	Fossil fuel systems
	Matter: Other materials	Sediments, pollutants, nutrients		Supply chains, waste disposal chains
	Energy	Seasonal cycles, flow of solar energy	Ecological energy flow, photosynthesis & respiration	Human energy systems
	Information		Genetics, life cycles, biodiversity	(Technology, economic and cultural diversity)
Change over Time	Reproduction and selection		Evolution: changes in size, diversity, central tendencies of populations	(Technological evolution in response to economics, regulations)
	Multiple causation, feedback loops	Global climate change, land use	Invasive species	Changes in technology, voluntary and involuntary lifestyle changes

Scientific accounts of environmental systems are complex and detailed, incorporating observations, patterns, and models, and built on carefully reasoned arguments from evidence. But they are inevitably incomplete. Scientists observe only a tiny fraction of all environmental systems in developing their accounts, and they cannot, of course, make direct observations of what systems will look like in the future.

The unique power of scientific patterns and models (and a key test for whether they can be called scientific at all) lies in their usefulness for predicting and explaining all observations within a class, including observations of systems or events that have not yet been made. Thus scientific patterns and models are *intellectual tools,* not just facts about the material world.

Environmentally literate citizens need to engage in using patterns and models as intellectual tools because environmental issues can rarely be resolved just by appealing to existing scientific accounts. Most environmental issues involve questions of what will happen in the future, so we have to use our knowledge of how systems function and how they change to predict the effects of our actions. Many environmental issues are also local in character. They require careful observations of local systems (perhaps made by citizens who are not professional scientists) and assessment of how these observations fit into the framework of more general scientific accounts.

Practices associated with using accounts as intellectual tools include the following:

1. Explaining examples or observations. Often, this means "locating" an unexplained observation within the general framework of scientific accounts. This can be an obvious and straightforward process, or much more difficult (e.g., classifying organisms, explaining observed changes in matter, identifying the niche of an organism in an ecosystem)
2. Predicting examples or observations. Predictions involve using patterns and models, including patterns and models of change over time, to project the future.
    a. Predictions can be qualitative or quantitative
    b. Predictions are always based on assumptions about what properties of environmental systems will stay the same and what properties are likely to change.
    c. Predictions usually involve uncertainty. Scientifically literate citizens can identify possible sources of uncertainty (e.g., limitations in data vs. limitations in models) and methods for quantifying uncertainty.
3. Evaluating or critiquing explanations and predictions.

4. Using scientific reasoning for responsible citizenship: Reconciling experience, authority, and values

The discussion above, of scientific arguments from evidence, scientific accounts of environmental systems, and scientific predictions and explanations, has deliberately focused solely on science and scientific reasoning. Responsible citizenship, however, requires us to use scientific knowledge effectively in arguments and decisions about human freedom, opportunity, and justice. We encounter these kinds of decisions, which concern both our relationships with other people and our relationships with the material world, in all of our roles as citizens. They arise around issues of consumer choice, technological design, support for policies or laws, deciding which candidates to vote for, and so forth.

Environmental science literacy does not involve teaching students which moral, legal, economic, and political actions are correct, but it does involve helping students to see the role that scientific knowledge and scientific reasoning can play choosing in those actions. This involves, in particular, understanding the nature and the limitations of scientific reasoning. We cannot decide by majority vote whether our economic policies and practices will lead to global climate change; the global climate operates according to its own rules, not ours. On the other hand, science cannot dictate what economic policies and practices we should adopt. These decisions legitimately involve different people and interest groups appealing to our legal, moral, and political rules and values. Scientific reasoning is also limited by the inherent uncertainty in scientific accounts and predictions.

Our arguments about environmental issues often hinge on questions about the *justice* or the *sustainability* of particular policies or courses of action. These are important questions, and scientific reasoning can play a role in answering them. Scientific accounts and predictions can help us understand how important goods and services are distributed among people and human populations today, and how a policy or course of action might affect that distribution. Scientific reasoning can also help us to project the short-term and longer-term consequences of our actions. Issues of justice and sustainability, however, are never merely scientific. They involve legal, moral, political, social, and economic considerations that go beyond the realm of science.

Thus we return to an idea developed above. Science provides our society with valuable communal resources whose nature and limitations we must understand if we are to use them wisely. We cannot fully anticipate the environmental issues that our children will face during their lifetimes, or the policies and practices that will be most appropriate in responding to them. We can, however, provide our students with opportunities to develop three critical abilities for environmentally literate citizens.

1. *Democratic participation and agency.* Environmentally literate citizens understand, value, and exercise both the rights and responsibilities of participation in a democracy. These responsibilities include balancing the good of individuals with the good of society. Thus students need to understand the import of their personal actions as well as how they can influence our collective actions.
2. *Understanding and evaluating scientific evidence and arguments.* Environmentally literate citizens understand and value the scientific dimensions of environmental issues and make informed judgments about arguments advanced by experts. This includes the ability to evaluate the empirical evidence that supports an argument, rather than simply trusting authorities.
3. *Reconciling our values and consequences of our actions.* Environmentally literate citizens relate their actions and the policies that they support with their own environmental and moral values. This includes the ability to understand the likely environmental effects of actions, policies, and lifestyles, and to decide whether those effects are compatible with their values.

We hold that the ultimate test of our science curriculum will be the ability of our citizens to use their scientific knowledge for these purposes. Thus in this paper set we begin the process of assessing how students can use their knowledge in support of responsible citizenship.

Research Goals

The papers in this session focus on different aspects of environmental literacy: Chemical and physical change, carbon cycling, diversity and evolution by natural selection, and connecting human actions with environmental systems. 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. We argue that they can fit together as a coherent conceptual domain that all of our citizens need to understand. Furthermore, treating them as a coherent domain reflects current developments in the natural sciences and in our global environment.

