

Disciplinary Research Strategies for Assessment of Learning

DIANE EBERT-MAY, JANET BATZLI, AND HEEJUN LIM

Science faculty who want to improve instructional strategies need to design appropriate methods for assessing and analyzing classroom data to determine the effectiveness of their approaches to learning. We used systematic strategies derived from methods of discipline-based science research to design problems to assess students' understanding of the carbon cycle in two introductory biology courses for science majors. Among typical misconceptions are the ideas that gaseous carbon dioxide is not respired during decomposition by organisms in the soil and that plants acquire carbon from the soil rather than from the air through leaves during photosynthesis. Diagnostic problems provided data on students' understanding and misconceptions. In-class instruction, problems, and laboratories were designed to focus on student misconceptions and provided formative assessment. After two semesters, results indicated that the majority of students responded accurately; however, 20 to 40 percent of the students maintained misconceptions even after instruction. Assessment strategies enabled us to collect, analyze, and report data that will influence future instruction.

Keywords: assessment, introductory biology, carbon cycle, active learning, misconceptions

How important is it to use data to assess student learning?" During the past year, we asked this question of approximately 100 faculty members from colleges and universities across the country, and the overwhelming majority (90 percent) responded that it was important. Yet, when the same faculty were asked, "How often do you use data to make instructional decisions?" less than 50 percent indicated they did so regularly.

Although most faculty believe it is important to assess student learning, especially when they implement new curricula and active-learning instructional approaches, it is difficult to design methods of assessment and analyses of data that test the efficacy of these approaches and that are convincing to our peers. We used systematic strategies derived from the methods of discipline-based science research to design questions and problems to determine student understanding of the carbon cycle. A research-based process moves us beyond grading. Grading is a measure of students' success in answering questions correctly—that is, *what* students know or do not know; research-based analyses help explain *why* students do or do not know. Although most scientists know the value of multiple kinds of assessment data for diagnosing student learning, few think about the process of assessment in relation to the process of research. We claim that assessing student learning in science parallels what scientists do as researchers, and such assessment can be fully integrated into the professional culture along with discipline-based research.

Over a decade ago, the American Association for the Advancement of Science (AAAS 1990) advocated that scientists treat science as a liberal art and teach science with the same rigor as science is practiced. Current reports echo the call (Annenberg/CPB 1997, NRC 1997, 1999, Bransford et al. 1999, Pellegrino et al. 2001, Cech 2003). To answer the call, scientists can draw upon what they know and do best by approaching their practice of teaching the same way they approach their practice of science. Assessment—data collection with the purpose of answering questions—is critical to both processes.

The majority of individuals completing their graduate scientific degrees and postdoctoral programs at research universities have limited preparation and experience in teaching, and even less experience in assessment of student learning. Although graduate education is often judged and guided by excellence at preparing individuals to design and carry out disciplinary research, it inadequately and haphazardly prepares them to take on the increasingly complex demands of the professoriate, especially the role of educator. Newly minted PhDs

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learn to teach science and improve educational practices serendipitously, generally without the consistent mentoring, peer review, or access to accumulated knowledge that builds over a sustained program of professional development in the sciences. During their first few years of college teaching, faculty often assume a survival mode (Uno 2002) and do not have the expertise or time to deal with meaningful assessment in their courses. The parallel pathways of assessment in teaching and assessment in scientific research provide a familiar model for scientists to fully integrate both into their professional discipline.

Parallel pathways of assessment

Scientists ask questions, develop hypotheses, and solve problems. To do so, they collect data. The data collected are guided by questions or hypotheses about problems. The questions asked, based on current knowledge and theories in the field, are creative, original, and relevant to the investigator. The research designs and methods used to collect data are appropriate to answer the questions. The instruments, field techniques, and procedures used are calibrated and validated by others in the discipline through peer review. Results are explained in the context of the hypotheses and are used to make predictions about future problems or to frame the next logical question. Ensuing steps are selected on the basis of interpretation of evidence and are often the result of “why” questions looking for causal explanations. The peer-review process validates the merit of the research and serves to disseminate the knowledge and products of the work, which can lead to other research questions worthy of future funding consideration.

