College student understanding of carbon transformation and cycling processes.

Jonathon Schramm[1,2], Brook Wilke[1], Laurel Hartley[3] and Charles (Andy) Anderson[1,2].
1 – Michigan State University, 2 – Great Lakes Bioenergy Research Center, 3 – University of Colorado, Denver

Many issues currently being debated in broader society often require an understanding of fundamental science concepts, despite the fact that many citizens lack that knowledge and thus the tools to participate fully. The sustainability of various biofuel production systems is one such issue, as it necessitates discussion of carbon cycling and various transformation processes (e.g. – photosynthesis, combustion, sequestration), among other concepts. Previous work by a number of researchers has illustrated that incomplete understandings about these processes are held by students across a wide spectrum of ages. This paper presents data from assessments of college students enrolled in general biology and ecology courses, both pre- and post-instruction. Students often possessed many of the same problematic understandings as younger students, although they also demonstrated stronger learning gains after instruction, particularly with regards to photosynthesis and respiration. Understanding of larger scales of carbon cycling, however, often lagged behind that of its constituent processes, thus making it more difficult for students to completely describe differences between bio- and fossil fuels. Further, students often conflated the concepts of global warming and stratospheric ozone depletion, leading to an emphasis on the relative pollution production of these fuels, rather than their different timescales of carbon sequestration and oxidation.

Introduction

An implicit goal of science education is to develop students into *informed citizens* who are aware of the possible consequences of their actions and take those consequences into account in their decision-making. Regardless of the work that students take up in their adulthood, we hope that they would have the knowledge necessary to understand the environmental implications of their decisions, even as they weigh those together with other considerations and values. Several practices inform citizenship of this type:

- *Inquiry:* learning from experience, developing and evaluating arguments from evidence. Inquiry includes evaluating both sources of evidence and the evidence itself.
- *Accounts:* describing, explaining, and predicting outcomes of processes in socio-ecological systems. In this context predictions focus on the effects of disturbances or human policies and actions on processes.
- *Deciding*: making choices (conscious or unconscious) about personal lifestyles or courses of action in private roles, as well as people or policies to support in public roles.

Although many issues being discussed in contemporary society could benefit from a citizenry with a more robust scientific understanding and set of practices, biofuels stand out as a particularly trenchant topic built on the crucial biological processes of photosynthesis, respiration and sequestration of carbon. In this study we investigated both college students' general understanding of carbon-transforming processes and their ability to apply that understanding to a specific environmental issue: biofuels. Without a robust understanding of the basic processes involved, citizens can quickly be swayed by any of the various slogans that are offered for ("Biofuels emit no pollution!") or against ("Biofuels drive up world food prices!") the use of biofuels in our energy portfolio. Acknowledging that it is unreasonable to ask that all high school graduates have an expert understanding of carbon cycling, it is nonetheless imperative for students to develop the abilities to reason about carbon-based phenomena that will allow them to participate in debates about biofuels and other topics.

The concept of learning progressions is helpful in approaching this problem of biofuel comprehension, as it builds from the knowledge students acquire at earlier levels, eventually allowing students to demonstrate mastery based on a more holistic understanding (See Paper 1 of this set). Similarly, students who have successfully worked through a complete learning progression will be better positioned to apply their knowledge to forthcoming debates in their adult years than students who are relying on a piecewise memory of biological facts (Covitt *et al.* 2009). Over the last few years, Anderson and his colleagues have been developing a learning progression to trace students' understanding of carbon-transforming processes across multiple grade levels (cf. Mohan *et al* [in press]). A number of pertinent findings have emerged from this work, including the consistent problems that students have with the movement of gases through biological processes and conflation of matter and energy transformations (see Paper 3 in this set). For instance, students routinely neglect the significance of gaseous CO_2 for the creation of biomass by autotrophs such as plants, at the same time as they forget to account for the loss of mass in a system when only respiration is occurring (through CO_2 and H_2O, Wilson *et al.* 2006). These miscalculations are often closely related to the casual definitions for matter and energy that students seem to operate with. Energy in particular is a loose term for students, and often acts as a balancing factor for processes where students acknowledge something is changing (often gas concentrations), but are not certain how to account for those changes. Because of this, students will describe photosynthesis as converting solar energy into the mass of glucose, often minimizing the importance of CO_2 and H_2O for that conversion. In many ways, the transitions students make through their formal schooling involve moving from only *informal* (everyday) patterns of reasoning to more *scientific* modes of thinking.

Another indicator of the distinction between informal and scientific reasoning in students' work lies in the common discrepancy between students' use of scientific terminology and the depth of their ability to accurately describe the phenomenon in question. We have termed these two types of performance *Naming* and *Explaining*, respectively (see Paper 2, this set). Although not universal, the vast majority of students develop *Naming* skills at a faster pace than their *Explaining* abilities, at least in terms of carbon-transforming processes. It seems likely that typical science course work, which is often centered around building vocabulary and awareness of details in biological phenomena, rather than focusing on common principles that underlie a range of phenomena, is at least partly responsible for this discrepancy. College biology courses, however, are notorious among students for requiring high levels of detailed memorization (e.g.-steps in citric acid cycle, electron transport chain, etc), and we believe that without concurrently drawing students' attention to the principles at work in these phenomena, especially the conservation of matter and energy, students will not necessarily close the gap between their *Naming* and *Explaining* abilities. This gap in turn will make it more difficult to reason through scientific issues in society as adults, since these issues are not usually presented in the same way as materials from college textbooks. Thus the question remains: are college students, who often begin college at varying stages along the learning progression, able to successfully synthesize all of their earlier learning about carbon with new material presented at college, such that they will be ready to discuss contemporary societal issues in depth?