Research Products

Working groups consisting of university-based researchers and K-12 teachers focused on each topic, reviewing relevant literature, developing assessments that revealed students' reasoning about the topic, and administering the assessments in the teachers' classrooms. The papers in this session present two products from the efforts of those working groups:

1 *Assessment tests* for K-12 students. These tests were designed to reveal how students are thinking about the topic. The teachers in the working group administered the pretests to their students in the fall. The results of the pretests were used to develop ideas about learning progressions and to develop improved tests that the teachers will use with their students after teaching the topic.
2 The results of these tests are presented as work toward *learning progressions* for each topic. Our goal is to describe a series of steps by which elementary, middle, and high school students can work toward environmental science literacy for high school graduates.

Learning Progressions as an Approach to Research Synthesis

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). They are crucially dependent on instructional practices if they are to occur.

Learning progressions are anchored on one end by what we know about the concepts and reasoning of students entering school. On the other end, learning progressions are anchored by societal expectations (values) about what we want middle school students to understand about science. Learning progressions propose the *intermediate* understandings between these anchor points that are reasonably coherent networks of ideas and practices and that contribute to building a more mature understanding.

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

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

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

In this session we both draw on and seek to expand current research on learning progressions, including work done by Smith, Wiser, Anderson, Krajcik, and Coppola (in press) on the development of children's understanding of matter and atomic molecular theory, and by

Catley, Lehrer, and Reiser (2005) on the development of understanding of evolution by natural selection.

Methods

In this session we present data from a study of students' understanding of issues connected with environmental literacy—the capacity to understand and participate in evidence-based discussions of the effects of human actions on environmental systems. Our data are based on pretests and posttests administered to elementary, middle, and high school students.

In this section we describe (a) data sources, and (b) data analysis methods.

Data Sources

The primary data source for these papers was pretests and posttests administered in K-12 classrooms. Initial drafts of the tests were based on reviews of existing research on that topic. For three of the topics a substantial research base existed, so we developed tests that combined items developed for previous research with new items focusing on application of key ideas in the topic to linked human and natural systems. For the fourth topic, connecting human actions with environmental systems, little previous research was available. In this case the test items were based on the experiences of members of the working group and our best guesses about questions that might produce interesting responses.

Each of the four topics was the focus of a Working Group coordinated by a university researcher (the first authors of the four papers), and teachers in urban, suburban, and/or rural Michigan schools. The composition of different working groups is described in the individual papers. Teachers participating in the working groups administered the tests to their students. The tests were revised based on the results of the initial tests. The summaries of papers below are based on the original drafts of the tests, but the papers presented at the conferences will also include data from the revised tests.

Data Analysis

The tests on the four topics each included a combination of multiple choice and open response items. Analyses were guided by Working Papers, written by the lead authors of the four papers, with rubrics for coding students' responses. Both the tests and the Working Papers are available on the project website. The rubrics were designed to highlight aspects of the students' responses relevant to the general theme of environmental literacy and the specific trends in the succession of students' reasoning described in the Overview of Results, below.

Reliability of the rubrics was assessed by having a second coder independently code a sample of the tests. When there were discrepancies, the rubrics were revised. For most of the tests, two or more rounds of revision were needed before satisfactory reliability was achieved. Additional revisions were based on discussions among the Working Group leaders, as we developed our ideas about connecting ideas and themes. Those connecting ideas are discussed in the Overview of Results, below, and in the descriptions of the individual papers.

Papers in the Set: Specific Findings

The four papers in this paper set all present data from studies of students' understanding and learning in elementary, middle, and high school. The results presented in each paper are briefly described below.

Paper 1: Understanding of matter transformations in physical and chemical changes

By In-Young Cho and Charles W. Anderson, Michigan State University

The focus of this study is how high school students can connect the idea of the conservation of mass in physical and chemical changes to the matter transformation processes in coupled human and natural environmental systems. Understanding environmental processes requires accounting for the flow of matter in and between systems and using appropriate model-based explanations to describe macroscopic processes in terms of atomic-molecular models. Connecting accounts of macroscopic matter transformations in and between systems to atomic-molecular explanations is fundamental to a scientific understanding of environmental systems. Most students were unable to do this consistently, especially for transformations between gases and solid or liquid materials.

The organizing criteria of the analysis of important key ideas from data were as follows which derived from environmental science literacy framework:

1. **Narrative reasoning to Model-based reasoning**: from students' accounts of separated events and entities in phenomena to the processes and scales in systems as a unit of analysis
2. **Tracing matter through the structure of systems**: from individual entity to connected mechanism in different levels of systems and progress of thinking from separated structure of systems to connected mechanism, tracing gases through systems
3. **Connecting accounts of molecular, cellular, organismal processes in environmental systems:** connecting different levels of understanding from microscopic to macroscopic accounts of processes in systems
4. **Quantitative reasoning with data and models:** connecting fundamental principles of conservation of mass and particulate properties of matter to accounts of processes and structure of the systems-significance of gases in applying fundamental principles

Data Sources and Analysis

We developed an assessment test called *Physical & Chemical Change*, 12 written questions administered in four 10th grade science classrooms. The data analysis was guided by *analytic induction* (Goets & LeCompte, 1981) which governs the overall process of extraction and construction of the core themes of the study and *phenomenological interpretation* method (Marton & Booth, 1997) in qualifying the content of the analysis. First, we developed rubrics for scoring students' responses for each questions in order to identify the relations of concepts about matter transformations. Each rubric highlighted students' responses in a hierarchical manner from model-based reasoning to narrative reasoning to unintelligible or no response. Rubrics were revised until reliability scored 100%. In the second stage of analysis, we interpreted concept relations and created phenomenographic categories. Finally, we were able to construct the core themes in students' conceptual relations encompassing the categories particularly important to understanding matter transformations in physical and chemical changes for environmental science literacy.

