The Development of an Environmental Literacy Learning Progression: Biological Diversity and Change over Time in Environmental Systems

Christopher D. Wilson[1], Blakely Tsurusaki[1], Brook Wilke[2], Josie Zesaguli[1], and Charles (Andy) W. Anderson[1]

[1]Center for Curriculum Materials in Science, College of Education, Michigan State University,
[2]Department of Crop and Soil Sciences, Michigan State University

INTRODUCTION

Biological diversity must be treated more seriously as a global resource,
to be indexed, used, and above all, preserved.

E.O. Wilson, *Biodiveristy*, 1988, p3.

This paper forms part of a set of papers presented at the 2007 Center for Curriculum Materials in Science *Knowledge Sharing Institute*, hosted by AAAS Project 2061. The paper set describes a number of aspects of our research team's work on developing learning progressions towards environmental science literacy – a construct that we believe to be an increasingly critical aspect of science literacy, and therefore one that should be a goal of the required K-12 curriculum.

We define environmental science literacy as the capacity to understand and participate in evidence-based discussions of the effects of human actions on environmental systems, and the feedback from those systems on human societies. Our education system is founded on the principal that all citizens must be prepared to participate in a democratic society. Such participation requires that all citizens have the knowledge and skills necessary to make responsible decisions that are in line with their values. Now, more than ever, it is incumbent upon our education system to provide citizens with the knowledge and practices that will enable them to be environmentally responsible citizens. While the addition of some content to the traditional K-12 curriculum may be necessary to achieve this goal, much of the science content required for environmental literacy is already present in the various national and state standards documents (e.g., AAAS, 1993; NRC; 1996; NAEP Framework, 2006; Michigan Department of Education, 2006), as well as in many school curricula. However, we argue that this content is not currently organized or presented in such a way as to allow students to make the connections between concepts necessary to reason about processes across a hierarchy of systems, or to make connections between these concepts and the role of human societies as beneficiaries and modifiers of natural systems. That is, the current science curriculum fails to prepare students to proficiently integrate science into citizenry in a manner that empowers them to participate in evidence-based discussion of the growing, and increasingly critical number of environmental issues that human societies face. Similarly, the research and products from the environmental education community, while often addressing decision-making with respect to environmental socio-scientific issues, largely fail to address the ways in which students learn, understand and apply appropriate scientific concepts.

Another way to frame the problem is with respect the “Loop Diagram”, shown in Figure 1. This diagram has been developed and used by the researchers in the Long Term Ecological Research (LTER) Network as a framework to guide research on socio-ecological systems. We believe that the diagram is as applicable to K-12 education as it is to ecological research. The loop diagram illustrates the connections between human systems and environmental systems as 1) human actions that have environmental impact, and 2) human societies’ utilization of ecosystem services.

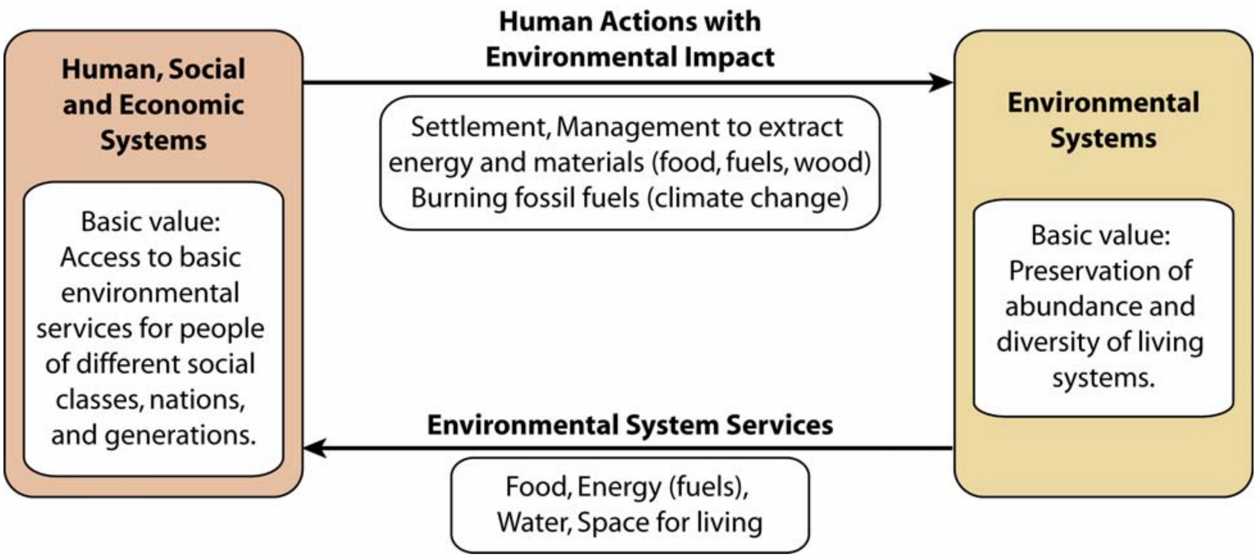

Figure 1. Generalized “Loop Diagram”, illustrating the connections between human and environmental systems as 1) human actions that have environmental impact, and 2) human societies’ utilization of ecosystem services. Modified from LTER Network report “Integrative Science for Society and Environment: A Strategic Research Plan”, 2007.

Since our goal is for students to understand the structure and function of natural systems; how human actions alter natural systems; and how our societies benefit from those systems, we aim for students to understand that the loop is dynamic, and, given information about any single part of the loop, to be able to connect and reason about the other three parts. For example, we currently face decisions regarding expanding the use of land to grow biofuels; an issue that impacts all three of our content strands – carbon, water and biodiversity. An environmentally literate citizen would be able to consider how such expansion would change current land uses, what the impacts of these changes might be on natural systems, and how those changes would affect human societies, both positively and negatively.

While our current research (and the current science curriculum) is situated largely in the ‘environmental systems’ portion of the loop, we are attempting to organize this content in such a way so as to enable students to ‘connect the arrows’, that is, apply their understanding of natural systems to reason about linkages and feedback between the biological and social domains. Our driving question is therefore:

What scientific knowledge and practices should all students learn that will give them the capacity to be environmentally responsible citizens?

The Learning Progressions Approach

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. They are in part a response to the problem defined in the recent NAS report "Taking Science to School: Learning and Teaching Science in Grades K-8":

Many standards and curricula contain too many disconnected topics that are given equal priority. Too little attention is given to how students' understanding of a topic can be supported and enhanced from grade to grade. As a result, topics receive repeated, shallow coverage with little consistency, which provides fragile foundation for further knowledge or growth.

Taking Science to School (National Academy of Sciences, 2007)

We can describe a learning progression as being anchored at one end by what we know about the concepts and reasoning of students entering school. On the other end, learning progressions are anchored by what we want high school students to understand about science when they graduate. In between these anchors, learning progressions propose the intermediate understandings as networks of ideas and practices that contribute to building a more mature understanding.

With respect to this work, one can think of learning progressions at a number of different grain sizes – which break down from learning progressions, to progress variables, to levels within those progress variables, as shown in Figure 2.

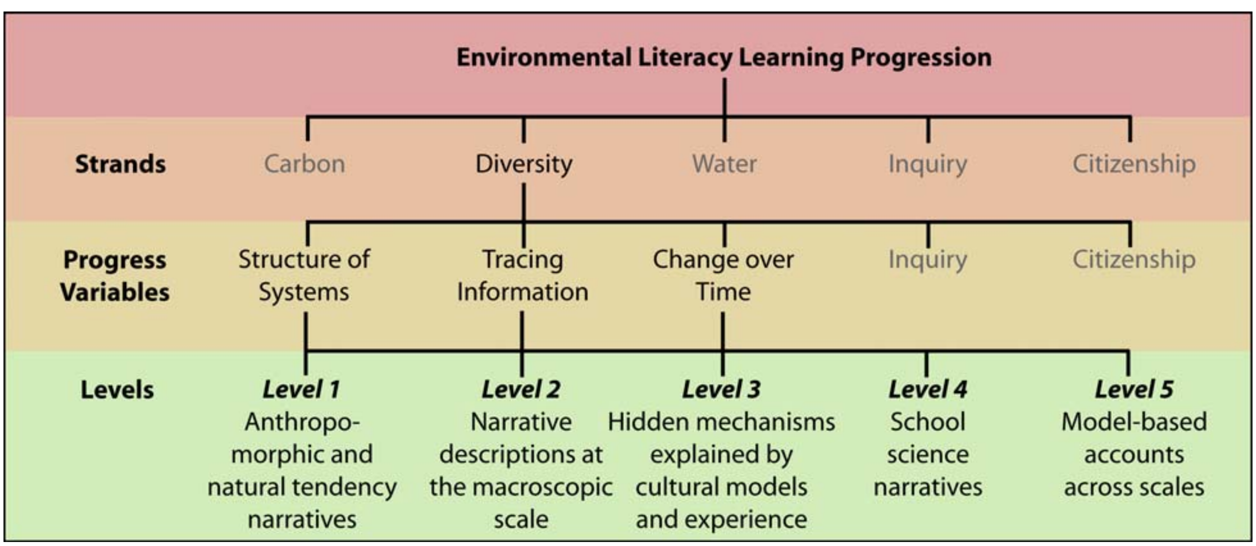

Figure 2. Breakdown of the Environmental Science Literacy learning progressions.