Assessment of student learning follows a parallel pathway. We ask questions and develop hypotheses to solve problems about learning. To do so, we collect various types of data for the purpose of understanding what our students know and can explain about the concepts we expect them to learn and understand. The questions we ask students are based on intended learning outcomes and are substantive rather than trivial. The assessment techniques we use, both quantitative and qualitative (i.e., objective questions, extended responses, problems, projects, laboratory investigations, and interviews), need to be valid measures of learning. Assessment helps us understand students’ thinking about the content and concepts of our discipline. We use data from assessments to guide our decisions about a course and to determine how effective instructional innovations are in terms of students’ understanding. Furthermore, the data provide an empirical basis to make better predictions about what students do not understand. Our ideas about assessment in the context of curriculum development and innovative instructional design are peer reviewed—informally by our peers, internally by curriculum committees, externally by funding agencies—and our findings should be peer reviewed for publication as well. This study is an example of the assessment process we used that parallels the process of research.

Theoretical background of assessment

Conceptual change theory provides a robust basis to frame our questions about assessment of student learning (Wandersee et al. 1994). Learning is the result of the interaction between what students are taught and what their current ideas or concepts are (Posner et al. 1982). Students’ concepts will develop and change with instruction if they are actively engaged in the learning process (Cech 1999, Stokstad 2001). To apply theory to practice, we must find out what students know and believe and account for this in our instruction (Fosnot 1996, Novak 1998, Svinicki 1999, Ausubel 2000, Novak et al. 2000). If we do not deal directly with students’ existing knowledge and alternative conceptions, they are forced to cope with the subject matter by rote memorization of isolated fragments and execution of meaningless tasks in laboratories (Hestenes et al. 1992).

Development of the current study

Using this theoretical framework, we explored how assessment questions helped us determine students’ prior understanding and progressive thinking about the carbon cycle over time. We chose the carbon cycle because it is a rich ecological topic that lends itself to different kinds of assessment problems, and it integrates many biological concepts at multiple scales (molecules to ecosystems). Elements intrinsic to the carbon cycle—bioenergetics and metabolism, for example, which have many real-world applications—can be addressed from various perspectives over two semesters of introductory biology. In addition, we know students have misconceptions about concepts in the carbon cycle (namely, respiration, photosynthesis, and decomposition). For example, many students believe that matter disappears during its decomposition by organisms in the soil, revealing their notions about transformation and conservation of matter and energy. Many students also believe that photosynthesis is simply a mechanism that provides energy for the uptake of all nutrients and carbon through plant roots, thus building biomass, and that no biomass is built through photosynthesis alone (Anderson et al. 1990, Songer and Mintzes 1994, Annenberg/CPB 1997).

We developed a process and method of data analysis to help us address the misconceptions that undergraduate students exhibit in their explanations of the carbon cycle, photosynthesis, cellular respiration, and decomposition. We designed a set of analogous assessments to gather data that track changes over time in students’ understanding of the ideas and concepts embedded in the carbon cycle, including the processes and organisms involved in the transformation of carbon from inorganic to organic matter and back again.

Methods

Students involved in this study completed two semesters of introductory biology for science majors and were categorized into three cohorts, *Bio 1*, *Bio1/Bio2*, and *Other/Bio2*. One hundred forty-one students enrolled in *Bio 1* (Organismal Biology, which included the study of ecology, evolution, and genetics). Upon completion of this course, 63 of these students

enrolled in Bio 2, the second course of this sequence (Cell and Molecular Biology), resulting in the Bio1/Bio2 cohort ($n = 63$). The third cohort (Other/Bio2, $n = 40$) was composed of students who took one of several other introductory biology courses that fulfilled the Bio 1 requirement (e.g., a general biology majors course, a community college course, or an advanced placement credit) but did not take Bio 1. These students then took Bio 2 as the second course.