The paper presents results from all 12 questions. In this summary we focus on results from three questions:

1. Sublimating iodine: Students were asked to predict what would happen to the mass of a sealed tube when 1 gram of solid iodine sublimated within the tube and to explain their reasoning.
2. Burning wood: Students were asked to account for what happened to the mass of a piece of wood after it burned.
3. Weight loss: Students were asked to explain what happened to the mass of the fat of a person who lost weight.

Key findings

The patterns in students' responses and limits to their understanding involve four of big ideas in general theme of environmental science literacy framework:

1. Model-based reasoning. Students often explain properties of materials or changes in materials in ways that rely on narrative reasoning and fail to make appropriate use of atomic-molecular models or principles such as conservation of mass. Only 1.25% of students could preserve the specific gas products in combustion of wood question and 32.5% of students stated the law of conservation of mass only for the purpose of validating the term technically, not with supporting arguments based on atomic-molecular model-based reasoning. In sublimating iodine question, 52.5% of students considered gaseous iodine to weigh less than solid iodine. Students often did not attribute equivalent mass to invisible gases in both physical and chemical changes and very often even phase change itself was misunderstood as becoming mixture of solid and gas or mixed with air.

2. Tracing matter through systems. Regardless of the types of changes such as physical and chemical, when the view of change is dominated by apparent disappearance of some materials such as gas, students don't conserve the mass within and across the systems. Furthermore, the ideas about the physical properties of materials influence how students interpret changes in processes in systems. When they considered gas as weightless, they didn't conserve mass in changes involving gases regardless of the processes of changes, physical or chemical or the structure of the systems, open or closed, human engineering or natural. This led students to fail in applying fundamental principles to accounts of phenomena. In an open chemical change system of rusting iron question, almost half of the students (48.75%) disregarded the mass of reactant oxygen added from the air. Also, in the weight loss question, they have difficulties tracing gaseous products between person's body and its environment.

3. Connecting accounts of molecular, cellular, organismal, and environmental processes in systems. Students often have difficulty in connecting cellular or atomic-molecular level microscopic explanations to macroscopic mass transformations. They tend not to have correct criterion of distinction between physical and chemical changes in different scales of systems. Students generally had trouble identifying components of mixtures and elements in substances. In the weight loss question, even though 7.5% of students mentioned total mass is conserved, only 1.25% of students indicated gas product produced by fat metabolism in cellular respiration process and emitted to outside of human body. 35.5% of students stated fat mass is converted into energy and 26.25% of students wrote that the fat mass was simply gone.

4. Quantitative reasoning with data and models. Despite of several years of experience, students do not appreciate the quantitative aspect of chemical change, particularly when the change involves transformation of matter into or out of gases. Students still tend to hold physical or visible changes such as match turning into smaller pieces or getting shorter as the main cause of losing weight and denied chemical identity of gases. Interestingly enough, in match burning question, 35.5% of students mentioned the law of conservation of mass whereas in person losing weight question, only 7.5% of students did. Instead, they mentioned conversion to energy. Students' ideas of applying fundamental principles of processes differed by context.

In summary, about half of these high school students were able to correctly apply conservation of mass to a simple phase-change process (sublimation of iodine). For more complicated processes, such as a burning match or a person losing weight, virtually no students were able to provide explanations that correctly accounted for the mass of the reactants and products, though some students showed commitment to the principle of conservation of mass in the answers that they constructed. Their inability to account for mass was partly due to lack of knowledge of the particular systems (e.g., not knowing the chemical identities of reactants and products) and partly due to confusion about other fundamental principles (e.g., atomic-molecular reasoning, mass-energy conversions).

Paper 2: Developing a Carbon Cycle Learning Progression for K-12

By Lindsey Mohan, Ajay Sharma, In-Young Cho, Hui Jin, and Charles W. Anderson, Michigan State University

Among the many substances transformed in environmental systems, compounds of carbon are arguably the most important. Carbon compounds are both the primary substances of which organisms are composed and the primary carriers of chemical potential energy through environmental systems. The accumulation of carbon compounds in the atmosphere is the cause of global warming. This paper discusses students' conceptions of carbon pools, fluxes and cycles at different levels of ecological systems, and the coupling of natural and human energy systems. It proposes a research-based carbon cycle learning progression for students from elementary to secondary level. These results presented in this paper have important implications for understanding students' progress toward developing environmentally science literate practices.

The analysis of assessment data was organized around the following key ideas from the Environmental science literacy framework:

1. **Transition from informal (metaphorical) to model-based reasoning**: Moving from events in the world to processes in systems as a unit of analysis and moving from metaphorical to model-based reasoning.
2. **Understanding of the structure of systems:** Ability to explain and make connections at different levels of scale, especially microscopic and large scale. Ability to explain the transformation of matter from organic to inorganic forms.
3. **Understanding of processes within systems**: Awareness of and ability to trace matter and energy in processes. Ability to trace gases through processes such as photosynthesis, combustion, and cellular respiration.

4. **Using scientific reasoning for responsible citizenship**: Ability to use scientific knowledge and practices as resources for reasoning about environmental issues. The ability to understand order of magnitudes associated with environmental issues and explain the role of carbon compounds in complex environmental systems.

Data Sources and Analysis

The researchers developed three assessments, one for elementary, middle, and high school students. The items were multiple choice and open response format and focused on multiple aspects of the ecological carbon cycle, such as processes in plants and humans, decomposition, human-energy systems, physical and chemical changes, and carbon pools and fluxes. The results presented in the paper are based on a sample of 120 assessments, which included 40 from elementary classrooms, 40 from middle school classrooms, and 40 from high school classrooms. The assessment items were coded using rubrics developed to look for patterns in responses. In order to assess reliability of the rubrics, two researchers independently coded a sample of tests and met to discuss discrepancies that occurred. Initial reliability of the rubrics ranged from 65-100% agreement. When there were discrepancies, the rubrics were revised until both researchers agreed completely.