Literature Review and Theoretical Framework – Biological Diversity and Society

> *"By changing global climate, expanding and intensifying land uses, polluting, introducing exotic species, and overharvesting biological resources, human activities have accelerated extinction rates massively. The biotic consequences of these factors . . . are apparent in progressive degradation of ecosystem services upon which humans rely."*

Kerr et al., Science, vol 316., 2007, p1581.

The above quote from a recent research paper in Science magazine embodies the problem that motivates this strand of the Environmental Literacy Project. The strand is focused on diversity at two different levels in a hierarchy of environmental systems:

1. Genetic diversity of individuals in populations
2. Diversity of species in ecosystems

In this paper we refer to both levels of variation as *biodiversity*.

Biodiversity has gradually built up in the earth's ecosystems through evolutionary time. More diverse systems are more likely to contain individuals, populations, or species that are capable of surviving when their environment changes. Consequently, biodiversity helps environmental systems to survive catastrophic changes, though particular populations or species may be decimated by the catastrophe. Human actions greatly affect the size and diversity of natural systems, either directly through the use of technologies to create production systems like farms; or indirectly through pollution, introduction of invasive species, habitat fragmentation, and climate change. Biodiversity is a resource that, once destroyed, cannot be fully restored; and so reductions in biodiversity significantly reduce our capacity to respond to future environmental changes.

For many years, ecologists have recognized the importance of biodiversity across scales, and are increasingly moving their attention to connections between that biodiversity and the human societies that modify and benefit from it. Recent prominent and well-cited studies include findings such as:

- Humans have substantially altered 1/3 to 1/2 of all land surface on the earth, altered the atmosphere and water resources, and have caused the loss of 1/4 of all bird species to extinction (Vitousek et al. 1997).
- Biodiversity increases the stability of plant production in grasslands (Tilman and Downing 1994).
- The decline in honeybee populations may adversely affect the conservation of biodiversity and the stability of food crop yields (Allen-Wardell et al. 1998).
- 92% of Iowa's cultivated land is planted to two crops – corn and soybeans. Agriculture is dependent upon internal and external biodiversity. Designing farming systems that are resilient, productive and include a diversity of plants and animals is necessary for a sustainable future (Kirschenmann 2007).

- Climate change is likely to occur faster than plants and animals can move, thus causing them to decline in numbers, perhaps to extinction (Flannery 2005).
- Agriculture is a major contributor of non-point source nitrogen and phosphorus pollution to aquatic ecosystems. This excess of nutrients causes a decline in aquatic biodiversity (Carpenter et al. 1998).

Traditionally, decisions relating to these issues have the domain of experts, developers and politicians, but as these problems continue to have increasingly greater effects on the lives and wellbeing of the general public, it is regular citizens who are becoming empowered and responsible as decision-makers; decision-makers who have need of an understanding of the fundamental scientific principles underlying the issues. A quick browse through recent covers of TIME magazine (Figure 3) shows headlines such as “Forget Organic, Eat Local” and others relating agriculture and biodiversity with climate change and pollution; illustrating how the intersection between environmental science and society has entered the forefront of everyday life.

Figure 3. Recent covers of TIME magazine, showing headlines such as “Forget Organic, Eat Local” and others relating agriculture and biodiversity with climate change and pollution.

The decisions that citizens make with respect to the intersection between society and biodiversity are wide-ranging, and include actions in roles such as:

- Consumers – e.g. decisions about the provenance of one’s food.
- Voters – e.g. for land use policies such as ANWR or for biofuels.
- Workers – e.g. decisions relating to commuting.
- Volunteers – e.g. at farmers markets or conservation societies.
- Advocates – e.g. for local issues, such as the preservation of natural areas.
- Learners – e.g. as viewers of nature documentaries.

In their book, *Environmental Values in American Culture*, Kempton et al., (1996) describe studies that found that despite holding strong pro-environment or pro-development values with respect to certain issues, people (acting in many of the roles described above) were unable to make decisions that were in line with those values, due to lack of understanding of the socio-scientific systems in which the issues were situated.

Current Research on Student Understanding of Diversity in Populations and Ecosystems

The research literature documents quite thoroughly students' misconceptions regarding diversity/variation in populations and evolutionary change, where common misconceptions often include, but are not restricted to, Lamarckian (inheritance of acquired characteristics) or teleological (traits evolve for a purpose) explanations for natural phenomena (Anderson, Fisher & Norman, 2002; Clough & Driver, 1986; Scharmann & Harris, 1992; Cummins, Demastes, & Hafner, 1994, Bishop & Anderson, 1990). Such teleological reasoning is predominant among students at all levels, from the middle school to undergraduates (Rudolph & Stewart, 1998; Clough & Wood-Robinson, 1985; Lawson & Wesser, 1990; Settlage, 1994; Tamir & Zohar, 1991; Bishop & Anderson, 1990), and even among physics doctoral candidates (Chan, 1998) and medical students (Brumby, 1984). A key characteristic of all of these misconceptions is that they fail to consider the existence of diversity in populations and its role in evolutionary change.

Students' understanding of diversity and change in ecosystems is not as well documented in the research literature, and tends to focus on the flow of matter and energy through food chains and food webs, rather than processes that generate, maintain, and reduce diversity. Some notable findings in the research literature include:

- Many students fail to understand the range of links between organisms in an ecosystem. Students tend to believe that organisms in a population are important only to those other organisms on which they prey for food sources (Griffiths and Grant, 1985 and Munson, 1991).
- Many students construct food webs based around a concept of stable, unchanging systems (Leach, Driver, Scott and Wood-Robinson, 1992)
- Many students recognize cycles and flow in ecosystems, but see matter as being created and destroyed in a series of cause and effect events (Smith and Anderson, 1986)
- Many 12-13 year olds conceived food webs as linear connections, and did not recognize interdependence with other organisms or systems, or matter cycling (Boschhuizen and Brinkman, 1989, in Driver, 1994).
- Students' definitions of ecological terms are restricted to their everyday, rather than scientific meanings (Adeniyi, 1985).
- Many students view organisms as existing for the benefit of humans (Brumby, 1982, in Driver, 1994)
- Ecology is typically included in the final section of textbooks, and may be ignored if time is short at the end of the school year (McComas, 2002).
- Many current biology texts feature both incomplete and outdated treatments of the concept of succession (Gibson, 1996)
- Many students confuse environmentalism with environmental science (Krebs, 1999)

It is therefore clear that the current science curriculum is largely failing to prepare students to reason about environmental systems across scales, and therefore engage as citizens in discussions of socio-ecological issues in coupled human and natural systems.

While the research literature on student understanding (such as many of the studies mentioned above) usually takes a deficit perspective, it is our intention with this work to focus on students' continuing accomplishments in constructing and reasoning with scientific models of ecological systems as they progress through school, and to build on those accomplishments in constructing the learning progression.

METHODS

We organize our learning progressions research around three constructs: a lower anchor, an upper anchor, and the intermediates between the anchors. In this paper, we present findings primarily relating to the upper anchor and the intermediate levels in the progression, the lower anchor being the concepts and reasoning of students entering school, or in the case of this progression, in fourth grade.

1. The Upper Anchor

The upper anchor describes the knowledge and practices that we want students to have mastery of to be environmentally literate citizens. Our first task was therefore to define this domain. As with the other strands within the project, we organized this work around three practices that we believe are important for students to be environmentally responsible citizens:

1. Inquiry: extending/connecting personal experience and developing arguments from evidence.
2. Accounts: applying fundamental scientific principles to complex systems.
3. Citizenship: using scientific reasoning in responsible citizenship.