The instructional design for Bio 1 consisted of two large class meetings per week (50 minutes each), during which groups of students had opportunities to analyze problems about the carbon cycle; small discussion sections (one per week for 50 minutes), during which groups continued to work with concepts; and 10 homework problems, one of which was an online module about the carbon cycle and another was a reading and written assignment about source, sink, and carbon flux in the biosphere. Finally, students were involved in multiweek, inquiry-based laboratory sessions (3 hours per week) using Wisconsin Fast Plants™ (*Brassica rapa*), which included measurement and discussion of net primary production.

Although Bio 2 followed Bio 1, its curriculum and laboratories were not connected with Bio 1. The instructional design in Bio 2 included two large, 50-minute class meetings per week. The course provided students opportunities to work collaboratively, complete online homework about photosynthesis and respiration at the cellular level, participate in small discussion sections (50 minutes per week), and work in an open-ended, research-based laboratory, during which students conducted independent experiments on carbohydrate metabolism and photosynthesis. Assessments included a pretest and a midterm and final exams (box 1), with additional formative assessment questions asked during class.

The large class meetings in Bio 1 and Bio 2 were taught by different instructors. The laboratories and discussion sections in each course were taught by 8 to 10 undergraduate teaching assistants and one graduate student. No data were collected regarding the instructors, pedagogy, and course design for the “Other/Bio2” organismal biology courses. All of the instructors in this study varied and could not be experimentally manipulated as part of the design. Rather, the diagnostic problems that were integrated into the curriculum were the independent variables, and student learning (assessed by students’ responses to the questions and problems) was the dependent variable.

After an initial pretest was administered in Bio 1, instruction about the carbon cycle was carried out during the next two class meetings. In the first class meeting, the content focused on the carbon cycle from macrolevels (ecosystems, energy, and matter) through microlevels (organic and inorganic material and processes involved in the cycle). During the second class meeting, students were given the “radish” problem to solve in groups (figure 1).

The purpose of the radish problem was to assess students’ current understanding of photosynthesis and cellular respiration, particularly their notions that transformation of matter allows for conservation of mass. As a formative assessment, it provided immediate feedback about the students who did not account for cellular respiration to explain the loss of mass of seedlings grown with water in the dark (e.g., many students predicted a slight gain in mass for this treatment). After students worked with the radish problem, instruction on biogeochemical cycles, energy, and matter continued throughout the remainder of the second class meeting.

Following instruction, we administered the “minke whale” problem to assess students’ understanding during the mid-