Key Findings

1. Transition from informal (metaphorical) to model-based reasoning: We found that students at each grade level tend to explain their ideas in terms of events or metaphors rather than processes, for example explaining decomposition of fish in terms of what happens to the fish and that fish are a 'source of protein,' rather than explaining the process of decomposition or tracing matter through this process. Middle school students are more likely to construct food chains when asked to make connections between living things compared to elementary students. High school students use metaphors to explain their ideas about global warming, such as "the ozone layer is like sunblock for humans and when it breaks apart we get more sun and heat". The data from our assessments indicate that very few students explain their ideas in terms of processes in systems, but rather rely heavily on the narratives they construct and visible aspects of systems.

2. Understanding of the structure of systems: We analyzed data from items that required students to reason about systems at different levels of scale and make connection between living and non-living systems. We found that elementary students rarely mention microscopic substances or organisms and primarily respond with macroscopic, visible explanations. Middle and high school students are more likely to mention microscopic levels of systems, such as photosynthesis, cellular respiration, and decomposition, but their understanding of the substances and organisms involved in theses processes is limited. High school students also struggled with connecting microscopic processes (i.e., photosynthesis) to human actions that have influenced large-scale phenomena (i.e., global warming). Middle and high school students tend to focus on a single level of scale, such as microscopic or macroscopic, when developing explanations. Elementary, middle and high school students also have difficulty tracing matter from organic to inorganic forms, although high school students are more likely to mention that microbes are involved in this process.

3. Understanding of processes within systems: We analyzed data from items that required students to trace matter and energy in processes. We found that elementary students are unable to trace matter, particularly gases, in processes and rarely mention energy in their explanations. Middle and high school students are more likely to conserve matter during processes, such as attempting to conserve the mass of fat during weight loss. Middle and high school students also show an awareness of the role of gases in photosynthesis, but less likely to understand the role of the same gases during cellular respiration. They are also more likely to mention energy during chemical processes, for example with 40-50% of middle and high school students explaining weight loss using their ideas about energy.

4. Using scientific reasoning for responsible citizenship*:* The assessment data indicates that students have some experiences with environmental issues, particularly middle and high school students showing more awareness of these issues compared to elementary students. We asked the students to respond to several items about preservation of forests and global warming, in which they would need to apply fundamental principles of science (e.g., the role of gases in plants, conserving matter) in order to reason about the question being asked. We found four interesting trends: 1) unidirectional connection between humans and natural systems, where humans rely on things provided by natural systems, such as oxygen from plants, 2) limited understanding of the substances involved in environmental issues, such as confusing CFCs as causing global warming or confusing carbon dioxide with causing ozone depletion, 3) generalizations of good and bad, such as generalizing pollution as 'bad' but not understanding what the pollution is, and generalizing plants as 'good' because they provide humans with oxygen, and 4) reliance on media and personal experiences to explain their understanding of global issues. We also found that high school students tend to place responsibility for global issues on a distant source, although some students did connect environmental problems to our actions, such as driving cars and relying on oil.

Paper 3: Diversity and Evolution in Environmental Systems

By Chris Wilson, John Lockhart and Charles W. Anderson, Michigan State University

In the past year there has been resurgence in interest in the teaching of evolution by natural selection, driven largely by reaction to the gains made by the Intelligent Design community. What these products of this interest usually fail to address is why it is desirable or important for school leavers to have an understanding of evolution, beyond meeting national or science standards or a cursory reference to Dobzhansky's oft-quoted assertion that "nothing in biology makes sense, except in the light of evolution." Further, other than efforts to align evolutionary theory with Nature of Science content, little research addresses the types of reasoning that are required to understand natural selection, or how that reasoning develops longitudinally through the K-12 curriculum. We propose that understanding the processes of evolution and the connected changes in diversity that occur in natural systems, is fundamental to environmental literacy, and is a critical component in environmentally responsible citizenship. Developing an understanding of the steps by which elementary, middle and high school students learn this content is essential in producing school-leavers who are able to apply their understanding of diversity and evolution to deciding on policies and personal actions that are consistent with their environmental values.

Diversity occurs at many levels in natural systems, from genetic diversity in populations, through diversity of species in communities, to diversity of habitats and ecosystems. Diversity at any level is not a constant, but rather it changes through a number of different processes. For example, genetic diversity in populations is increased by sexual reproduction and mutation, and is decreased by selection. Changes in the diversity in systems at different levels have direct effects on diversity in systems at other levels (e.g. habitat fragmentation can lead to smaller population sizes and reduced genetic diversity). Humans are increasingly altering the structure of natural populations, and are consequently having dramatic impacts on diversity at all levels, be that through altering the rate of births and deaths in populations; by removing selection pressures by introducing invasive species; or by altering ecosystems through agricultural or urban development. Since evolutionary theory is not merely science that can describe what has happened in the past, but also science that is predictive of what will happen in the future, it empowers us with a crucial understanding of the consequences of human alterations to natural systems.

One of the frameworks consistent throughout the work of the Environmental Literacy Research Group is the concept of applying fundamental principles to coupled human and natural systems. We perceive the fundamental principles in understanding evolution and diversity as follows:

1. Structure of systems. Natural systems can be perceived as a set of nested boxes, with alleles and genes at one extreme, and global systems at the other. In-between lie organisms, populations, species, communities and ecosystems – some of these systems being familiar to students, some of them being largely invisible. The first step in a learning progression towards understanding how diversity functions in natural systems is a disconnected awareness and understanding of these systems.