While all three practices are important for environmental science literacy, the research presented in this paper is focused on the 'accounts' practice. Work was undertaken to define scientific principles, and the important systems in which those principles need to be applied, that are required to reason about diversity within an environmental literacy framework. This was largely a top-down process, and involved:

a) Identifying the decisions that citizens are required to engage in relating to changes over time in diversity and variation.
b) Describing the processes that are driving those changes.
c) Identifying the structures and functions of natural systems that students would need to understand to reason about the changes over time.

We found it helpful to use multiple structures to organize our defined content, and each cast a different lens on the content. Some of these frameworks are presented here, and include organization around structure, function and change over time across a hierarchy of systems; processes that generate, maintain, and reduce diversity in natural systems; and distinctions between processes and changes in natural and non-natural systems. Wherever possible, current standards documents were consulted to learn from previous frameworks for the content.

2. Intermediate Levels of the Progression

Our work here was primarily focused on developing, administering and analyzing assessments across the 4th through 12th grade range (results from middle and high school students are presented here), although teaching experiments and clinical interviews are planned for the following round of data collection. Assessment items were designed to measure students' understanding of, and ability to apply the fundamental scientific concepts described in the upper anchor. Items were developed to cover as much of the framework of the upper anchor as possible. The research base regarding student understanding of our content areas was stronger in some areas than others (e.g. students understanding of variation as it pertains to evolutionary change is well documented, whereas the literature on species diversity and ecological change is sparse). We therefore built upon previous assessments wherever possible, while new items focusing on application of key ideas in the topic to linked human and natural systems.

Tests were administered by teachers in urban, suburban, and rural Michigan middle and high schools. Multiple versions of the tests were used to obtain student responses to a wide range of items, without having to make the test too long. Fifteen teachers administered tests in this round of data collection; some to a single class of students, and some across all of their classes and/or others in their departments. Approximately 1000 students completed the tests. The same questions were asked to middle and high school students to get a range of responses across age levels.

To develop levels that represent the stages in student understanding between the lower and upper anchors, we used a combination of a top-down and bottom-up approach. To begin, the research literature on ways in which students often conceive (and misconceive) of the content was consulted, along with our previous research and the defined upper anchor, and discrete levels between novices and experts were hypothesized. The assessment data were then analyzed in the following fashion:

- Sampled student responses to each item until a range of proficiency was thought to have been obtained (the data were revisited if we later found this to not be the case).
- Transcribed these responses into a spreadsheet.
- Ranked the responses from the most to least sophisticated.
- Identified patterns in responses with respect to the various frameworks.
- Grouped responses in accordance with these patterns.
- Identified levels of mastery reflected in these patterns.

The levels were modified and reshaped to reflect both what we already knew about how students learn and think about this content, as well as our new findings from our assessment data. Following the construction of these levels, the student data were revisited to further identify patterns and trends in students' responses across the levels, and to identify student responses that could serve as exemplars of student reasoning at each level.

RESULTS

1. The Upper Anchor

We can represent the upper anchor as a modified version of the loop diagram in Figure 1, shown below in Figure 4. It is our contention that citizens need to be able to navigate the entire loop in order to match their decisions regarding these issues with their values. The four parts of the loop are described below, but the focus of our attention is the environmental systems portion of the loop.

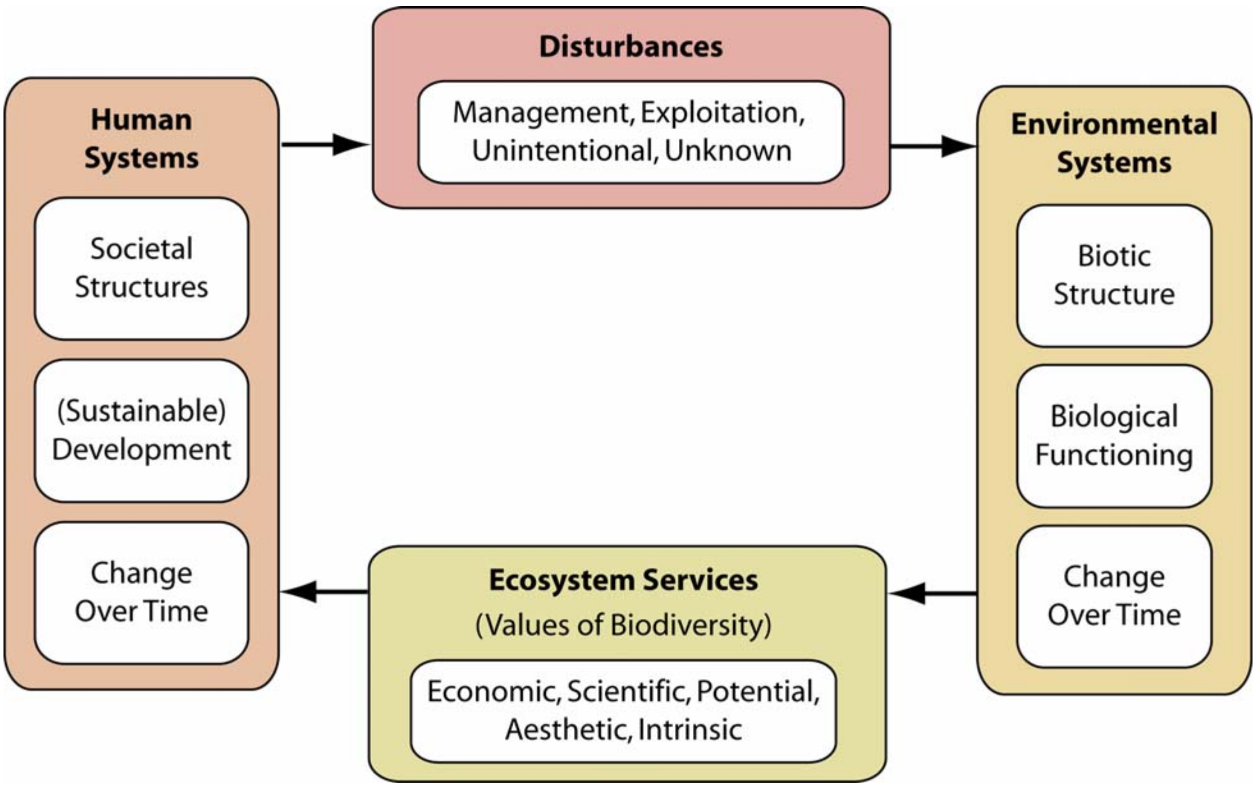

Figure 4. The generalized LTER Loop Diagram from Figure 1, modified to be specific to the Biodiversity strand.

1. ***Human Systems***

The content here is largely the domain of the social studies curriculum, and so we do not include an understanding of these systems in our learning progression. However, we believe that the social studies curriculum should teach students about human social and economic systems in ways that enable them to connect those systems to the arrows. Human systems particularly relevant to this strand include food distribution and consumption systems, and land ownership and use.

2. Disturbances

This box contains the many human actions that modify environmental systems such as:

- Management for agriculture, forestry and fisheries.
- Settlement in cities, suburbs, and exurbs.
- Hunting
- Introduction of non-native species
- Pollution
- Climate change

While many of the human actions are intentional and known, many others, such as the long term effects of transgenic crop species or the impact of forest fire management policies, are either unintentional or unknown.

3. Environmental Systems

The majority of our work is situated within this box, but as described above, this content needs to be organized and presented in such a way as to allow students to make the connections between concepts necessary to reason about processes across a hierarchy of systems, and to make connections between these concepts and the role of human societies as beneficiaries and modifiers of natural systems. We can organize the content within this box as *principles, processes,* and *changes over time*.

a) Principles: Tracing information across a hierarchy of systems

Across all three science-content strands within the larger Environmental Science Literacy project, the concept of a hierarchy of systems is present. We simply define *systems* as biological structures or scientific constructs contained within boundaries through which matter, energy and/or information can flow; in that sense, they are open systems. Sometimes these boundaries are physical, such as cell membranes, and sometimes these boundaries are constructs that help scientists organize matter into functional groupings such as species. Organizing these systems in a hierarchy leads us to perceive of systems as a series of nested boxes, ranging from the atomic-molecular level, all the way up to the global system level. In relation to this strand, our hierarchy consists of ecosystems, which are made up of multiple living and non living communities. Within those communities, there are multiple species, and each species is made up of multiple populations. Each population contains many individuals, and those individuals contain multiple genes. The hierarchy plays out slightly differently across strands, depending on which systems are important to consider, for example, the boundaries defined by cells are critical in the carbon strand, but not here. This set of nested boxes can been seen as similar to the Linnaean classification system, which includes many species being housed in a smaller number of genera, which in turn are housed within a smaller number of families, and so on.