Procedure

This study was centered on assessments of students from 14 university and college settings enrolled in general biology or ecology courses in community colleges, four-year colleges and research universities. The instructors in these courses were participants in an NSF-funded faculty development program. Most but not all students were science majors, at levels ranging from freshmen to seniors. Written pretests were administered to students, often as diagnostic question clusters (DQCs; Appendix A). Each DQC was structured with a broad introductory question that involved several carbon-transforming processes, followed by 5-7 questions that each focused on a single process. A small subset of the students was given a pretest that involved selected questions from a number of separate DQCs. Following instruction in the relevant material, including one or more active-learning lessons designed to teach students to explicitly trace and conserve matter and energy, students were given written posttests, with some students retaking their original DQC and others being provided with a different one, although parallel in coverage (Table 1). A subset of the students in an introductory biology course completed a posttest concentrating on biofuel-specific questions (Appendix B). Instruction in this course had not focused on biofuels, but did scaffold all topics with the conservation of matter and conservation/degradation of energy across multiple scales, as with students participating in the larger DQC assessments.

Table 1. Sample sizes of students for each written assessment used in this study. Responses to complete diagnostic question clusters were spread over 4 distinct DQCs, while students in the latter categories received questions selected from a larger pool of DQC items.

	Complete DQCs	Selected Items	Biofuel-specific Items
Pre-test	762	70	n/a
Post-test	546	n/a	68

From the student responses, we tabulated how many students chose each distracter for each question that was in a multiple-choice or true/false format. In addition, each student's written explanation to each question (multiple-choice, true/false, and short answer) was scored using a rubric that we developed from an initial subset of 25-30 actual student responses. Initially, the scoring rubric contained 5 codes arranged somewhat hierarchically. The top code was reserved for students who demonstrated an exemplary understanding of conservation of matter and energy, the bottom code was used when the student did not exhibit any understanding of the laws of conservation, and the middle codes were used when the student demonstrated some understanding of the laws of conservation, but had some specific indicators of informal reasoning or a misapplication of the laws of conservation. The middle codes were not hierarchically arranged. We subsequently collapsed the middle codes into a single code used for "mixed" reasoning. Thus in this paper, a score of 4 indicates *scientific* reasoning, a score of 3 indicated *mixed* reasoning, a score of 2 indicates *informal* reasoning and a score of 1 ("*no data*") indicates that the answer was uncodeable.

An additional coder coded every 10th student answer to each question to look for discrepancies in coding. If the discrepancy rate between coders was greater than 10%, we revised the coding rubric to resolve the issue that caused unreliable coding and then recoded all answers for that question. In addition to the written data samples, a small number of students were interviewed in order to better understand their reasoning on carbon-transforming process in general, and biofuels in particular. Two freshman and two seniors biology majors were interviewed using a protocol initially devised for K-12 students, to trace thinking about carbon transformations in general (see Paper 4 in this set). Four additional underclassmen, three science majors and one English major, were also interviewed specifically about biofuels and carbon cycling (see Appendix C). Their responses were transcribed and analyzed for patterns in reasoning.

Analyses and Findings

General Carbon Transformations

Although we found many of the same misconceptions in students' answers as previous research has found, it is also clear that deeper problems with principled reasoning, particularly at atomic-molecular scales, underlay many of the responses. Three important trends were as follows: 1. Students often use energy as a convenient "fudge factor" when they either can't or don't see the necessity of tracing matter and energy. 2. Students who lack a robust understanding of atoms and molecules will not be able to apply principled reasoning to problems. 3. Students reason at the macroscopic scale even when questions are posed at the microscopic or ecosystem scale. These patterns held across all major carbon-transforming processes, including photosynthesis, transformation (biosynthesis) and respiration (incl. decomposition).

Incorrect Energy to Matter Conversions: Answers across multiple questions support the idea that students often use energy as a convenient "fudge factor" when they either can't or don't see the necessity of tracing matter and energy (Table 2). Furthermore, the use of energy as a "fudge factor" appears to be more common when students are asked to reason at the atomic-molecular scale than when students are asked to reason at the organismal scale. Students often chose distracters that indicated that they thought matter could become energy and energy could become matter in a biological context. While it is true that energy and matter often are coupled in organic molecules that move through biological systems, an inability to separately trace matter and energy becomes problematic when it is necessary to reason about the coupling of matter and energy during photosynthesis and the decoupling of matter and energy during oxidation. Many students also chose distracters that included energy disappearing, being "used up" or being "burned up". This indicates that students are using words and ideas from their informal discourse, not realizing that those meanings are not directly translatable to scientific discourse. Faculty need to explicitly address vocabulary when words are common across multiple discourses. Alternatively, the use of words like "burned up" or "used up" also may indicate that a student is drawing boundaries around systems that are inappropriately narrow (e.g. thinking of respiration as affecting only an organism, rather than the organism and the urrounding atmosphere). Once energy (or matter) leaves the boundaries of the system, students no longer feel the need to account for it.

Table 2. - Sample of questions from DQCs that provide evidence that (a) students use energy as a convenient "fudge factor" when they either can't or don't see the necessity of tracing matter, (b) Students who lack a robust understanding of atoms and molecules will not be able to apply the principle of conservation of matter, and (c) Students reason at the macroscopic scale even when questions are posed at the microscopic or ecosystem scale. For each question, the correct answer is in italics and the incorrect answer that is related to conservation of matter and energy is in bold.