2. Processes that Connect Systems. The systems mentioned above are connected by a number of natural processes, and making the connections between these systems is the next step in developing a conceptual understanding of the role of diversity in natural systems. For example, students should be able to describe the connections between genotype and phenotype, and the connections between traits / adaptations and environmental pressures. We see this stage as being distinct from the next in that in this stage students describe the connections that are present in systems at a single instant, whereas in the next they move to understanding these connections as dynamic processes that result in change in systems over time.

3. Change over Time. The processes that connect the systems described above result in change in the diversity in systems over time. Reasoning about how change occurs in these systems requires students to be aware of and apply a number of scientific rules, and to model the mechanisms governing the connections. For example, the process of natural selection is governed by the rules that individuals in a population are not identical; survival is not random (certain traits provide an advantage); and that populations change over time as the frequency of advantageous alleles / traits increases. When reasoning about processes involving natural selection, students need to select and apply the rules that are appropriate to the particular system.

Data Sources

Tests were developed that included items that were aligned with each of the fundamental principles described above, and were administered in the fall of 2006 to classes of elementary, middle and high school students. The teachers participating in the working group administered the tests to their students, who were from suburban and rural Michigan schools. The items were a primarily open ended / short answer, but some items were multiple-choice, followed by an opportunity for students to explain why they chose their answer. The results presented in this paper are based on a sample of 90 students, which included 30 from two different elementary classrooms, 30 from a single middle school classroom, and 30 from two different high school classrooms. The assessment items were coded using rubrics developed to look for patterns in responses. To assess reliability of the rubrics, two researchers independently coded a sample of tests and met to discuss discrepancies that occurred. Rubrics were refined based on this discussion.

Key Findings

1. Structure of Systems. We analyzed the data from 2 items concerning the structure of natural systems, one requiring students to diagram their conceptions of the diversity of life, and the other concerning students' awareness of diversity within individual populations. In the former, all students' diagrams contained various types of animals (consumers), whereas only around 50% of middle and high school students' diagrams included plants (producers). This figure was 90% for the elementary school students – it is unclear why the elementary school students (from two different schools) included plants in their diagrams so much more frequently than the middle and high school students. Importantly, decomposers were very rarely mentioned by students at any level. In the item on diversity within populations, we saw that awareness of diversity increased progressively from elementary to high school, but genetic variation as the origin of that diversity was rarely mentioned. Instead of making that connection, students used rules with little scientific basis, such as *"It is a proven fact that no two organisms look exactly alike and act the same."*

2. Processes that Connect Systems. To examine students understanding of the connections between levels of systems, the test included items about why strawberries do not all look identical, and how students connected the adaptations of a porcupine fish to environmental pressures. In the first of these items, students saw the phenotypic variation in strawberries as being entirely the result of environmental variation and not genetic variation (or a combination of the two), and so were failing to make a significant connection between systems. In the porcupine fish item, students were relatively successful at identifying characteristics of the fish that were adaptations to its environment, as well as connecting those adaptations to specific environmental pressures.

3. Change over Time. Two items dealing with change in diversity in systems over time were included on the test, one asking students to explain how modern day cheetahs that can run at 60mph evolved from ancestors that could run only at 20mph, and one asking students to predict if a diverse or homogenous population of elephants would be more likely to survive a severe drought. In the cheetah item, few middle school students saw a need for a mechanism for *how* change occurred, and instead described *why* they adapted. High school students saw a greater need to describe a mechanism, but those that did mostly described Lamarckian or teleological mechanisms, rather than constructing their responses around a scientific model. Similarly, in the elephants item students rarely constructed their responses around the scientific model, and instead thought in non-scientific ways that made sense to them. Interestingly, these often included anthropomorphic explanations involving elephants sharing water or other human society-influenced accounts.

Implications for Developing a Learning Progression

The results from our tests highlight two of the other common themes across the work of the Environmental Literacy Research Group, these being the transition from stories about events to model-based accounts of processes in systems; and increasing awareness of "invisible" parts of systems. As they got older, students consistently saw a greater need to describe mechanisms for changes over time (moving from a *"why"*, to a *"how"*), but were unable to use scientific models in developing those explanations. This need for model-based reasoning is a critical step in developing environmental science literacy. Students also need to move from focusing their thinking around highly visible parts of systems such as individual organisms, to a more conceptual view of the natural world that includes the connected, but more "invisible" parts of systems such as populations and communities. The challenges of model-based reasoning and making the invisible visible came together in the Cheetah item, where when older students began reasoning to discover the mechanism by which the evolutionary change had occurred, part of the model (genetic variation in populations) was invisible to them. The inevitable conclusion to reasoning with this incomplete model is to reach the same conclusion as Lamarck, and conclude that evolution is a goal oriented process.

Paper 4: Connecting Personal Actions to Environmental Systems

By Blakely K. Tsurusaki and Charles W. Anderson, Michigan State University

This strand focuses on a particular class of human actions: Our actions as consumers of essential goods and services, including food, clothing, shelter, air, water, and transportation. Goods and services in each of these categories pass through a number of environmental systems on their way to us (the supply chain) and go through additional systems after we are done with them (waste disposal). The human systems that supply all of our essential goods and services - food, clothing, shelter, water, transportation - begin and end in the earth's natural systems. The goal of this strand is to find out more about student understanding of the connection between human engineered systems and natural systems. This is essential in order to help them develop model-based reasoning about supply and waste disposal chains, which requires that students be able to trace matter and energy through these chains and make connections between them. Through understanding supply and waste disposal chains, students can begin to examine human ecological footprints, how they can have a greater or lesser impact on the environment based on decisions that they make with regards to supply and waste disposal chains, and realize that individual and societal decisions make a difference.