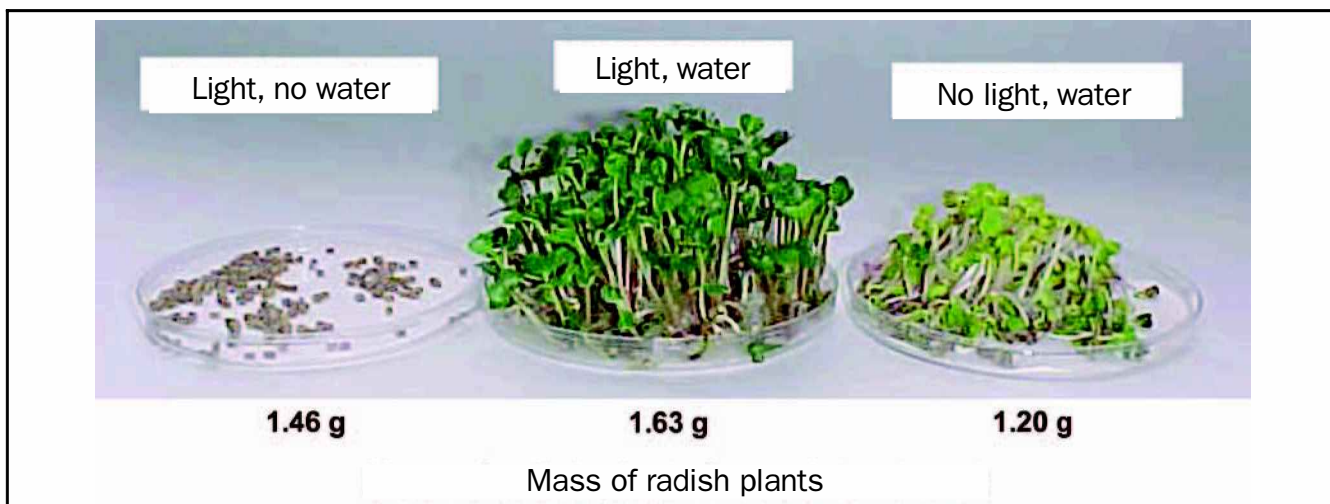


Figure 1. Radish problem that was presented in class: “In the laboratory, three equal batches of radish seeds are weighed at 1.5 grams (g) each. Two batches are watered and allowed to germinate (radish seeds germinate rapidly). One of these batches is put in the light and the other in the dark. The third batch is not watered and is left in the light. The dry biomass for each batch is measured after 10 days. Predict the biomass of the plants in each treatment after 10 days.” In groups, students discussed the problem and made predictions. The instructor recorded predictions from a sample of randomly selected groups. Then the results of the experiment were shown to the class, and each student wrote an explanation.

Box 1. Course problems and coding rubric

The sequence of assessment problems and the coding for the Bio 1 and Bio 2 courses are represented in the rubric below. The same rubric was used to code students' extended responses to the minke whale, Grandma Johnson, and spider monkey problems. Coding of the written responses took account of students' mention of organisms in the carbon cycle and the processes and pathways applicable for each organism. Coding was used to count the frequencies of responses for each problem; it was not used for grading.

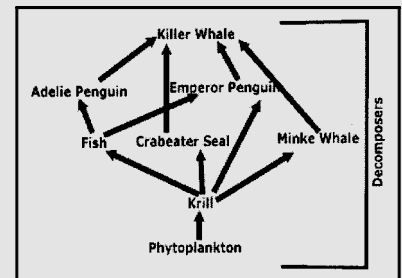
Source of biomass in plants: Pretest (Bio 1)

The majority of actual weight (dry biomass) gained by plants as they progress from seed to adult plant comes from which of the following substances?

- a. Particle substances in soil that are taken up by plant roots.
- b. Molecules in the air that enter through holes in the plant leaves. [correct choice]
- c. Substances dissolved in water taken up directly by plant roots.
- d. Energy from the sun.

Minke whale problem: Midterm exam (Bio 1)

Two fundamental concepts in ecology are "energy flows" and "matter cycles." In an Antarctic ecosystem with the food web shown here, how could a carbon atom in the blubber of the minke whale become part of a crabeater seal? Note: Crabeater seals do not eat minke whales. In your response, include a drawing with arrows showing the movement of the carbon atom. In addition to your drawing, provide a written description of the steps the carbon atom must take through each component of the ecosystem. Describe which biological processes are involved in the carbon cycle.



Grandma Johnson problem: Final exam (Bio 1)

Hypothetical scenario: Grandma Johnson had very sentimental feelings toward Johnson Canyon, Utah, where she and her late husband had honeymooned long ago. Her feelings toward this spot were such that upon her death she requested to be buried under a creosote bush overlooking the canyon. Trace the path of a carbon atom from Grandma Johnson's remains to where it could become part of a coyote. Note: the coyote will not dig up Grandma and consume any of her remains. In your response include a drawing with arrows showing the movement of the carbon atom through various forms within the ecosystem. In addition to your drawing, provide a written description of the steps AND types of matter the carbon atom must go through to cycle through the ecosystem.

Spider monkey problem: Final exam (Bio 2)

Deep within a remote forest of Guatemala, the remains of a spider monkey were buried under an enormous mahogany tree. Although rare, jaguars have been spotted in this forest by local farmers. Use coherently written sentences and clearly labeled drawings to explain how a carbon atom in glucose contained within a muscle cell of the spider monkey might become part of a cell within the stomach lining of a jaguar. Note: the jaguar does not dig up the monkey and eat the remains. Include in your answer descriptions of the key features (although not complete biochemical pathways) of the organismal and cellular processes that explain how the carbon atom of the monkey's corpse could become a part of the jaguar's body.