Energy as a "fudge factor"	**Difficulties with the atomic-molecular scale of matter**	**Inability to transition reasoning to appropriate scales**
Compost (N = 448) When the leaves in a compost pile decay, they lose mass. What do you think happens to the mass of the leaves? Circle True (T) or False (F). A) T *F* The mass goes away when the leaves decompose. **B)** **T** *F* The mass is converted to heat energy. **54% chose True** C) *T* F The mass is converted into soil minerals. D) *T* F The mass is converted into carbon dioxide and water. Please explain your answers.	**Mass Change (N = 156)** When a plant absorbs CO_2 and releases O_2 during photosynthesis: *A) The process increases the mass of the plant 47%* B) The process decreases the mass of the plant C) The process does not affect the mass of the plant. **47%** Please explain your answer. *Most wrong answers treated molecules of both O_2 and CO_2 as equivalent in terms of mass (i.e.- "one in + one out = no change")*	**Bread Mold (N=652)** A loaf of bread was left uncovered for two weeks. Three different kinds of mold grew on it. Assuming that the bread did not dry out, which of the following is a reasonable prediction of the weight of the bread and mold together? **A)** The mass has increased, because the mold has grown. **22%** **B)** The mass remains the same as the mold converts bread into biomass. **30%** C) The mass decreases as the growing mold converts bread to energy. *D) The mass decreases as the mold converts the bread into biomass and gases. 36%*
Tree Forest (N = 462) The trees in the rain forest contain molecules of chlorophyll a ($C_{55}H_{72}O_5N_4Mg$). Decide whether each of the following statements is true about the atoms in those molecules. Some of the atoms in the chlorophyll came from … A) *T* F carbon dioxide in the air. **B)** **T** *F* sunlight that provided energy for photosynthesis. **65% of students chose true** C) *T* F water in the soil. D) *T* F nutrients in the soil. E) *T* F glucose produced by photosynthesis F) *T* F the seed that the tree grew from.	**Grape Glucose (N = 213)** You eat a grape high in glucose content. How could a glucose molecule from the grape provide energy to move your little finger? A) The glucose is digested into simpler molecules having more energy. 6% B) The glucose reacts to become ATP (adenosine triphosphate)**38%** C) The glucose is converted into energy. 41% *D) The energy of the glucose is transferred to other molecules. 13%* E) The energy of the glucose is	**Deer and Wolves (N=135)** A remote island in Lake Superior is uninhabited by humans. The primary mammal populations are white-tailed deer and wolves. The island is left undisturbed for many years. Select the best answer(s) below for what will happen to the average populations of the animals over time. *a) on average, there will be more deer than wolves. 17%* b) On average, there will be more wolves than deer. c) On average, the populations of each would be about equal. **d)** The populations will fluctuate, with sometimes more deer, sometimes more wolves. **43%** e) None of the above.

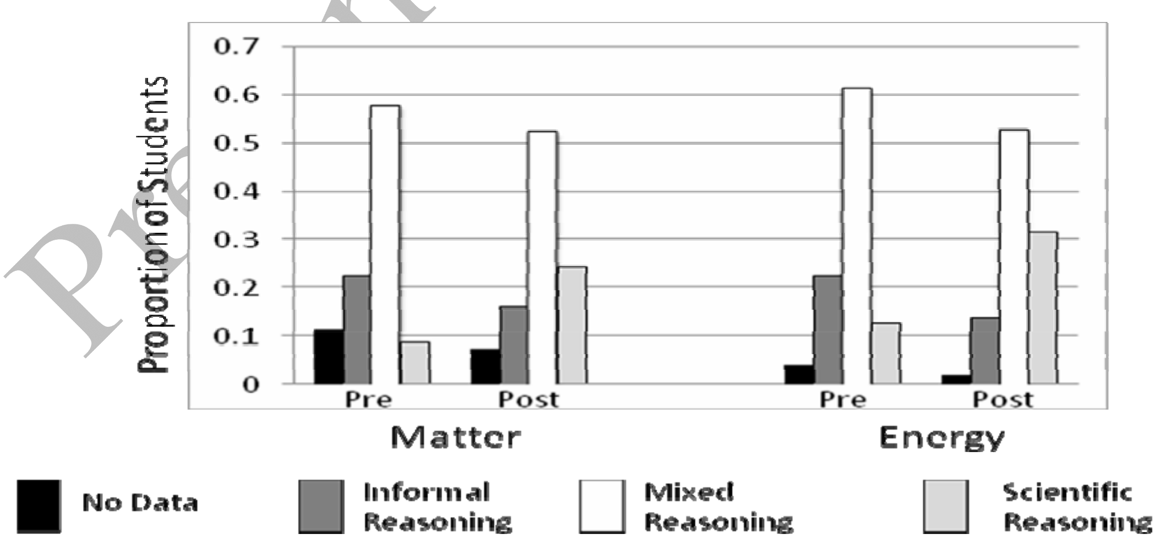
	transferred to CO_2 and H_2O. 3%	
Ecoener1 (N = 483) Which of the following are energy sources for plants? Please circle ALL correct answers. **A) nutrients 68%** *B) sunlight 99%* **C) water 64%** **D) carbon dioxide 59%** **E) others: List sources: 7%**	**Potato Mass (N = 441)** A potato is left outside and gradually decays. One of the main substances in the potato is the starch amylose ($(C_6H_{10}O_5)_n$). What happens to the atoms in amylose molecules as the potato decays? **T** *F* Some of the atoms are converted into nitrogen and phosphorous: soil nutrients. **62% choose True** T *F* Some of the atoms are consumed and used up by decomposers. *T* F Some of the atoms are incorporated into carbon dioxide. **T** *F* Some of the atoms are converted into energy by decomposers. **35% chose True** *T* F Some of the atoms are incorporated into water.	When an animal breathes in O_2 and breathes out CO_2: A) The process increases the mass of the animal. **14%** B) The process decreases the mass of the animal. *21%* C) The process does not affect the mass of the animal. **64%**
Carbon Pathways (N = 557) Once carbon enters a plant, it can … D) be converted to energy for plant growth. Circle **True** or *False* **80% chose True**		