Data Sources

Pretest Questions. Because little previous research is available regarding students' knowledge of how human actions are connected to environmental systems, the test items were based on the experiences of members of the working group and our best guesses about questions that might produce interesting responses. We developed opened-ended questions, with some questions given in the form of tables, asking students to trace the supply chain of products as far as they could back towards the product's origins, or the waste disposal chain forward as far as they could for waste that they throw away. For the purposes of this paper, one supply chain question and one waste disposal chain question were analyzed: 1) Where did the hamburgers come from? and 2) How would you get rid of a paper cup and what might happen to it? In addition, we asked students if there could be any connection between hamburger and a corn field and between a tree and a paper cup and to provide a rationale for their response. Another question asked students to list the resources that are used when handwashing and using a dishwasher to wash dishes, and the impact that using these various resources have on the environment. This question indirectly asked students to trace the supply chains or waste disposal chains of various resources used when washing dishes. The final question analyzed consisted of three parts. First, students were asked if they have ever heard of global warming or global climate change, then they were asked if they knew what causes global warming, and finally, they were asked what could help reduce global warming. The purpose of this question was to discover how aware students are of a major environmental issue and what they know about it.

Participants. Three high school teachers, one sixth grade middle school teacher and one fourth grade elementary school teacher, all teaching in rural areas, administered the assessment. Data from 44 high school students, 26 middle school students, and 34 elementary school students were analyzed.

Key Findings

- **Actors and location/places.** Students generally depicted supply and waste disposal chains in terms of actors and location/places. The number of steps (actors and places) mentioned in supply and waste disposal chains is significantly associated to school level (elementary, middle, and high). Elementary school students mentioned the fewest steps and high school students mentioned the most steps when tracing supply and waste disposal chains.
- **Tracing matter and energy.** Students mentioned matter more often than they mentioned energy. When students did mention energy, it was high school students, as opposed to elementary school students. Students of all ages failed to recognize the role of energy consumption in supply chains and waste disposal chains. For example, only 6.8% of the high school students (and none of the elementary or middle school students) mentioned energy to heat the hot water as an environmental impact of handwashing dishes.
- **Processes/Transformation of matter and energy.** In general, more high school students mentioned some type of *transformation of matter*. In the paper cup recycling waste disposal chain, more high school students than middle or elementary school students mentioned some process that the paper cup undergoes in order to be recycled and made into a new product. When explaining the possible connection between hamburger meat and a corn field, a small percentage of high school and middle school students mentioned that cows eat corn in order to grow, while no elementary school students gave this reason. Elementary students who saw a connection explained that cows and corn exist on the same farm; they did not mention that cows may eat corn. In their rationales for the connection between a tree and a paper cup, only high school students mentioned some process that the tree had to go through in order for paper to be made.
- **Connections between human and natural systems.** In part because they were describing sequences of locations and events rather than transformations in matter and energy, students were generally vague about how human supply chains and waste disposal chains were connected with natural environmental systems.
- **Infrastructure and by-products.** Systems and processes require infrastructure that connects various steps or stages of the systems and processes. While more middle school than elementary or high school students mentioned transportation, a form of infrastructure that connects steps, in the hamburger supply chain, more high school than elementary or middle school students mentioned transportation in the paper cup waste disposal chain. Therefore, it is difficult to determine if high school students recognize infrastructure more often than elementary or middle school students from this data. In the dish washing question, more high

school students mentioned an impact that using resources has on the environment. One way to view impact on environment is in terms of the by-products that the dish washing process creates. Elementary school students most often mentioned that using resources had no impact on the environment. (Elementary students may have had trouble understanding the question due to the difficulty of its wording. They may not have known what *resources* and *impact* meant.)

Supply and waste disposal chains are a means of examining the connection between human engineered systems and natural systems. It is essential that students understand the actors and places involved in these systems and processes, be able to trace matter and energy and recognize the transformations that they undergo as they travel through them, and know the infrastructure that connects various steps and stages and the by-products created. If students have scientific understanding of these processes and recognize how human engineered and natural systems are connected, then they can understand the role that humans play in environmental issues such as global warming. They can think about how various decisions that humans make have different degrees of positive or negative impact on the environment and think about the efficiency of human actions and systems. It is crucial that students understand how human engineered and natural systems are connected in order to make responsible decisions as citizens and stewards of our environment.

Discussion: Common Themes

As we look across the papers in this set, we see a number of themes or common trends that emerge across papers. We organize our discussion of those themes around the practices of environmental science literacy as discussed in the theoretical framework and in the individual papers. Since our assessments did not address scientific inquiry (Practice 1), we focus the discussion in this section on the remaining practices: Understanding and applying scientific accounts (Practices 2 and 3) and using scientific accounts for responsible citizenship (Practice 4).

Practices 2 and 3: Understanding and Using Scientific Accounts

We have defined scientific literacy as the ability to *apply fundamental principles to processes in coupled human and natural systems.* The results of the research indicate trends from elementary through high school that show increasing understanding of both fundamental principles and processes in environmental systems. In general, though even high school students fall short of full environmental science literacy. We discuss four of these trends below.

1. From stories about events to model-based accounts of processes in systems. We see that as they grow older, students pay increasing attention to mechanisms and constraints in their accounts of systems and how they work. For example, elementary and middle school students did not go beyond invoking the need of cheetahs to run fast as an explanation of how their speed evolved, while some high school students saw the need to explain how changes in one generation of cheetahs could be passed on to the next. **However,** we also saw evidence that students often lacked critical knowledge that they needed to produce appropriate model-based accounts. For example, the students who attempted to suggest a mechanism for evolution used Lamarckian misconceptions rather than population change by natural selection and reproduction. Thus we can see how Lamarckianism represents a substantial intellectual achievement that is accomplished by only a minority of high school students while being disturbed about their failure to understand evolution by natural selection.