Fundamental to this strand is the notion of *information*. At one level, this is genetic information exists in sequences of nucleotides, at the next, it is genetic variation contained within populations. Further up the hierarchy it becomes the structure of populations, species diversity, and the structure of communities. To effectively reason about natural systems, students need to trace information across this hierarchy. Tracing information is a little more abstract than the principles in the *carbon* and *water* strands of this project, these being tracing matter (keeping track of atoms and molecules through processes and across systems) and tracing energy (keeping track of energy through processes and across systems as it is converted from one form to another), in that there is no scientific law or theory that is consistent across the hierarchy. A key characteristic of living systems is that they maintain continuity in structure and function even as their subsystems disappear and are replaced. For example, individual humans' structures and metabolic processes are sustained even though virtually every atom in a baby has been replaced by the time the baby becomes an adult. Similarly, populations maintain continuity as individuals live and die, and ecosystems maintain continuity as populations change size or are replaced. We label the principles of genetics and other disciplines that explain how structure and function of living systems are sustained and how they change "Tracing Information."

b) Processes in systems.

We can categorize the processes through which students need to trace information in a number of different ways. Below (Table 1), we break them down along two dimensions: 1) the systems in which the processes operate – simplified to processes that occur within populations, and processes that occur between populations (or within communities), and 2) processes that create, sustain and reduce biodiversity.

Table 1. Organization of relevant processes by system level, and the generation, maintenance, and reduction of biodiversity.

	Processes within Populations	Processes within Communities
Processes that create biodiversity	Mutation, sexual recombination	Colonization by new species
Processes that sustain biodiversity	Life cycles, reproduction, relationships among individuals	Relationships among populations with different niches, habitats, survival strategies
Processes that reduce biodiversity	Natural selection, human selection (deliberate and unintended)	Reduction of niches and habitats by human management, invasive species

c) Change over Time

By change over time, we are referring to long term, largely irreversible changes in the structure and function of populations and communities. As mentioned above, biodiversity at all scales is a resource that once lost, is impossible to recover, and so the processes that govern these changes, natural and otherwise, are at the heart of many of the citizenship decisions that motivate this strand.

In natural systems, these changes include evolutionary changes and ecological succession. With respect to the relationship between natural and human systems, the changes over time that we are concerned with are:

- Reduction of genetic diversity in populations and species
- Reduction of species diversity in communities (including extinction)

4. *Ecosystem Services*

The LTER researchers describe ecosystem services as *"directly support[ing] components of human well-being including security, basic material for a good life, health, good social relations, and freedom of choice and action"*, and categorize them as:

a) Provisioning ecosystem services: the products that people obtain from ecosystems, such as food, fuel, fiber, fresh water, natural biochemicals and genetic resources.
b) Regulating services: benefits that people obtain from natural regulation of air quality, climate, erosion, disease, soil and water quality.
c) Cultural services: nonmaterial benefits that people obtain from the aesthetic, educational, recreational and spiritual aspects of ecosystems.

With respect to biodiversity, these ecosystem services are essentially the values that human societies place on biodiversity, those being traditionally defined in categories similar to those in Table 2.

Table 2. Traditional categorization of the values of biodiversity.

Values of Biodiversity	
Scientific	Ecological roles of organisms (producers, consumers, decomposers, pollinators, competitors, dispersers . . .). Evolutionary importance of genetic diversity in both natural and artificial systems.
Economic	Production of raw materials, food and drink, and medicines derived from plants. Ecosystems services such as air and water purification, climate regulation, decomposition and the maintenance of soil fertility, and the generation of moisture and oxygen. Benefits for agriculture, such as pollination of crops and control of pests.
Potential	Services from, and uses for, organisms and ecosystems that are currently unknown, such as medicines, unknown ecological roles, and the potential for adaptation to future environmental changes.
Aesthetic	Enjoyment of the beauty of organisms and ecosystems for recreation, leisure, artistic, or spiritual fulfillment.
Intrinsic	Organisms as having non-anthropocentric value in their own right, as products of the same evolutionary processes as humans.

2. Levels of Student Reasoning

Tables 3a and 3b represent the intermediate stages in students' models between the upper and lower anchors. Table 3a shows the levels with respect to the Structure and Function of environmental systems (the structure and function progress variables were combined in response to it being often impossible to talk about processes occurring in systems without explicitly referring to the systems themselves), while Table 3b shows the levels for the change over time progress variable. It should be noted that these levels are a work in progress, and will continue to be revised as more student data are analyzed.

Levels Illustrated by Student Responses to Test Items

Table 4 illustrates the connections between the levels and students' responses to test items. Three items are represented here, one concentrating on the structure of ecological systems, one on the processes occurring within and between systems, and one concerned with change over time. Only levels one through five of the progression are shown here, since a) no questions asked students to reason beyond level 5, and b) we see level 5 as an achievable goal of K-12 education, with levels 6 and 7 being largely the domain of undergraduate and graduate level college education.

Table 3a. Levels in the combined Structure/Function progress variable across populations and communities.

	Populations	Communities
Level 7 Accounting for uncertainty	Models that include quantification of uncertainty in population structure and function, such as mutation and genetic drift.	Models that include quantification of uncertainty in ecosystem structure and function, such as natural and human-caused disturbances.
Level 6 Quantitative accounts across scales	Quantification of the relative contribution of multiple sources of variation, such as Vp = Vg + Ve and the Hardy Weinberg equilibrium. Quantification of gene-gene and gene-environment interactions.	Quantification of measures of species diversity. Can compare ecosystems quantitatively in terms of species richness and relative abundance. Quantification of spatial distribution. Quantification of population dynamics between species.
Level 5 Model-based accounts across scales	Considers multiple sources of variation - any population is variable for at least 3 reasons (and a 4th for the tomatoes - post growth selection, same for sisters). Individuals described as collections of traits that can be sorted into the 3 categories (genetic, environmental, lifecycle). Genetic traits can be associated with fitness / adaptation or other selection criteria such as desirability for human purposes (e.g., focus on adaptability as a genetic trait rather than adaptations of individuals). Fitness is associated with reproductive success. Have resources for describing populations in general (size and variability - quantification of variability not until level 6).	Non-living environment and living community. Within the living community, models include species diversity (size, richness, relative abundance), and species relationships (competition, symbiosis, i.e. strategy in the ESS sense). Community structure - assigning plants, animals and decomposers to categories based on niche and habitat (i.e. a structure oriented way of looking at relationships).
Level 4 School science narratives of systems	Most pieces of a level 5 understanding are present, but pieces are disconnected (i.e. not connected in a model-based way). E.g. Limited ability to connect systems (e.g. explain the relationship between a gene and a chromosome), or connect systems (genes, traits, organisms, species) with processes selection, adaptation, differential survival. Populations are largely missing as a system. Descriptions of individuals use attribute-value frameworks, but students may have difficulty identifying genetic and environmental traits. Explanations of variability in populations tend to focus on some but not all	Students have narratives of processes and systems, just can't connect them. Again, most pieces of the Level 5 model are present, but the pieces are connected with terms and stories rather than models of processes and mechanisms. Narrative accounts of ecosystem structure and function, such as simple descriptions of ecosystem structure without a model of the underlying processes, or without tracing matter or information between systems. Limited ability to connect systems (e.g. interaction between biotic and abiotic systems). Ecosystem structure described in terms of different species, or the size of

	possible sources (genetic, environmental, life cycle) in ways that are cued by the way the question is posed. Descriptions of fitness of individuals may mix genetic and acquired traits; a variety of different traits are recognized as conferring fitness depending on interactions of individuals with other organisms and the environment.	populations, but rarely both together.
Level 3 Hidden mechanisms explained by cultural narratives or embodied experience	Students recognize the three sources of variation - but descriptions of individuals or populations don't take more than one source into account. Recognizes material kind at microscopic scale but hidden mechanism between source of variation (i.e. genetics, the environment) and the variation itself. Cultural narratives or embodied experience used to connect sources of variation and the variation itself. Descriptions of individuals may use attribute-value structure, but may have narrative or metaphorical elements. Traits are not described in ways that facilitate differentiating genetic from acquired traits. Fitness of individuals is associated with desirable traits (size, strength, speed). There is no clear distinction between genetic and acquired traits.	Hidden mechanism between species diversity and the causes of species diversity (e.g. variation in the environment, relationships between species). Descriptions of community structure limited to producers and consumers (rarely decomposers) - relationships between populations / species limited to simple predator / prey and food-web or symbiotic interactions (no relationships such as competition for resources as the driving force behind ecosystem structure). Difference between plants and animals: animals interact as predators and prey, animals eat plants, but plant interactions are largely invisible.
Level 2 Narrative descriptions of systems at the macroscopic scale	Describes systems purely at the macroscopic level, such as environmental effects on phenotype (adaptations to environmental conditions). Variability is only recognized in populations where phenotypic variation is visibly obvious, and is only accounted for by environmental conditions or life cycle stage.	Describes ecosystems at the macroscopic level in terms of the visible components (animals, plants). Conceptions of species diversity limited to the different species of macroscopic organisms, with little assignment to functional groups (producers, consumers). Students describe interactions among species in narrative form as interactions among individuals rather than as parts of ecosystem function.
Level 1 Anthropomorphic and natural tendency narratives	Accounts based on human analogy or "folk" cultural models about organisms and species, e.g. responses such as "everything is different – no two things can look the same".	Accounts based on human analogy or "folk" cultural models about organisms, species and ecosystems, e.g. movie caricatures of harmonious and well-balanced ecosystem relationships.