Tracing Atoms and Molecules at Microscopic Scales. Another common trend in our data is that students lack an understanding of atoms and molecules (Table 2). At the extreme, this issue manifests as students viewing objects as homogenous, whole entities rather than as associated particles. The small proportion of students expressing this view would not be able to trace matter across a hierarchy of scales or be able to trace matter as it is converted from one form to another across processes. This extreme mascroscopic view of matter was not common in our sample of college students, most of whom had experience with college chemistry, but it is more common among K-12 students (Mohan et al. 2009). Not quite as extreme are the views that all atoms are equivalent in terms of their mass and that atoms can be converted to other atoms. Also not quite as extreme, but still problematic, is the view that molecules are equivalent in terms of the energy they store. These students may know that matter and energy must be conserved, but may still not be able to properly trace matter and energy because they don't have correct conceptions about the particulate nature of matter. Finally, students have difficulty tracing matter from solids to gases and gases to solids – they see oversimplified gas-gas and solid-solid cycles. Several common misconceptions (e.g. plants get carbon from the soil, most carbon returns to the soil during decomposition, organisms intake food as solids and lose solid mass rather than gas mass during respiration or weight loss) are indicative of students having difficulty tracing matter from solids to gases and gases to solids.

Tracing Matter and Energy at Macroscopic Scales. As educators, we would like students to be able to organize systems hierarchically from the atomic-molecular to the organismal to the ecosystem scale, and to be able to move back and forth among scales within the hierarchy. We posed many questions at the macroscopic scale that required students to make connections to microscopic atoms and molecules. We also posed questions that required students to scale-up microscopic phenomena to large scale processes like the growth of an individual plant or an entire forest. We found that students tended to default to macroscopic explanations, perhaps because macroscopic, observable phenomena are those that students have the most experience with (Table 2). In order to be able to scale up or down from the macroscopic, students need to have an understanding of atoms and molecules and they need to realize that they must apply their knowledge of atoms and molecules in order to reason about larger scale processes.

Unlike younger students, college students often show strong improvement between data pre- and post- instruction (Fig. 1). The proportion of students using only informal reasoning, in particular, dropped for both matter and energy focused items, while the proportion using scientific reasoning increased. Overall, though, the majority of students continued to use some form of mixed reasoning, illustrating the difficulties remaining for even these students to consistently reason about these phenomena robustly. In addition, students finishing their course of study in biology do indeed

Figure 1. Proportions of students responding with various reasoning strategies before and after instruction. We classified each of the 42 DQC items according to the principle it addressed and compared all pre-test responses to all post-test responses in each category. 'No Data' primarily means that a student either skipped the question or answered "I don't know."



demonstrate much more scientific ways of describing phenomena. Contrast the informal answers of freshmen/sophomores with the scientific answers of graduating seniors:

> **Photosynthesis** – *How does a tree change the air around it as it grows?*
> (Informal) "There's like a cycle thing…carbon dioxide is taken in and then…when, like, if trees fall or whatever and it goes into the ground, and then it decomposes and that comes out as carbon dioxide, which takes the tree, which gives off the oxygen, in some kind of big cycle, but I'm not exactly sure of the way of it (FP)."
> (Scientific) "Right at that [leaf/air] boundary you are going to have oxygen being released. Oxygen is kind of a byproduct of photosynthesis, because it takes the carbon dioxide in, uses the carbon, and releases the oxygen. So you are going to have an increase in the concentration of oxygen slightly and a decrease in the concentration of the carbon dioxide, because that goes into the leaf and then is used up (EM)."
>
> **Respiration** -- *Where do we (animals) get energy from?*
> (Informal) RESPONDENT (TG): Our cells; in the mitochondria, like the contraction of the muscles and things. INTERVIEWER: And where do they get that energy if we trace it back a little further? TG: From the food that we eat... mostly protein would be good for that or carbohydrates to burn up while you're doing it... INTERVIEWER: Could you describe a little bit more about what that burning looks like? TG: The little carbohydrates are broken down into molecules and the cells would probably use certain things inside it, in order to make the energy for the muscles to use I guess.
> (Scientific) "We need a carbon source to add to most of our cells and such, and that will come from food. So humans, it could be anything from plants to, say, other animals, to nuts, that sort of stuff. But that will come in the form of different sugars and proteins and fats that can be broken down into the simpler sugars and then distributed throughout the body. But again, you will have the energy transfers into ATP again, getting energy like the last time [earlier discussion of plants respiring], through cellular respiration (EN)."

Even though the level of familiarity with scientific terminology varies widely, even among informal reasoners, they can be characterized by difficulty with the areas discussed above, especially when the item is phrased in a way other than that which students typically experience through textbooks and lectures.