2. From focus on macroscopic systems to awareness of a hierarchy of systems. Students at the elementary school level focused on macroscopic systems (e.g., plants, animals, people, automobiles) in their accounts they very rarely invoked cellular or molecular processes; similarly, they very rarely described macroscopic systems as parts of larger natural or engineered systems. High school students generally showed that they were aware that macroscopic systems were composed of smaller cellular and atomic-molecular systems, and that macroscopic systems were parts of larger systems. **However,** very few students were successful in connecting atomic-molecular, macroscopic, and large-scale processes. Thus students were rarely successful, for example, in explaining chemical or biological processes by invoking atomic-molecular models.

3. Increasing awareness of constraints on processes. Older students were much more likely to recognize that processes were constrained, especially by conservation of matter. For example, many elementary students made no attempt to explain where the matter in a growing tree came from; the tree "just grows." In contrast most high school students recognized that the matter must have come from somewhere, recognizing conservation of matter as an important constraint. **However,** their attempts to reason in ways that recognized constraints were often frustrated by their incomplete knowledge of the systems that they were reasoning about. Although many high school students invoked energy in their explanations, conservation of energy seems almost completely useless as an accounting tool for these students. Thus students often invoked energy as a reactant or product in chemical or biological processes when they should have invoked gases such as carbon dioxide.

4. Increasing awareness of "invisible" parts of systems. Older students described systems and processes with increasing detail and connectedness, showing their awareness of processes and parts of systems that were "invisible" to younger students. **However,** important aspects of environmental systems, including gases, decomposers, and connections between human and natural systems, remained "invisible" to most students (and thus were unaccounted for in their explanations of processes in systems).

Thus we see evidence of learning from elementary through high school, as students accounts became increasingly detailed and sophisticated. Even at the high school level, though, most students' understanding of coupled human and natural systems is disturbingly incomplete.

Practice 4: Using Scientific Accounts for Responsible Citizenship

We conclude with a discussion of the implications of these results for the preparation of students as environmentally responsible citizens. We organize this discussion around their preparation for three practices that we associate with environmentally responsible citizenship:

1. Democratic participation and agency. Although our data are limited on this issue, we have a sense that most students have a very limited sense of the relationship between their personal actions and large-scale economic and environmental issues. They have little sense of how their actions or their lifestyles affect the environment, or of which aspects of economies have the greatest environmental impact. Thus their abilities to connect their actions with environmental impacts is limited.

2. Understanding and evaluating scientific evidence and arguments. We see a number of respects in which students' abilities to understand scientific evidence and arguments about environmental issues were limited:

a. Generalized good and bad. Students rely on informal or metaphorical reasoning that sees things as generally good or bad (e.g., trees are good; pollution is bad). This makes it hard to connect specific actions or policies with specific problems (e.g., what specific changes would significantly reduce global warming or declining fish populations in lakes).

b. Reliance on media and personal experience. Student responses and patterns of awareness seem to be based more on personal experience and media than on formal science education.

c. Unidirectional connections between human and natural systems. When students were aware of connections between human and natural systems, it was often in ways that imply unidirectional good or bad connections (e.g., good: we get food, water, energy from the environment; bad: we cause pollution, cut down forests, pollute water). Students generally don't see the bad connections as effects or consequences of the good connections.

d. Limited awareness of comparative scale of processes. Students had little sense of which processes made major contributions to environmental problems and which made minor contributions. Similarly, they had difficulty judging the scale of ameliorative actions necessary to be effective.

3. Reconciling our values and consequences of our actions. Students with limited scientific understandings will also be limited in their abilities to reconcile their values with their actions. They have a general sense of which actions are good and bad for the environment, but little ability to attach actions to specific consequences or to judge the scale and importance of the effects of different policies or actions.

Next Steps

The work report in this session comes from early in a long-term process of research and development leading toward a more complete learning progression for environmental literacy. Some key elements of our planned future work are outlined below.

Filling in the Gaps

Our framework contains many elements that are not addressed by the data reported in this session. Most prominently, inquiry (Practice 1) is not addressed, and applications to citizenship (Practice 4) is addressed only in a preliminary manner. These practices are clearly essential for environmental science literacy. As discussed below, inquiry encompasses people's modes of engagement with the material world and ways of reconciling personal experience with scientific evidence and theories. Our rationale for environmental science literacy as a curricular focus depends on students' abilities to use what they learn in their roles as citizens. Thus we must find better ways to assess these practices and incorporate them into our developing learning progression.

Similarly, there are important gaps in our investigations of students' accounts of processes in coupled human and natural systems (Practices 2 and 3). These gaps are evident as the "black cells" in Table 1. We note several gaps as particularly important:

- We have investigated change over time primarily in the context of evolution by natural selection. We need to understand much better how students think about change over time in other systems, including climate change, human engineered systems, and responses of ecosystems to anthropogenic and other disturbances.

- Engineered human systems have not played a major role in the current standards-based reform movement. (The chapter in *Benchmarks* on The Designed World has received less attention than other science content chapters.) Thus we need both to decide what the curriculum should be and investigate students' understanding of engineered systems.
- Our current assessments mostly document what students do not understand about energy. We need to develop a better set of ideas about how students can make the transition from metaphorical to analytical uses of energy and do develop assessments that document that transition.

Understanding Elementary School Children

This paper set mostly documents ways that elementary school children do not reason scientifically. While this is useful information, we aspire to a learning progression that does a better job of describing the key elements of children's reasoning on their own terms. This is especially important since some important elements of children's reasoning remain prominent in the reasoning of older students and adults.

Here are some sketchy ideas that we think are worth investigating. Sharma and Anderson (2003) wrote about scientific understanding as built around two ongoing dialogues: a dialogue with nature and a dialogue with other scientists. Developmental research suggests that these dialogues have their roots in early childhood, and that those practices of early childhood are the foundations for the practices of scientific inquiry and scientific accounts—Practices 1 and 2 in our framework. We suggest lines of inquiry for each below.