Table 3b. Levels in the Change over Time progress variable across populations and communities.

	Populations	**Communities**
Level 7 Accounting for uncertainty	Predictive and reconstruction models of change that include quantification of probabilities (uncertainty) of events, such as mutation rates, drift, birth and death rates.	Predictive and reconstruction models of change that include quantification of probabilities (uncertainty) of events, such as natural and human-caused disturbances.
Level 6 Quantitative accounts across scales	Quantitative descriptive models of natural and artificial selection and other changes in population structure.	Quantification of changes in species diversity and the structure of ecosystems over time. Quantification of rates of succession.
Level 5 Model-based accounts across scales	Scientific models of change over time in population structure: Natural and artificial selection and reproduction. Students explain changes in population composition in terms of adaptations of individuals to relationships within the population (e.g., competition, mating) and conditions in the non-living and living environments (e.g., food sources, predation). Change over time in population size (extinction, factors that influence the chances of survival of populations as a whole).	Human alterations to ecosystems that favor the growth of one population or another (intentionally - cultivation, unintentionally - pests, weeds, invasives). Direct human intervention through cultivation. Scientific models of dispersal, colonization, and succession. Students explain changes in biotic structure (e.g., succession and invasive species) in terms of adaptations of different species to changing environmental conditions.
Level 4 School science narratives of systems	Disconnect between models of systems (genes, populations, species), processes (inheritance, mutation) and change over time (evolution). Recognizes traits to be passed from one generation to the next, but fails to connect that with the micro-systems governing traits and inheritance, therefore all adaptations can be inherited, not just those that vary genetically, leading to Lamarckian explanations for evolutionary change.	Disconnects within and between systems and processes, resulting in students failing to connect the processes driving ecological change with the change itself, e.g. disconnect between competition and succession.

Level 3 Hidden mechanisms explained by cultural narratives or embodied experience	Hidden mechanism of random mutation and the existence of population level genetic variation, so individuals change in response to need, leading to teleological explanations for evolutionary change. Mechanisms of inheritance are also hidden.	Some idea of succession, no concept of what is driving it. Uses experiences and cultural models of weeds growing tall, and forests/jungles containing large animals, to reason about change over time in ecosystems.
Level 2 Narrative descriptions of systems at the macroscopic scale	Larger and smaller systems are not considered when reasoning about evolutionary change, so individuals just strive to change to meet a conscious desire. Changes only described in terms of why they occurred, not how.	No recognizable change over time (other than catastrophic events) occurs in ecosystems.
Level 1 Anthropomorphic and natural tendency narratives	Individuals just change to become suited to their environment, no need for a mechanism.	Species diversity changes in response to anthropomorphic relationships between species.

Table 4. Student responses to three items that exemplify each level in the progression.

Exemplar Responses to Items Across Levels				
	Level	**Structure of Systems**	**Tracing Information**	**Change over Time**
		If a scientist wanted to measure the diversity of species in a given area, what types of data might she collect?	a) The strawberries in the picture all grew in a large field on the same farm, but they all look a little different. Why do you think they all look a little different? b) The carrots in the picture all grew in a greenhouse under identical conditions, but they all look a little different. Why do you think they all look a little different?	Farmers often use pesticides to help prevent insects from eating their crops. Over time, the insects slowly become resistant to these pesticides, and so the farmers have to use different pesticides to protect their crops. Tell a story about how the insects become resistant to the pesticides.
Level 5	**Model-based accounts across scales**	*Different species of organisms; Population of each species; Total number of organisms; Percentages of each species. (SSD)*	*a) The strawberries look different because when they pollinate or reproduce they are coming from different parents and are given different genes. Also things such as minerals and water will also affect them.* *b) They all look a little different because they were given different DNA codes. Just like kids are not the same even from the same parents. (NED)*	*When the crops are sprayed some bugs are killed but some may live and when the living mate they will give their kids genes to help them survive through the pesticides so the bugs adapt to the pesticides and because the bugs reproduce fast and don't live long it doesn't take long for them to adapt to the pesticides. (NED)*
Level 4	**School science narratives of systems**	*# of each animal; # of types of animals; how many predator and prey animals are in the area. (WMM)*	*a) Because they probably came from different parts of the field where conditions might be different like water type and amount, crowded or not, how much sunlight, and the soil difference. And combinations of the conditions.* *b) Their genetics. (HAP)*	*As the bugs live in and around these pesticides, their immunity to it becomes stronger, and this immunity becomes stronger as they pass them down to their young in genes. (EET)*

Level 3	**Hidden mechanisms explained by cultural narratives or embodied experience**	*The different kinds of living things in an area. The most has the most diverse population. (CJW)*	*a) They all look a little different because they may not have had the same nutrients or sun in certain parts of the field. b) The light in the greenhouse wasn't reaching everywhere. (CEM)*	*The insects eventually become immune to the pesticides because when one insect takes it in, then they reproduce there is already pesticides in the offspring so they are used to it and the pesticide doesn't really affect them. (EAT)*
Level 2	**Narrative descriptions of systems at the macroscopic scale**	*She might want to walk through the forest and collect different species throughout it. (JJDK)*	*a) The light could have been different, some could have had more sunlight than others. b) Maybe they were different kinds of carrots. (KAV)*	*Their bodies try to fight off the pesticides. Once they figure out how to fight them it's easy for them to fight so the pesticides no longer work. (EDE)*
Level 1	**Anthropomorphic and natural tendency narratives**	*Just like how tall the grass and the plants are (HAJ)*	*a) All plants are different. No two are the same. It's impossible to have two of the same plants. b) Like I said above. No two "carrots" can look the same! (SS)*	*Insects become resistant by they get used to the smell and taste and eventually it doesn't bother the insects. (KKC)*

The *Structure of Systems* item in Table 4 asked students *“If a scientist wanted to measure the diversity of species in a given area, what types of data might she collect?”* Students’ responses indicated what they believed to be the components of species diversity, and therefore their conceptions of the structure of ecological communities. Only one student responded with what we would consider a Level 5 Model-based answer, in which they represented species diversity as both a function of species evenness (the relative abundance of different species) and species richness (the number of species in a given area). Most other students described species diversity as simply a measure of the number of different species (species richness). To a similar question which asked students to compare three communities with different ratios of three species, one student responded, *“They each contain 3 kinds of animals. Species diversity doesn't include the amount of species for each. (JSC)”*, indicating that despite recognizing the species evenness variable, they rejected it as a component of species diversity.

a) The strawberries in the picture all grew in a large field on the same farm, but they all look a little different. Why do you think they all look a little different?

b) The carrots in the picture all grew in a greenhouse under identical conditions, but they all look a little different. Why do you think they all look a little different?

Figure 5. The “Strawberries and Carrots” item.

The Tracing Information item in Table 4 asked student two questions, and is shown in Figure 5. In part a, all three sources of phenotypic variation (genetic variation, environmental variation, and lifecycle stage (in this case, age) are possible explanations, whereas in part b, the environmental variation is limited. Student responses to this item ranged in sophistication from the assertion that no two things can look alike, to recognizing environmental sources of variation, to recognizing genetic sources of variation (albeit largely limited to cultural models represented in phrases such as “it’s in their genes), to a three students whose accounts included both genetic and environmental sources of variation. No students suggested the age of the fruit/vegetables as an explanation.