Biofuel-specific Assessments

When asked more directly about global carbon cycling and the potential roles of biofuels in society's energy systems, students often identified the most important points of the debate, but nonetheless revealed a number of misunderstandings at the same time. The majority of students were able to articulate the ways in which fossil fuel combustion is affecting global carbon cycling (i.e.- releasing carbon from sequestered pools into biologically-active circulation), but only a small minority were successful at describing how biofuels were different than fossil fuels (example responses: "biofuels emit the same toxic gases but in far less quantity so there won't be as much in the atmosphere," "biofuels are better on the environment due to less carbon dioxide being emitted into the atmosphere. Therefore this is better for the ozone," "Biofuels would slow the rate of global climate change because there is much less waste from biofuels than fossil fuels which are doing damage to the ozone layer."). About half of the students identified timescale of sequestration as being the key difference between bio- and fossil fuels, while the other half described the difference less precisely or incorrectly. Nearly a quarter (22%) focused on the fact that biofuels were from "organic," aboveground sources and thus were harmless to the environment, or didn't emit CO_2. One interview respondent actually grew more confused after reading a pamphlet designed to improve readers' understanding of cellulosic ethanol production:

> "The fermentation of glucose to ethanol actually produces carbon dioxide... my understanding was that the intention of making ethanol and things like that was to avoid carbon dioxide production... My only assumption from that would be that fossil fuels obviously give off more carbon dioxide then just one per consumption, but maybe [biofuels] aren't as green as they seem (WJR, college sophomore)."

A complete explanation of the differences between fossil and biofuels requires discussion of multiple processes at multiple spatio-temporal scales, which likely largely contributes to students' difficulties with that explanation. Even more straightforward questions about related issues, however, often revealed problematic thinking. When asked to discuss the cause of the greenhouse effect, students struggled to a surprising degree given the massive amounts of media and scientific coverage devoted to the topic. A substantial minority of students identified stratospheric ozone depletion as the culprit behind global warming, rather than greenhouse gas accumulation (Thirty percent of students attributed global warming to "more particulate pollution (smog) in the atmosphere" or "deterioration of the ozone layer"). These students then tended to focus on differences in the levels of pollutants (i.e.- NO_X and SO_X) produced by fossil and biofuels, rather than their effects on the rate of contemporary carbon cycling.

Discussion

This study connects and contributes to several important areas of research in science education. First, it adds to the discussions on learning progressions by carrying work on carbon transformations in K-12 students into the college level. In so doing, the relative similarity of college freshman to high school students becomes apparent and quantifiable. At the same time, data from the limited number of interviews with graduating biology majors shows that a significantly more robust understanding is possible for students only a few years later. Clearly a great deal of synthesizing of earlier material can occur as students move through college, and that process can only be made more efficient if learning at earlier levels more directly supports the underlying framework for that synthesis. Based on the improvements seen in the DQC portion of this project, we believe that one of the most effective ways to facilitate this transition is to consistently scaffold course material around the major principles in biology: conservation of matter and energy across scales (as well as the continuity of genetic information in other topic areas). Teaching activities that force students to develop metacognition about these principles will greatly enhance their understanding and retention of the details typical concentrated on in college biology.

Second, the results point to the inherent difficulty of applying knowledge across multiple scales of space or time, particularly when those scales are dramatically different from the everyday human experiences of the "here" and "now." In addition to gaining knowledge about how biological systems work, students must become comfortable using practices and language that moves fluidly to connect concepts across disparate scales. This manner of thinking about otherwise familiar processes requires a great deal of practice to gain proficiency, as with so many other types of scientific reasoning skills (see Papers 1 & 3 of this set). Yet it is frequently understated in discussions of science pedagogy improvements. In addition, the very difficulty of these large-scale phenomena and disconnect from everyday experiences tends to make any discussion of them in the media or in public forums quite simplified.

This simplification is especially likely and problematic when the biology has a bearing on contested issues in contemporary politics, as is the case with the science behind biofuel sustainability. These results add to the slim literature pertaining to public understanding of this science. Since application of energy solutions will require collaborations between politicians, businesspeople and public interest groups, not just scientists, it is crucial that students from a variety of majors have a working understanding of the science involved. Yet from the struggles of the predominantly science major students involved in this study, it seems our colleges and universities have a ways to go before a majority of graduates are prepared to properly incorporate scientific reasoning into their decisions on this and related issues as citizens.

References

Covitt, B. A., Tan, E., Tsurusaki, B. K., & Anderson, C. W. (2009). Students' use of scientific knowledge and practices when making decisions in citizens' roles. Paper presented at the Annual Conference of the National Association for Research in Science Teaching, Garden Grove, April 17-21, 2009

Ebert-May, D., J. Batzli and H. Lim (2003). Disciplinary research strategies for assessment of learning. *Bioscience* **53**(12): 1221-1228.

Mohan, L., Chen, J., & Anderson, C. (2009). Developing a multi-year learning progression for carbon cycling in socio-ecological systems. Journal of Research in Science Teaching. 46(6): 675-698.

Wilson, C.D., Anderson, C.W., Heidemann, M., Merrill, J.E., Merritt, B.W., Richmond, G. Sibley, D.F., & Parker, J.M. (2006) Assessing students' ability to trace matter in dynamic systems in cell biology. *CBE Life Science Education* 5: 323-331.

Appendix A

All of the questions used in the four primary DQCs. Note that some questions appear in more than one DQC, thus leading to variable sample sizes of students answering each question.

Grandma Johnson DQC

1. Grandma Johnson had very sentimental feelings toward Johnson Canyon, Utah, where she and her late husband had honeymooned long ago. Because of these feelings, when she died she requested to be buried under a creosote bush in the canyon. Describe below the path of a carbon atom from Grandma Johnson's remains, to inside the leg muscle of a coyote. Be as detailed as you can be about the various molecular forms that the carbon atom might be in as it travels from Grandma Johnson to the coyote. **NOTE:** The coyote does not dig up and consume any part of Grandma Johnson's remains. *Thank you to Diane Ebert-May, Janet Batzli and* Bioscience *for permission to reprint this item.*

2. A loaf of bread was left uncovered for two weeks. Three different kinds of mold grew on it. Assuming that the bread did not dry out, which of the following is a reasonable prediction of the weight of the bread and mold together?