Rubric			
Code	Organism	Code	Processes and pathways
1	Decomposers	IA	Cellular respiration
		IB	Release of CO ₂
2	Primary producers	IIA	Pathway of carbon IIA 1: through air IIA 2: through root IIA 3: no mention about pathway
		IIB	Make glucose
		IIC	Photosynthesis
3	Herbivores	III	Respiration (glycolysis, Krebs cycle)
4	Carnivores	IV	Respiration (glycolysis, Krebs cycle)

semester exam in Bio 1 (box 1). An analogous problem (“Grandma Johnson”) was repeated on the final exam for Bio 1 students. Both were extended response problems and were equivalent in design (box 1). During Bio 2, an in-depth exploration of photosynthesis and respiration at the cellular level was carried out, which included an independent laboratory investigation on carbohydrate metabolism. On the final exam, Bio 2 students responded to a third analogous problem (“spider monkey,” box 1). Instruction during Bio 2 did not directly discuss the connection of photosynthesis and respiration to the carbon cycle first addressed in Bio 1.

Responses to all three problems (minke whale, Grandma Johnson, and spider monkey) were evaluated using a coding and scoring scheme (i.e., parallel to calibration techniques used in science) that was revised after each problem, because student responses included new ideas we had to fit within the scheme (box 1). Each time we revised the coding scheme, student responses were reevaluated for all three problems. The revision process increased the predictability and repeatability of student responses and thus increased our confidence in our interpretation of the data.

We examined two major concepts integral to the carbon cycle in each of the problems: (1) Decomposers respire carbon dioxide (CO_2), and (2) primary producers take in CO_2 from the air during photosynthesis. Students’ explanations about respiration and photosynthesis fell into two groups: those that explained movement of carbon through the organisms in the various trophic levels and those that addressed metabolic processes and pathways of organisms using the carbon. Samples of coded answers are shown in box 2. The frequencies of student responses for each coded variable were determined for each problem and formed the basis for analysis.

Results and discussion

On the multiple-choice pretest, students in Bio 1 ($n = 141$) were asked to select what substances account for the majority of plant biomass gain during its growth from seed to adult plant (box 1). Students could choose as many substances as desired. Of those who chose only one substance to account for the biomass, 28 percent indicated substances dissolved in water were taken up directly by the plants, 15 percent selected particle substances in the soil taken up by plant roots, and only 4 percent correctly selected molecules in the air that enter through openings in plant leaves. These data confirmed the range of students’ prior understanding of the concept how plants gain biomass. A large proportion of students think that the majority of plant biomass comes from substances in the soil.

Bio 1 students were given the minke whale problem on the midterm exam. Responses indicated that nearly all students identified and explained the role of decomposers accurately, yet only 62 percent explained further that CO_2 left decomposers via the process of respiration (figure 2). The results suggest that most students understood the concept of decomposers as organisms, but not all had a complete

Box 2. Coding the answers

Here are two examples of students’ answers to the Grandma Johnson problem, coded in accordance with the rubric in box 1. After all of the student responses were coded, Friedman’s test was used to determine the difference among all three extended response questions based on the frequencies of each coded component for each.

(1) Example of acceptable understanding: This student explained all of the organisms and processes and pathways in the Grandma Johnson problem accurately.

After Grandma Johnson was buried at Johnson Canyon her body began to decay and decompose. The decomposition was aided by decomposers [1] who used the glucose and carbohydrates from Grandma Johnson and released carbon through cellular respiration [IA] in the form of CO_2 . The CO_2 was released [IB] into the atmosphere [IIA-1] and in turn taken in by the plants [2] through photosynthesis [IIC]. Once the CO_2 is taken in by the plant, it is transformed into glucose and carbohydrates [IIB], as well as given off through cellular respiration. A prairie dog [3] consumes the plant, taking in the glucose and carbohydrates for its own use. The glucose taken in by the prairie dog remains in the animal as glucose and is transferred to a coyote [4], a secondary consumer when it consumes the prairie dog.