The Change over Time shown in Table 4 item framed a traditional natural selection problem within the context of a coupled human and natural system, and asked students: “Farmers often use pesticides to help prevent insects from eating their crops. Over time, the insects slowly become resistant to these pesticides, and so the farmers have to use different pesticides to protect their crops. Tell a story about how the insects become resistant to the pesticides.” Level 1 students described the process of evolutionary change as similar to how people become acclimated to small changes in their environment, while students at Level 2 represented the change occurring over longer time scales, they had no models of mechanisms to account for this change, so change is only explain in terms of why it occurred, and not how. For students at Level 3, the concept of variation within a population is hidden, so organisms change in response to need during their lifetimes, while students at Level 4 gave what are often considered to be Lamarckian explanation, in which changes occurring during an organism’s life time are somehow heritable. Again, only a very small number of students gave Level 5 responses (and at what we would consider to be low-Level 5 responses at that), in which population level variation, differential survival, and change in population structure between generations, are all represented.

One further item presented students with the following scenario:

When Europeans first came to Peru, the found that the Peruvians were growing a crop that they hadn’t seen before: potatoes. Each Peruvian field contained many types of potatoes, as shown in the picture on the left. The Europeans selected the biggest and best type of potatoes (shown in the picture on the right), took that back to Europe, and planted fields containing just this one type of potato.

And asked them to describe the advantages and disadvantages of each approach. Responses to the “advantages of the Peruvian way” question included:

Level 5: Model-based accounts across scales
No suitable responses

Level 4: School science narratives of systems
They had a better chance of more potatoes surviving extreme conditions (RTB)

Level 3: Hidden mechanisms explained by cultural narratives or embodied experience
They have more kinds of potatoes if one dies out (SLB)

Level 2: Narrative descriptions of systems at the macroscopic scale
They grow all different types and have more varieties (ETB)

Level 1: Anthropomorphic and natural tendency narratives
Because that you can eat all kinds of different potatoes (SYN)

3. Achievement Data

With respect to the frequency of types of responses to individual items, two findings are particularly interesting; one relating to students' conceptions of the hierarchy of systems, and one concerning how students draw on different sources of variation to explain phenotypic variation in different contexts.

Figure 6 shows students' responses to the item:

Put the following items in the boxes below, going from the smallest (on the left) to the largest (on the right). Be sure to include all the terms.

Population
Gene
Species
DNA
Ecosystem
Dog
Chromosome

Smallest $\longrightarrow$ **Largest**

atom								***planet***

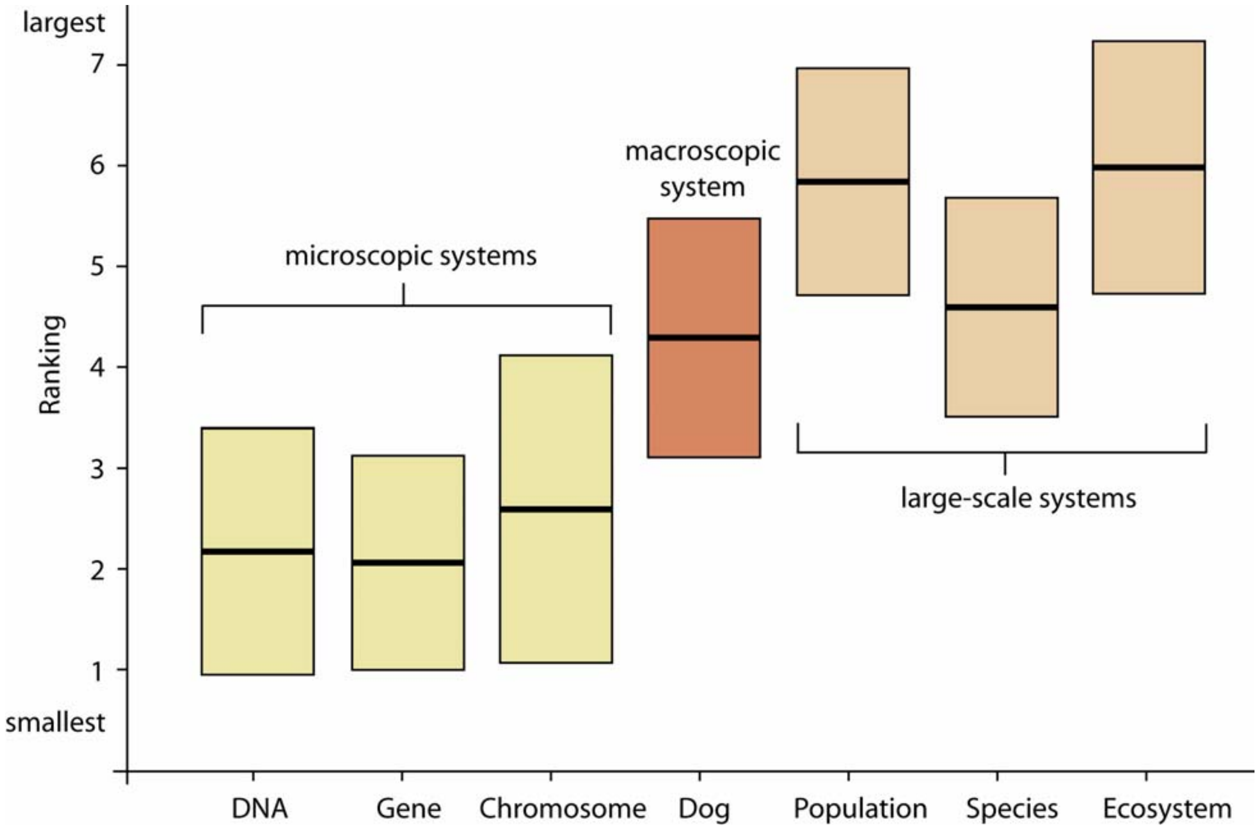

Figure 6. Mean student rankings of each system (black bar) plus and minus two standard deviations (colored blocks). Data from 60 students.

It can be seen from figure 6 that students, on average, correctly placed the dog in the center of the seven systems, but were confused by the organization of the microscopic and large-scale systems. Of particular note is the switched placement of populations and species. Since populations are a critical unit of analysis in reasoning about both ecological and evolutionary processes, students' inability to fit them correctly into the hierarchy suggests a significant deficit in their models. In the 60 responses analyzed for this figure, not one student correctly ranked all seven systems.

Figure 7 shows categorizations of students' responses to five items that asked them to explain phenotypic variation in various living things, these being strawberries grown in a field; carrots grown in a controlled greenhouse; supermarket tomatoes vs. garden tomatoes; and twins, sisters and friends. Some interesting patterns across the questions include:

- Life cycle stage was only mentioned to explain why twins look more alike than sisters (the explanations usually being along the lines of "they were born at the same time").
- Very few students ever mentioned more than one possible source of phenotypic variation.
- Genetic variation was only common as an answer when environmental variation could be ruled out.
- References to genetics were never explicitly about population level genetic variation, but rather were usually references to cultural or informal models such as "it's in their genes".