A) The mass has increased, because the mold has grown.
B) The mass remains the same as the mold converts bread into biomass.
C) The mass decreases as the growing mold converts bread into energy.
D) The mass decreases as the mold converts bread into biomass and gases.

Please explain your answer.

3. A mature maple tree can have a mass of 1 ton or more (dry biomass, after removing the water), yet it starts from a seed that weighs less than 1 gram. Which of the following processes contributes the most to this huge increase in biomass? Circle the correct answer.

A) absorption of mineral substances from the soil via the roots
B) absorption of organic substances from the soil via the roots
C) incorporation of CO_2 gas from the atmosphere into molecules by green leaves
D) incorporation of H_2O from the soil into molecules by green leaves
E) absorption of solar radiation into the leaf

4. Once carbon enters a plant, it can …

A) exit the plant as CO_2. Circle True or False
Explain
B) become part of the plant cell walls, protein, fat, and DNA. Circle True or False
Explain
C) be consumed by an insect feeding on the plant and become part of the insect's body. Circle True or False
Explain
D) be converted to energy for plant growth. Circle True or False
Explain
E) become part of soil organic matter when parts of the plants die and fall off the plant. Circle True or False
Explain

5. Coyotes are carnivores. Their bodies include many substances, including proteins in all their cells. What percent of the carbon atoms in a coyote's body were once in the following substances and locations? Fill in the blanks with the appropriate percentages; you may use 0% in your response if you feel it is appropriate. The percentages will add up more than to 100% if you think that the same carbon atoms could have gone through two or more of these places on their way to the coyote.
____% from CO_2 that was used by plants for photosynthesis
____% from animals that the coyote ate
____% from CO_2 that the coyotes inhaled
____% from inhaling O_2
____% from drinking water
____% from soil nutrients that plants absorbed while growing
Please explain your answer.

6. A potato is left outside and gradually decays. One of the main substances in the potato is the starch amylose ($(C_6H_{10}O_5)_n$). What happens to the atoms in amylose molecules as the potato decays? Choose True (T) or False (F) for each option.
T F Some of the atoms are converted into nitrogen and phosphorous: soil nutrients.
T F Some of the atoms are consumed and used up by decomposers.
T F Some of the atoms are incorporated into carbon dioxide.
T F Some of the atoms are converted into energy by decomposers.
T F Some of the atoms are incorporated into water.

Forest Carbon Balance DQC

1. Explain your ideas about how plants, animals, and soil in a forest interact with carbon dioxide.

Plants	Animals	Soil	Which parts **absorb carbon dioxide from the atmosphere?** (Circle all correct)
Plants	Animals	Soil	Which parts **release carbon dioxide into the atmosphere?** (Circle all correct)
Plants	Animals	Soil	Which parts **store carbon?** (Circle all correct)

Please explain your answers. What are the roles of plants, animals, and soil with respect to carbon dioxide in a forest?

2. In plants, …
A) photosynthesis occurs but there is no respiration.
B) photosynthesis occurs in the light and respiration occurs in the dark.
C) respiration occurs 24 hours a day and photosynthesis occurs in the light.
D) photosynthesis and respiration occur but not at the same time.
E) Responses B and C are correct.

3. Considering the cellular processes of photosynthesis and respiration, which statements are true? Circle True (T) or False (F) for each response.
T F Photosynthesis is the process by which plants respire.
T F Both animals and plants respire and release CO_2.
T F During respiration, animals release CO_2 and plants release O_2.
T F During respiration, animals release O_2 and plants release CO_2.

4. Circle all correct answers. In most terrestrial ecosystems, soil respiration ...

A) happens when rocks break down.
B) is not linked to decomposition rates.
C) typically decreases as soil moisture increases.
D) refers to respiration by organisms living in the soil.
E) typically decreases as temperatures increase.
F) includes gases from plant roots.

5. Once carbon enters a plant, it can …

A) exit the plant as CO_2. Circle True or False
Explain
B) become part of the plant cell walls, protein, fat, and DNA. Circle True or False
Explain
C) be consumed by an insect feeding on the plant and become part of the insect's body. Circle True or False
Explain
D) be converted to energy for plant growth. Circle True or False
Explain
E) become part of soil organic matter when parts of the plants die and fall off the plant. Circle True or False
Explain

6. How do each of the processes below affect the mass of the systems where they are occurring?
6a. When a plant absorbs CO_2 and releases O_2 during photosynthesis:

A) The process increases the mass of the plant
B) The process decreases the mass of the plant
C) The process does not affect the mass of the plant.

Please explain your answer.
6b. When an animal breathes in O_2 and breathes out CO_2:

A) The process increases the mass of the animal
B) The process decreases the mass of the animal
C) The process does not affect the mass of the animal.

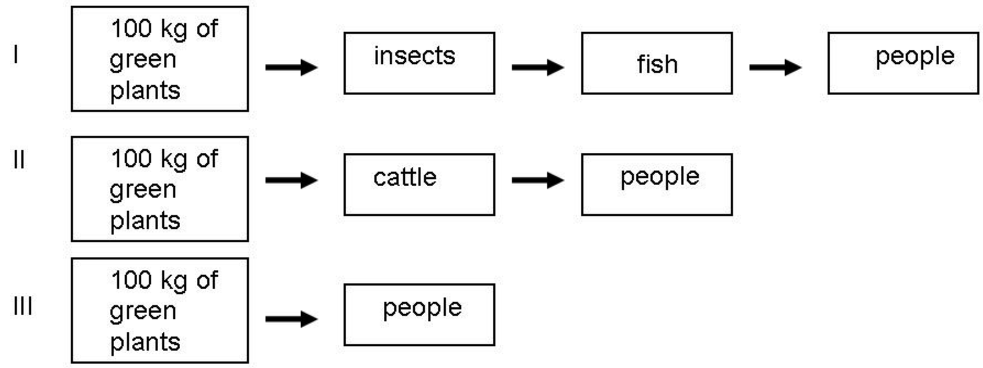
Please explain your answer.
6c. When leaves in the soil decay:

A) The process increases the mass of the soil
B) The process decreases the mass of the soil
C) The process does not affect the mass of the soil.