(2) Example of inadequate understanding: This student mentioned only the organisms, not the processes and pathways of carbon movement. Note the typical misconception about the pathway of carbon through the roots in photosynthesis.

After Grandma is buried, her remains are broken up by the many microorganisms [1] that are found in the soil. After these organisms break down her remains the bush [2] can take the carbon up into its roots [IIA-2] to use the nutrients, then the coyote [4] can eat the bush to gain Grandma’s carbon, or a bird [3] can eat the bush, and if the coyote eats the bird it will gain the carbon. Then when the coyote passes the carbon the cycle starts over again.

understanding of the processes of decomposition. Students’ explanations of the pathway of carbon movement from decomposers to primary producers showed that the majority knew phytoplankton photosynthesized within the cycle, but only 60 percent explained clearly *how* carbon moved from the decomposers into phytoplankton. A small percentage of students (9 percent) explained that phytoplankton take up carbon from their roots (even though phytoplankton do not have roots) and that any plant with a root gets its biomass from the soil (water in this case), a well-documented misconception (figure 2).

Bio1/Bio2 students ($n = 63$) responded to all three analogous problems during the two-semester course sequence. Approximately 60 percent of the Bio1/Bio2 students accurately explained that cellular respiration is the process by which

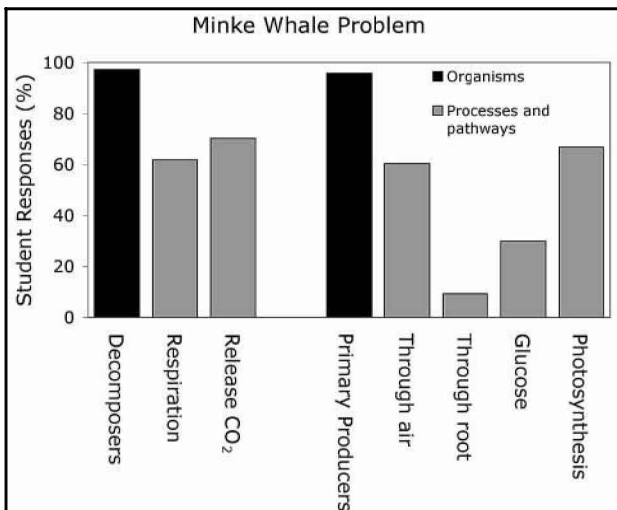


Figure 2. Responses of Bio 1 students (cohort 1, $n = 141$) to the minke whale problem with regard to organisms through which the carbon moved (correct responses: decomposers and primary producers) and processes and pathways (correct responses: respiration, release of carbon dioxide, photosynthesis, production of glucose, and movement of carbon through the air; incorrect response: roots).

decomposers release carbon into the soil and atmosphere in response to the minke whale problem; 70 percent accurately described the same process in the Grandma Johnson problem. The Friedman test showed a significant overall difference among the percentage of correct student responses to the three questions ($\chi^2 = 20.16$, $p < 0.01$). The post hoc comparisons showed there was a significant difference between responses