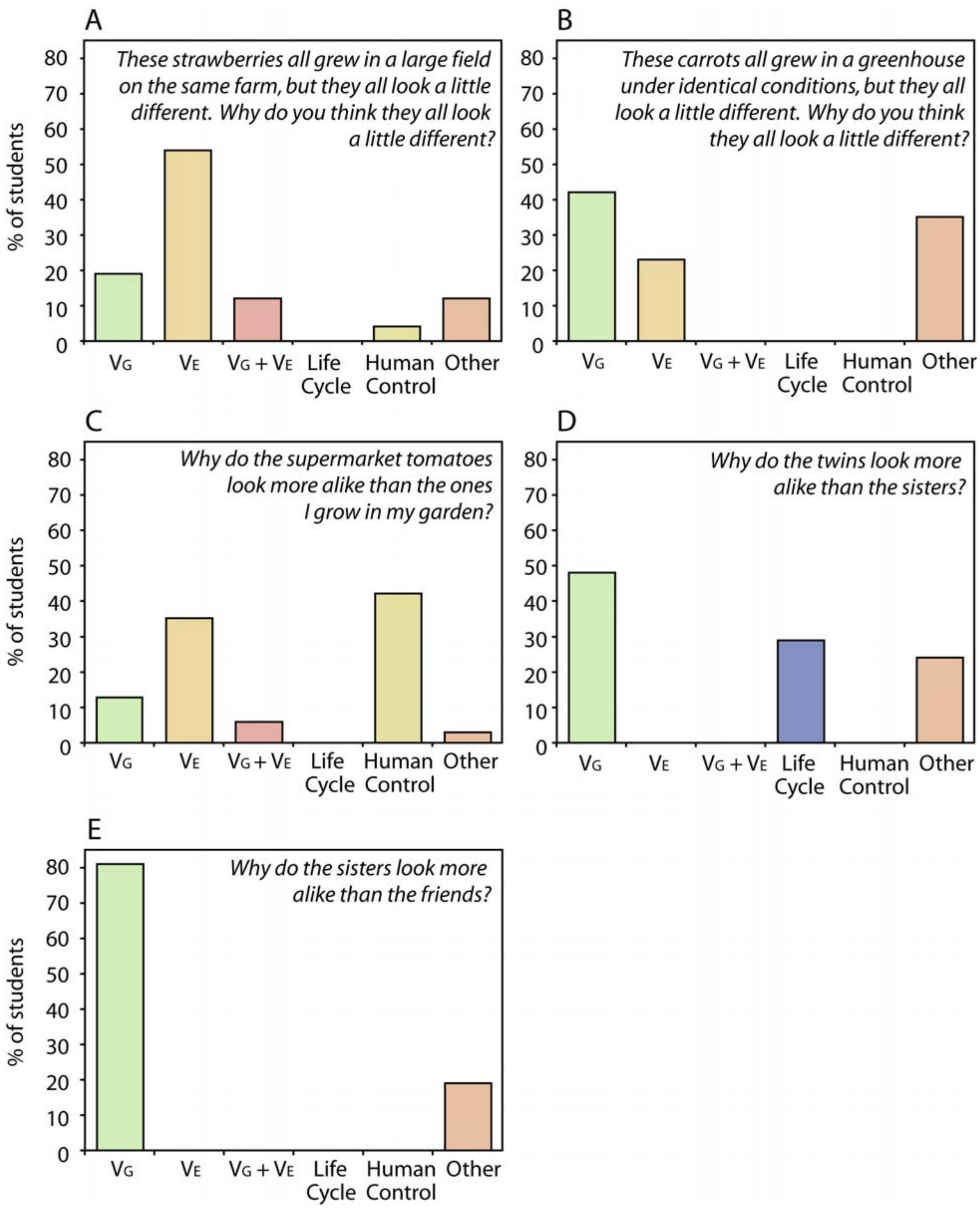

Figure 7. Percentage of student describing different sources of phenotypic variation in responses to questions set in different contexts. Data from 30 students in each figure. (V_G = genetic variation and V_E = environmental variation).

DISCUSSION

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

General Trends in the Learning Progression

1. Awareness of Systems and Processes: From Invisible to Visible

Parts or aspects of the phenomena in the upper anchor that are invisible to younger children enter the awareness of more advanced learners. This general trend has multiple dimensions, including increasing awareness of microscopic and atomic-molecular scale parts of systems, and increasingly common descriptions of invisible mechanisms.

Small scale systems:

At all levels, students made references to small scale systems such as genes and DNA, but lower level students were unable to use these systems when trying to explain phenomena at the macroscopic scale, with usage being largely limited to cultural models represented in phrases such as "it's in their genes". At level 4, students recognized that genes were the material by which traits were passed between generations, and while many of these students could tell stories about reproduction and inheritance, they were unable to connect these systems into a workable model. Invisible small scale parts of ecological systems include decomposers and detritus-based food chains, as well as soil systems and many abiotic factors.

Invisible mechanisms:

Many mechanisms were invisible to students at the lower levels, including relationships between organisms other than simple predator-prey relationships; differential survival within populations; and the mechanisms governing ecological succession. Students at lower levels of the progression usually saw no need to describe a mechanism, and instead described changes in systems as events with causes. At increasingly higher levels, students recognized a need for a mechanism, but their scientific models were too weakly structured and were missing important systems.

2. Precision in Measurement and Description: From Impressions to Data

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

Precision in description, measurement, and data representation:

Descriptions of organisms ranged in sophistication from organisms that live in certain areas, to organisms as collections of traits, to the assignment of those traits to genetic, environmental or lifecycle stages. There was also a trend towards the assignment of organisms to functional groupings (e.g. consumers, decomposers, and producers).

With respect to evolutionary change, it was interesting that some students (usually at around Level 3) sometimes attempted to represent their thinking with scientific notations of crosses, including letters representing different alleles.

In relation to the measurement of species diversity, lower levels students merely define the construct as the different types of things that were there, while higher level students recognized that communities could be described both in terms of the size and the relative abundance of different species.

Use of scientific descriptive terms and categories:

Students at increasingly higher levels of the progression were able to describe organisms as being collections of traits, and were able to assign those traits into categories defined by genetic causes, environmental, and life cycle stages (e.g. age, or connect an apple seed with an apple with an apple tree).

There was little evidence of students using more sophisticated scientific language as the moved through the progression, other than inherited material progressing from being undefined, to genes, to DNA; and terms such as ‘adaptation’ and ‘evolve’, switching from their lay definitions at lower levels to their scientific usage at higher levels.

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

Model-based reasoning is what we normally think of as scientific reasoning. Model-based reasoning uses patterns in observations of phenomena (i.e., laws) and models or theories to explain and make predictions. Model-based reasoning puts widely applicable laws, models, and theories in the foreground and seeks to understand the details of particular phenomena through their application.

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

Thus narratives and model-based reasoning are alternative approaches to making sense of the world. Narratives put events in order; models function as flexible intellectual tools that can be systematically applied within their domains. As learners mature, they are able to use model-based reasoning more widely, they learn to use principles such as conservation of matter to constrain and connect models, and they learn to make distinctions among types of knowledge claims that are essential to model-based reasoning.

Changing balance between narrative and model-based reasoning

Most students relied on narrative accounts to make sense of the phenomena and changes presented to them in the assessment items. They explained changes in populations and communities as events with causes and outcomes, driven by no particular mechanism and through which information is rarely accounted for. Students are higher levels began to have models each of the individual systems (genes up to ecosystems), but had limited ability to connect them together, or to connect them with the processes occurring within them. For example:

- In describing the causes of phenotypic variation, students at lower levels generally gave macroscopic accounts (connecting the appearance of organisms with visible environmental variables), progressing to accounts that include microscopic systems (genetic causes), to a small number of students who gave model-based account including multiple sources of variation.

- In response to an item that asked students to explain how the diverse range of domestic dog breeds could have originated from a wolf ancestor, students at the narrative level described how the variation must have come from breeding with different species, whereas the highest level students recognized that variation already existed within the wolf population. Interestingly, all students told natural selection type stories in response to this item, and not one student mentioned humans and/or artificial selection for desirable traits.

While, understandably, evidence of embodied experience was lacking with respect to these items, many students at the lower levels resorted to cultural models to explain hidden processes. Phrases such as “you get it from your mother”, and “they have the same blood” were commonplace.

Using principles to constrain and connect models

The principles governing many aspects of ecological change are less well defined, even within the scientific community, than those governing other types of changes, in that there is no law such as the conservation of matter that must constrain students reasoning. Evolutionary change is however constrained by some simple rules, such as the types of traits that can be inherited or the ways in which genetic information can change. We saw a range in the inclination and ability of students to reason with these constraints, ranging from species just becoming acclimated to their environments, to change occurring in response to need, to Lamarckian stories lacking a genetic basis, to lower level model-based accounts involving variation within a population and differential survival.

CONCLUSION

Biodiversity on earth is valued in multiple ways, and is directly related to the structure of human systems now and in history. Human activities tend to reduce biodiversity at the population and ecosystem levels, altering structure and function of these systems through time. There is an interesting conflict between natural and human systems with regards to diversity. Within natural systems heterogeneity is valued, in that we strive to maintain biodiversity, protect endangered species by efforts to increase genetic diversity, and maintain and restore diverse natural habitats. In agricultural and other human land use systems however, we are the homogenizers. The goal is usually to control and limit diversity as much as possible, by engineering genetically identical crops, creating homogenous growing conditions, and discarding products of these systems that are not sufficiently uniform. The problem is that it has become evident that simply dividing the world into separate natural and non-natural systems, and playing by different rules in each, is not a sustainable way to move forward. The intersection between the two is becoming increasingly problematic, and many of the environmental issues that face our societies are situated in this intersection, such as habitat fragmentation, fertilizer runoff, water availability, pesticide resistance, soil degradation, and the introduction of invasive species.

In the natural sciences, traditionally separate fields are becoming increasingly integrated; where once there were biologists, geologists and chemists, there are now biogeochemists. Similarly, there has been a trend in the natural sciences away from the description of the world around us and its origins, to the prediction of how the natural world will change in response to our actions, e.g. where once many evolutionary biologists studied the fossil record, they now study pesticide resistance and the cross pollination of transgenic plants. Since human populations survive by altering natural ecosystems and the processes occurring within them, taking materials we need out of those systems and putting our wastes back into them, 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. That is, modern ecology has focused increasingly on *coupled human and natural systems* (see, for example, AC-ERE, 2003).