Please explain your answer.

Energy Pyramid DQC

1. Consider the three diagrams below. They represent three situations in which 100 kg of green plants serve as the original source of food for each of the food chains. In situation II, for example, cattle eat 100 kg of green plants and then people eat the beef that is produced by the cattle as a result of having eaten the plants.



In which of the three situations is the most energy available to people?

A) I
B) II
C) III
D) Situations I and II will roughly tie for the most energy.
E) The same amount of energy will be available to people in all three situations.

Please explain your answer.

2. A remote island in Lake Superior is uninhabited by humans. The primary mammal populations are white-tailed deer and wolves. The island is left undisturbed for many years. Select the best answer(s) below for what will happen to the average populations of the animals over time.

_____a. On average, there will be more deer than wolves.
_____b. On average, there will more wolves than deer
_____c. On average, the populations of each would be about equal.
_____d. The populations will fluctuate, with sometimes more deer, sometimes more wolves
_____e. None of the above.

Please explain your answer to what happens to the populations of deer and wolves.

3. Does a living tree have energy? Yes / No
Does a dead tree have energy? Yes / No
Please explain your answers.

4. You eat a grape high in glucose content. How could a glucose molecule from the grape provide energy to move your little finger?

A) The glucose is digested into simpler molecules having more energy.
B) The glucose reacts to become ATP (Adenosine Triphosphate).
C) The glucose is converted into energy.
D) The energy of the glucose is transferred to other molecules.
E) The energy of the glucose is transferred to CO_2.and H_2O.

5. The top of a food web:

A) accumulates all of the energy that existed in the consumed organisms that were lower in the food web.
B) has less available energy than trophic levels below it.
C) has the same amount of accumulated energy as each of the trophic levels below it.
D) has available to it all of the energy of the food web.

Please explain your answer.

6. A loaf of bread was left uncovered for two weeks. Three different kinds of mold grew on it. Assuming that the bread did not dry out, which of the following is a reasonable prediction of the weight of the bread and mold together?

A) The mass has increased, because the mold has grown.

B) The mass remains the same as the mold converts bread into biomass.

C) The mass decreases as the growing mold converts bread into energy.

D) The mass decreases as the mold converts bread into biomass and gases.

Please explain your answer.

7. Each Spring, farmers plant about 5-10 kg of seed corn per acre for commercial corn production. By the fall, this same acre of corn will yield approximately 4-5 metric tons (4,000 – 5,000 kg) of dry, harvested corn. What percent of the dry biomass of the harvested corn was once in the following substances and locations? Fill in the blanks with the appropriate percentages; you may use 0% in your response if you feel it is appropriate.

___ % from absorption of mineral substances from the soil via the roots

___ % from absorption of organic substances from the soil via the roots

___ % from incorporation of CO_2 gas from the atmosphere into molecules by green leaves

___ % from incorporation of H_2O from the soil into molecules by green leaves

___ % from absorption of solar radiation into the leaf

Please explain your answer.

Rainforest DQC

1. A tropical rainforest is an example of an ecosystem. Which of the following statements about matter and energy in a tropical rainforest is the most accurate? Please choose ONE answer that you think is best.

A) Energy is recycled, but matter is not recycled.

B) Matter is recycled, but energy is not recycled.

C) Both matter and energy are recycled.

D) Neither matter nor energy are recycled.

Please explain why you think that the answer you chose is better than the others.

2a. Which of the following are energy sources for plants? Please circle ALL correct answers.

A) nutrients

F) sunlight

G) water

H) carbon dioxide

I) others: List sources:

2b. Owls are nocturnal, meaning that they search for food at night. Therefore, could owls live without sunlight? Circle Yes or No.

Why or why not?

3. Sunlight helps plants to grow. Where does light energy go when it is used by plants? Please decide whether you think each statement is true or false.

T F Some light energy is converted into glucose of the plants.

T F Some light energy is converted into ATP in the plants.

T F Some light energy is used up to power the process of photosynthesis.

T F Some light energy becomes chemical bond energy.

4a. Of the energy gained by a plant (i.e. producer), what percentage is typically transferred to a rabbit that eats the plant?

A) 90-100%
B) 60-70%
C) 30-40%
D) 10-20%

4b. If you chose B, C or D, what happens to the energy that does not get transferred between the plant and rabbit?

5. A loaf of bread was left uncovered for two weeks. Three different kinds of mold grew on it. Assuming that the bread did not dry out, which of the following is a reasonable prediction of the weight of the bread and mold together?

A) The mass has increased, because the mold has grown.
B) The mass remains the same as the mold converts bread into biomass.
C) The mass decreases as the growing mold converts bread into energy.
D) The mass decreases as the mold converts bread into biomass and gases.

Please explain your answer.