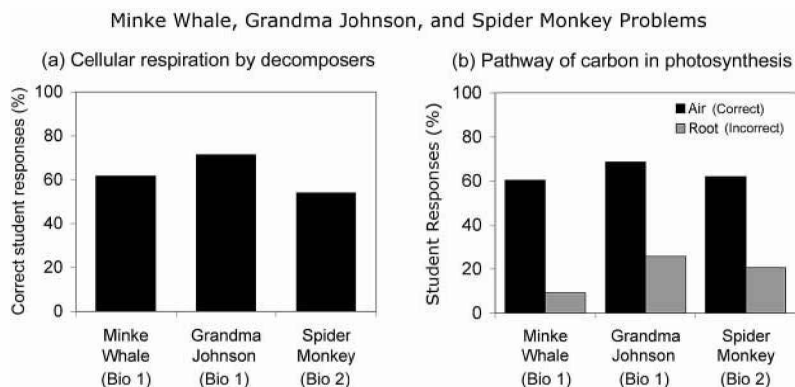


Figure 3. Responses of Bio1/Bio2 students (cohort 2, $n = 63$) to three analogous problems that required explanations about (a) cellular respiration and (b) the pathway of carbon. The percentage of students who gave correct explanations about cellular respiration in the Grandma Johnson problem was significantly higher than the percentages for the other two problems ($\chi^2 = 20.16$, $p < 0.01$). The percentage of correct explanations about the pathway of carbon in photosynthesis did not significantly change among the three problems; some students retained their belief that roots absorb carbon dioxide.

to the Grandma Johnson and spider monkey problems (figure 3a), with fewer of the same students correctly explaining cellular respiration in the spider monkey problem at the end of Bio 2. So in this case, the context of the problem and course changed from organismal biology to cellular biology with a detailed focus on metabolic processes. Although students spent considerable time on cellular respiration in Bio 2, many were unable to connect the process to decomposers in the spider monkey problem. Perhaps the connection was not practiced in Bio 2 and some students simply forgot or did not carry over concepts about the carbon cycle from Bio 1.

Between 60 and 65 percent of the same students explained the pathway of carbon into plants accurately in all three problems—that is, carbon dioxide moves through the air (figure 3b). Although data from extended responses further revealed that the percentage of students' correct conceptions about the pathway of carbon into plants increased from the minke whale to the Grandma Johnson problem and decreased in the spider monkey problem, the Friedman test showed these differences were not significant ($\chi^2 = 4.78$, $p = 0.09$). About 20 percent of the students still held to their belief that roots absorb CO₂ in response to both the Grandma Johnson and spider monkey problems (terrestrial context, vascular plants). In contrast, in the minke whale problem (marine context, phytoplankton) only 9 percent of the students explained that CO₂ was absorbed by phytoplankton through the roots, even though phytoplankton do not have roots. The ecological context of the problem may have influenced their responses.

Other/Bio2 students were compared with Bio1/Bio2 students in their responses to the spider monkey problem. Significantly more Bio1/Bio2 students correctly explained that carbon is released from cellular respiration by decomposers in the carbon cycle ($\chi^2 = 14.59$, $p < 0.01$; figure 4a). Significantly more students who took Bio1/Bio2 also correctly explained the pathway of carbon through the air in photosynthesis ($\chi^2 = 8.89$, $p < 0.05$; figure 4b). Over 40 percent of the Other/Bio2 students still explained that carbon was taken up by the roots of plants in the spider monkey problem, compared with 21 percent of the Bio1/Bio2 students, who took both courses in sequence (figure 4b). Other/Bio2 students did not demonstrate an ability to connect the details of carbohydrate metabolism (i.e., carbohydrates made in chloroplasts and carbohydrates broken down for energy in mitochondria) to a broader-scale question involving organisms and metabolic processes.

Conclusion

Our research was designed to develop and test a robust suite of analogous problems to assess students' understanding of the carbon cycle. Our methods, which parallel the processes used in disciplinary research, provided a systematic way

to analyze in detail what students understood of the carbon cycle. Students' explanations during two sequential semesters of introductory biology supplied the evidence we needed to modify what and how we taught in class meetings, laboratories, and discussions not only in ecology, where the carbon cycle is usually taught, but also in cell and molecular biology. Faculty increasingly acknowledge the acute need for greater integration of course content so that students practice and understand connections between biological scales from cells to ecosystems.