We believe that the required school science curriculum should reflect this change. This problem has been recognized and responded to at the university level in courses for science majors specializing in conservation biology, in response to criticisms and concerns from the like of Jacobson and Clark, quoted below.

"The growing urgency of training individuals to protect, maintain and restore the planet's biological diversity is challenging academic institutions to overcome narrow disciplinary perspectives".

Jacobson, Conservation Biology (1990) p 431.

"Some conservation biologists question the ability of current university curricula to prepare students to meet the needs of the profession in solving real-life conservation problems or to integrate the goals of conservation biology with other societal goals. The gist of the criticism is that curricula tend to emphasize narrow, technical proficiency at the expense of more integrative, 'policy-oriented' problem solving".

Clark, Conservation Biology (2001) p31.

Since we recognize the many roles citizens play that have direct impact on these issues (consumers, voters, advocates, workers, volunteers, and learners), this sort of integrated understanding can no longer be exclusive to conservation biologists. A science curriculum that truly provides *science for all*, and that meets the goal of public education of preparing citizens to participate in a democratic society, must change to reflect and respond to pressing and growing number of environmental issues that require citizens to integrate scientific understanding into societal decision-making.

Biodiversity on earth is valued in multiple ways, and is directly related to the structure of human systems now and in history. Human activities tend to reduce biodiversity at the population and ecosystem levels, altering structure and function of these systems through time. There is an interesting conflict between natural and human systems with regards to diversity. Within natural systems heterogeneity is valued, in that we strive to maintain biodiversity, protect endangered species by efforts to increase genetic diversity, and maintain and restore diverse natural habitats. In agricultural and other human land use systems however, we are the homogenizers. The goal is usually to control and limit diversity as much as possible, by engineering genetically identical crops, creating homogenous growing conditions, and discarding products of these systems that are not sufficiently uniform. The problem is that it has become evident that simply dividing the world into separate natural and non-natural systems, and playing by different rules in each, is not a sustainable way to move forward. The intersection between the two is becoming increasingly problematic, and many of the environmental issues that face our societies are situated in this intersection, such as habitat fragmentation, fertilizer runoff, water availability, pesticide resistance, soil degradation, and the introduction of invasive species.

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REFERENCES

Adeniyi, E. (1985). Misconceptions of Selected Ecological Concepts Held by Some Nigerian Students. Journal of Biological Education, 19(4), 311-316.

Allen-Wardell, G., P. Bernhardt, R. Bitner, A. Burquez, S. Buchmann, J. Cane, P. A. Cox, V. Dalton, P. Feinsinger, M. Ingram, D. Inouye, C. E. Jones, K. Kennedy, P. Kevan, H. Koopowitz, R. Medellin, S. Medellin-Morales, G. P. Nabhan, B. Pavlik, V. Tepedino, P. Torchio and S. Walker (1998). "The potential consequences of pollinator declines on the conservation of biodiversity and stability of food crop yields." Conservation Biology 12(1): 8-17.

American Association for the Advancement of Science (1993). Benchmarks for science literacy. New York: Oxford University Press (http://project2061.aaas.org/tools/benchol/bolframe.html). Michigan Department of Education (2006). Michigan Science High School Content Expectations. Lansing, MI: Michigan Department of Education

Anderson, D.L., Fisher, K.M., and Norman, G.J. (2002). Development and evaluation of the conceptual inventory of natural selection. Journal of Research in Science Teaching 39(10): 952-978.

Bishop, B. A., and Anderson, C. W. (1990). Student conceptions of natural-selection and its role in evolution. Journal of Research in Science Teaching 27(5): 415-427.

Boschhuizen, R., & Brinkman. F. G., 1995, The concept of cycles for environmental education, Environmental Education Research, v. 1, p. 147-158.

Brumby, M.N. (1984). Misconceptions about the concept of natural selection by medical biology students. Science Education 68: 493-503.

Brumby, M.N. (1982). Students' perceptions of the concept of life, Science Education 66(4): 613-922

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley and V.H. Smith (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications 8(3): 559-568.

Chan, K.S. (1998). A case study of a physicist's conceptions about the theory of evolution. Paper presented at the annual meeting of the National Association of Research and Science Teaching, San Diego, CA.

Clark, T.W. (2001). Developing Policy-Oriented Curricula for Conservation Biology: Professional and Leadership Education in the Public Interest. Conservation Biology 15(1): 31-39

Clough, E.E., and Driver, R. (1986). A study of consistency in the use of students' conceptual frameworks across different task contexts. Science Education 70: 473-96.

Clough, E.E., and Woodrobinson, C. (1985). How secondary students interpret instances of biological adaptation. Journal of Biological Education 19(2): 125-130.

Cummins, C.L., Demastes, S.S., and Hafner, M. S. (1994). Evolution - Biological educations under-researched unifying theme. Journal of Research in Science Teaching 31(5): 445-448.

Driver, R., Squires A., Rushworth, P. and Wood-Robinson, V. (1994) Making Sense of Secondary Science: Research into children's ideas. London: Routledge Falmer

Flannery, T. (2005). The weather makers: How man is changing the climate and what it means for life on Earth. New York, Atlantic Montly Press.

Gibson, D. J. (1996). Textbook misconceptions: The climax concept of succession. The American Biology Teacher, 58(3), 135-140.

Griffiths, A.K. and Grant, B.A.C. (1985). High school students' understanding of food webs: Identification of learning hierarchy and related misconceptions. Journal of Research in Science Teaching, 22(5), 421-36.

Kerr, T. K., Kharouba, H.M., and Currie, D. J. (2007). The macroecological contribution to global change solutions. Science 316, 1581-1584.

Jacobson, S.K. (1990). Graduate education in conservation biology. Conservation Biology, 4(4) 431-440.

Kempton, W., Boster, J.S., and Hartley, J.A. (1995). Environmental values and American culture. Cambridge, MA: MIT Press

Kirschenmann, F.L. (2007). "Potential for a new generation of biodiversity in agroecosystems of the future." Agronomy Journal 99(2): 373-376.

Krebs, R.E. (1999). Scientific Development and Misconceptions Through the Ages. Westport, CT: Greenwood Press.

Lawson, A.E., and Wesser, J. (1990). The rejection of nonscientific beliefs about life: Effects of instruction and reasoning skills. Journal of Research in Science Teaching 29: 375-388.

Leach, J., Driver, R., Scott, P. & Wood-Robinson, C. (1996). Children's ideas about ecology 3: Ideas found in children aged 5-16 about interdependency of organisms. International Journal of Science Education, 18, 129-141.

Long Term Ecological Research Network Research Initiatives Subcommittee (2007). Integrative Science for Society and Environment: A Strategic Research Plan. Long Term Ecological Research Network.

Munson, B.H. (1991). Relationships Between an Individual’s Conceptual Ecology and the Individual’s Conceptions of Ecology. Unpublished doctoral dissertation, University of Minnesota, Minneapolis.

National Research Council (1996). National science education standards. Washington, DC: National Academy Press (http://www.nap.edu/readingroom/books/nses/html).
NAEP 2009 Science Framework Steering Committee (2006). Science Framework for the 2009 National Assessment of Educational Progress. Washington, DC: National Assessment Governing Board

National Research Council (2007).Taking Science to School: Learning and Teaching Science in Grades K-8. Washington, DC: National Academy Press (http://www.nap.edu/readingroom/books/nses/html).

Rudolph, J.L., and Stewart, J. (1998). Evolution and the nature of science: On the historical discord and its implications for education. Journal of Research in Science Teaching 35(10): 1069-1089.

Scharmann, L.C., and Harris, W.M. (1992). Teaching evolution - Understanding and applying the nature of science. Journal of Research in Science Teaching 29(4): 375-388.

Settlage, J.J. (1994). Conceptions of natural selection: A snapshot of the sense-making process. Journal of Research in Science Teaching 31(5): 449-457.

Tamir, P., and Zohar, A. (1991). Anthropomorphism and teleology in reasoning about biological phenomena. Science Education 75: 57-67.

Tilman, D. and J.A. Downing (1994). Biodiversity and Stability in Grasslands. Nature 367(6461): 363-365.

Vitousek, P.M., H.A. Mooney, J. Lubchenco and J.M. Melillo (1997). "Human domination of Earth's ecosystems." Science 277(5325): 494-499.

Wilson, E.O. (1988) Biodiversity. National Academy of Sciences