6. The trees in the rain forest contain molecules of chlorophyll a ($C_{55}H_{72}O_5N_4Mg$). Decide whether each of the following statements is true about the atoms in those molecules. Circle True (T) or False (F).
Some of the atoms in the chlorophyll came from …

T F carbon dioxide in the air.
T F sunlight that provided energy for photosynthesis.
T F water in the soil.
T F nutrients in the soil.
T F glucose produced by photosynthesis
T F the seed that the tree grew from.

7. When the leaves in a compost pile decay, they lose mass. What do you think happens to the mass of the leaves? Circle True (T) or False (F).

T F The mass goes away when the leaves decompose.
T F The mass is converted to heat energy.
T F The mass is converted into soil minerals.
T F The mass is converted into carbon dioxide and water.

Please explain your answers.

Appendix B: Biofuel Assessment Items

Full text of questions given to students in an introductory biology class, at the end of the course. Instruction had not focused on biofuels in particular, but had been geared around relevant principles (conservation of matter, conservation and degradation of energy; across multiple scales).

1a. Microbiologists have discovered several microorganisms that are able to decompose gasoline. What happens to the carbon atoms in the gasoline during decomposition?
1b. Do the carbon atoms following decomposition by microorganisms end up in a different location than if the gasoline was burned in a car? Please explain.

2. Coal, oil, and natural gas are called fossil fuels. What were they before they became fossil fuels?

3. Climate data indicates that the average temperature of the earth's atmosphere has been increasing during the past 100 years. What is the major cause of this?

A) More heat is released from vehicles and factories into the atmosphere.
B) More particulate pollution (smog) is in the atmosphere.
C) More carbon dioxide is in the atmosphere.
D) Deterioration of the ozone layer.
E) None of these causes global warming.

4a. On average, how long do you think a molecule of carbon dioxide remains in the atmosphere after being released by a human being?
4b. After a period of time, the carbon atom released by a human being will leave the atmosphere. Where might the carbon atom go when it leaves the atmosphere?

5. What are biofuels? How are they different from fossil fuels?

6. Explain why the use of biofuels instead of fossil fuels is a strategy to slow the rate of global climate change. Use as much detail in your answer as you can.

Appendix C: Biofuels Interview Protocol

The following clinical interview protocol is designed to probe adults' understanding of both the broader carbon cycling dynamics at work in energy production and consumption, as well as the specific hurdles to industrial cellulosic ethanol production (as per GLBRC). Although each interview will begin with similar questions, and try to include several landmark questions at some point, the specifics of each interview can and should change in response to answers from the interviewee. Throughout, questions in parentheses are somewhat tangential, and may only be useful if earlier responses indicate the interviewee may have something to say on that topic.

***Phase I*: Global Carbon Cycling**

Begin by asking the interviewee general questions about the carbon cycle diagram (below).

[Diagram is standard textbook carbon cycle, with reservoirs and fluxes shown]

For instance: *What does this cycle depict?*

How do you know that?

What is the significance of the red arrows on the diagram?

Then move into some more specific probes about the content and processes:

Does the amount of carbon in the atmosphere appear to be steady or not?

What biological process is represented by the arrow labeled 121.3?

(Do you know anything about the processes that carry carbon between the ocean and atmosphere?)

Why is some carbon moving from both soils and vegetation to the atmosphere?

What process is responsible for the arrow labeled 5.5?

After concluding the discussion of the carbon cycle diagram, transition to a more explicit discussion of biofuels. Begin with a few general questions, such as:

Do you know about any types of biofuels?

If so, where and what have you heard about them?

Do you know if any biofuels are already in widespread or commercial use?

(Referring back to carbon cycle) Can you explain why liquid biofuels would be a fundamentally different approach to energy than liquid fossil fuels?

Then show the interviewee the following diagram, adapted from the GLBRC pamphlet, "Why is it so difficult to make cellulosic ethanol?"

[Diagram shows steps necessary for converting glucose, starch and bulk plant material to ethanol, illustrating increasing complexity with more complex plant materials.]

Explain that ethanol is one potential biofuel under consideration, and that in order to make it, some form of sugar is needed as a raw material.

Do you know the process that sugar/glucose undergoes to become ethanol?

What sorts of organisms can carry out this process?

Then make the leap to the more complex macromolecules:

Why are there more steps involved in converting starch and cellulose to ethanol?

Which of these intermediate steps would you anticipate being the most difficult or expensive for us to engineer a solution to?

(Are major investments of energy likely to be needed at any of these steps?)

Then provide a copy of the entire "Cellulosic Ethanol" handout and allow the interviewee time to read through it.

Does this change your understanding of the ethanol chart in any way?

What, if anything, surprised you about the route researchers are taking to address these problems?

What was the most interesting part of the article for you?

Do you have any questions prompted by the material we've just discussed?

Why are researchers studying the waste piles of leaf cutter ants for resources?

The interview to this point will probably have taken about 25 min. to this point. If you have more time with an interviewee, or they are particularly interested, you could venture into one or more of these related topics.

1. Discussion of sustainability, along the lines of the ESA Position Statement on Biofuels, which you could have the interviewee read. In either case, pursue questions along these lines:

Which issue do you think would pose the most problems for society if biofuel production was implemented on a massive scale?

Why is the use of annual vs. perennial crop species important to the global carbon balance?

Are there any ways to avoid or minimize the trade-off between food and fuel?

2. Further discussion of the global feasibility and potential role of biofuels. Diagrams such as the one below may be an interesting prompt.

[Diagram depicts the % of earth's net primary productivity at each point on the earth's surface that is used annually for human purposes.]

What would you interpret this figure to show (before you provide a description)?

Why are areas such as the Amazon basin and boreal forests dark blue?

Judging just from this figure, which areas have the most potential for widespread biofuel crop development? Should we be concerned about that for any reason?