The pretest indicated that only 4 percent of the students coming into Bio 1 understood that plants' biomass comes from molecules taken in through the plants' leaves. Iterative use of the radish problem (in class) and the minke whale, Grandma Johnson, and spider monkey problems (on exams) furnished more detailed information about student thinking than did objective questions only. The data show that 60 to 65 percent of the students who took Bio1/Bio2 explained for all three problems that plants take in carbon dioxide from the air through the leaves. Results from the spider monkey problem alone indicate that over 60 percent of the students from the Bio1/Bio2 cohort accurately explained the pathway of carbon in photosynthesis, and 55 percent explained that decomposers conduct cellular respiration, a significantly higher percentage of students than in the Other/Bio2 cohort. We believe this improvement by students in the Bio1/Bio2 cohort occurred because students were repeatedly exposed to concepts related to the carbon cycle in class, in homework assignments, and on exams. We recognize that the effect of students' repetition and practice explaining the four analogous problems is difficult to determine, yet the significant improvements in student understanding guided our decisions to modify instructional design in these introductory biology courses. Specifically, we included more detail about cellular metabolism in bacteria and archaea as well as in eukaryotes in subsequent iterations of the course sequence. We designed more activities in the laboratory so that students could actively measure net primary production. Homework included readings and questions to help students analyze the concept of source and sink from global change research. We frequently revisited major concepts embedded in the carbon cycle within the course sequence, looping back and forth from macro- to microscales, a process we predict will help more students achieve understanding.

Unquestionably, written response forms of assessment took more time to evaluate, especially for large numbers of students. However, the data gave us reliable information we could use to develop problems that better diagnosed students' understanding; the data also enabled us—and the students—to gain insight into students' misconceptions.

Assessment is data collection to answer questions. Although the purposes of questions differ in undergraduate biology education and discipline-based research, the processes and

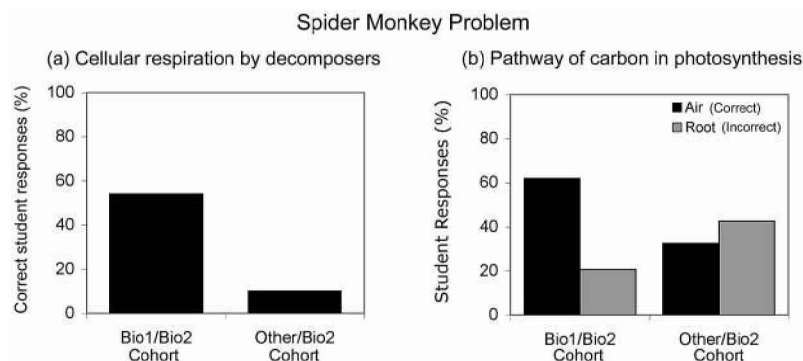


Figure 4. Explanations given by students to the spider monkey problem, which required addressing (a) cellular respiration and (b) the pathway of carbon. Paired comparisons showed that the percentage of correct responses by Bio1/Bio2 students (cohort 2, $n = 63$) was significantly higher than that of Other/Bio2 students (cohort 3, $n = 40$) for both cellular respiration ($\chi^2 = 14.59$, $p < 0.01$) and the pathway of carbon ($\chi^2 = 8.89$, $p < 0.05$).

reliability should not. Assessment will enable scientists to collect, analyze, and use information about student learning to guide their teaching, and it will enable students to explain what they know and understand in multiple ways. Evidence about student understanding of the carbon cycle was dependent on the use of problems and activities, not on variation in teaching strategies or instructor pedagogy, which we could not control in this study. Therefore, we predict that any instructor who uses these problems in the context of active learning-based instruction about the carbon cycle will get comparable results about student understanding. More important, these data influence what and how we teach for the purpose of improving student learning.

Increasingly, scientists are asked to integrate the practices of their disciplines into their classrooms (Cech 2003, NRC 2003) and to contribute toward the reform of learning assessment in undergraduate science education. To do so, we need examples of rigorous assessment that are accessible in the scientific literature and useful to our practice. More journals of scientific societies are calling for articles about substantive questions and problems in undergraduate education. Who better than scientists in the disciplines to use the process they know best to gather the data about student learning to guide the direction of biology education?

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