Children's inquiry: Embodied reasoning as a foundation for scientific arguments from evidence. Rath and Brown (1996) suggest that children exhibit a number of different "modes of engagement" with the material world; scientific inquiry is a refined version of one of those modes. We need to investigate the modes of engagement of children and adults, particularly "engineering modes" in which the goal is to make something happen. Our personal and collective dialogues with nature arise in part when nature "pushes back"—does not allow us to do things that we would like (e.g., Enfield, 2004; Schauble, Klopfer, & Raghavan, 1991; Bazerman, 1988; Pickering, 1993). These modes of engagement lead to "embodied reasoning"—expectations about how the world will act that are deeply grounded in personal experience and form the basis for our scientific intuitions (e.g., Warren, et al., 2001; Pozo & Gomez Crespo, 2005; Inagaki and Hatano, 2002).

We need to understand both the nature of children's embodied and practical reasoning about the material world and how embodied reasoning can develop into more sophisticated forms of inquiry and argument. One part of this process involves a transition from personal impressions to measured data as a reliable foundation for our understanding of the world. (See, for example, the discussion of the transition from felt weight and perceived amount to measured mass, volume, and density in Smith, et al., in press.) Children also develop more refined forms of argument based on scientific evidence. We hope to study how these transitions occur—and the roles that embodied reasoning based on personal experience continue to play in older students and adults—in the context of reasoning about processes in coupled human and natural systems.

Children's accounts: Stories connected by metaphors as a foundation for scientific models. Kieran Egan (1983, 1985, 1987, 1995), argues for a form of Vygotskian recapitulationism, in which we can understand the development of children's reasoning in part by investigating kinds of reasoning that are supported by differing arrays of intellectual tools, in children and adults. Egan argues that children's (and adults) stories play an essential role in making sense of the ongoing flow of experience, and that the nature of those stories changes as children acquire more sophisticated intellectual tools. Scientific accounts are grounded in children's narratives, but take on a different character, focusing on the application of general models rather than the actions of characters (see Bruner, 1985; Olson, 2005; Bazerman, 1988).

Anderson, Mohan, and Sharma (2005) use the example of a food chain to illustrate the contrast: Grass grows in the sunlight, a rabbit eats the grass, a wolf eats the rabbit. From a narrative perspective, these are facts to be put in the proper order and labeled appropriately: producer, first-order consumer, second-order consumer. From a narrative perspective, becoming more knowledgeable about science involves adding details to the story: how the grass uses sunlight to grow, how the wolf stalks the rabbit, how the wolf digests the rabbit, etc. In contrast, from a model-based perspective the little sequence of events involving the grass, rabbit, and wolf becomes data that can be explained or interpreted using a variety of different models—about matter cycling and energy flow in ecosystems, evolution by natural selection, etc. Thus the protagonists in the story—the rabbit and the wolf—become subsystems in a hierarchy of systems and the dramatic events—the wolf stalking and eating the rabbit—become processes that are constrained by fundamental principles. As with narrative reasoning, many levels of detail are possible in model-based reasoning, but the expectations are always the same: Model-based reasoning requires explicit connections between features of the model and specific observations in the data.

The papers in this set document some aspects of this transition, but we do not understand well the kinds of problems and intellectual tools that make the transition possible. We hypothesize, for example, that children's interest in mechanisms—why and how things happen—and in conditions for processes or needs of organisms can help them move toward more sophisticated kinds of reasoning. We still have a lot of work to do, though, to understand children's stories on their own terms and to understand how children can move toward model-based accounts.

Improving Assessments

We will be developing our current tests into validated assessments that measure student understanding of matter and energy transformations in biogeochemical systems at the upper elementary, middle school, and high school levels. These assessments will include item pools that are coordinated with the learning progression and can be used for classroom or large-scale assessment. The assessments will be made available to large-scale assessment developers and classroom teachers through the BEAR Assessment System (Wilson, 2005; Wilson & Sloane, 2000). The assessment system is based on progress variables defined by the core learning goals identified in the longitudinal description of children's learning, and will include embedded assessments for use in classrooms as well as "link tests" that are designed to form the basis of a systematically designed large-scale assessment program. These assessments will be used for a survey of student learning in a sample of rural, urban, and suburban classrooms.

Teaching Experiments

We are also planning to enrich and validate the developing learning progression through teaching experiments that will provide rich and challenging environments for studying student reasoning and learning. Our focus in the teaching experiments will be on students and their reasoning, not on developing models for successful curriculum. We need to observe and interview students who are engaging the key questions and have access to the key conceptual tools that we have identified. Even for students who are not successful in achieving all our goals, the teaching experiments will create environments that stress the connections among domains that are initially disconnected for most students, thus allowing us to sample richer examples of student reasoning.

Conclusion

There is currently a widespread consensus among science educators that the science curriculum—even the reduced curriculum defined by Benchmarks for Science Literacy or the National Science Education Standards—is too large and too diffuse for students to learn with understanding (e.g., Valverde and Schmidt, 2003). One way to move toward a more focused curriculum is to emphasize the conceptual tools and practices that our students will need to be effective and responsible citizens and consumers.

We argue that such a curriculum would include a focus on environmental literacy—the capacity to understand and participate in evidence-based discussions of the effects of human actions on environmental systems. In this paper set we begin the process of exploring what such a curriculum would entail.

The products of the research will include conference papers like those in this paper set, assessment tools, and published reports. We hope that those products will influence policy by giving policymakers well-crafted recommendations for contents of standards documents and other policies. We also hope that the assessments will influence classroom and large-scale assessments, and that the reports (including future reports of teaching experiments) will influence curriculum development and, ultimately, the common practices of classroom teachers.

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