INQUIRY & INVESTIGATION

Understanding Cellular Respiration in Terms of Matter & Energy within Ecosystems

RECOMMENDED FOR *AP Biology*

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Abstract

Using a design-based research approach, we developed a data-rich problem (DRP) set to improve student understanding of cellular respiration at the ecosystem level. The problem tasks engage students in data analysis to develop biological explanations. Several of the tasks and their implementation are described. Quantitative results suggest that students from the experimental class who participated in the DRP showed significant gains on cellular respiration posttest items, and students from the control class who participated in a non-DRP task showed no significant gains. Qualitative results from interviews and written responses showed that students from the experimental class progressed to deeper "levels of achievement" in cellular respiration. The data-rich tasks promote student understanding of cellular respiration, matter transformation, decomposition, and energy transformation – all goals recommended by the Next Generation Science Standards.

Key Words: *Cellular respiration; ecosystem; design-based research; matter; energy; Next Generation Science Standards; carbon cycling.*

Students frequently demonstrate difficulty understanding cellular respiration, thinking it is exclusive to animal cells, that plants obtain energy directly from the sun, and that there is no need for cell respiration (Barman et al., 2006). Other students confuse the processes of cellular respiration and photosynthesis, creating a hybrid alternative conception that mixes the products and reactants of these distinct biochemical processes (Carlsson, 2002a). Despite instructional efforts, many students maintain these conceptions when they move on to other science courses (Songer & Mintzes, 1994; Tamayo Alzate & Sanmartí Puig, 2007).

Students frequently demonstrate difficulty understanding cellular respiration.

It is not surprising that students' conceptions about cellular respiration in plants are connected with difficulties in broad and overarching topics such as energy flow and matter cycling (Songer & Mintzes, 1994; Lin & Hu, 2003; Mohan et al., 2009). Matter and energy flow in organisms and ecosystems is one of the organizing themes in biology in both the *Next Generation Science Standards* targeting K–12 science instruction (NGSS Lead States, 2013) and AAAS's *Vision and Change* designed for postsecondary biology teaching (Brewer & Smith, 2011). Yet much research is still needed in the design, implementation, and effectiveness of instructional activities or strategies in the teaching and learning of the biological processes associated with matter and energy flow, especially cellular respiration (Lin & Hu, 2003; Brown & Schwartz, 2009; Mohan et al., 2009). In an effort to foster scientific thinking about cellular respiration and matter cycling in an ecological context, we designed, implemented, and analyzed an instructional intervention. Here, we provide an overview of the multiday interventional module and summarize the significant gains in student understanding of cellular respiration at an ecosystem level as a result of engaging in the newest series of intentionally designed data-rich problems.

○ A Design-based Approach to Concept Refinement in Cellular Respiration

Building upon a preexisting ecosystem module described by Maskiewicz (2006), we designed a new data-rich problem (DRP) set focused on promoting understanding of cellular respiration in producers. The DRP is considered "data rich" because the questions and activities require students to refer to existing quantitative data from experiments in order to test their hypotheses. An example of the data-rich nature of the DRP set is seen in a task in which students are asked, "Do the data in the table support your explanation for why the algae die?" Students are then referred to specific parameters (turbidity, dissolved oxygen, carbon dioxide, etc.) in a table to defend their explanation. EcoSpheres – small, closed, self-contained, and commercially available ecosystems that contain microbes, brine shrimp, and algae – provide the context for these problem tasks (Figure 1; Ecosphere Associates, Tucson, AZ; http://www.ecosphere.com/). The original instructional module using EcoSpheres was designed with students' existing ways of thinking about biological systems and ecological understandings in mind. In the

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EcoSphere module, students develop and discuss hypotheses about how such a closed ecosystem might function and then test those hypotheses by consulting the data provided by the instructor (for the entire EcoSphere module, see https://sites.google.com/site/ecospheremodule/home). In an earlier study, Maskiewicz (2006) found that the EcoSphere problems help introductory college students develop an understanding of the role of biological processes in facilitating the flow of matter and energy. Students also began to reflect ecologists' multilevel thinking patterns, connecting molecular and cellular level processes with organism and ecosystem levels.

More recently, Maskiewicz et al. (unpublished data) found that the EcoSphere module promoted significant gains in high school and undergraduate students' understanding of the transformation of matter in ecosystems. In the same study, however, qualitative data showed that students had difficulty with the concept of cellular respiration occurring in all living organisms. Because of the conceptual difficulty with cellular respiration found in that study and others (Tamayo Alzate & Sanmartí Puig, 2007; Brown & Schwartz, 2009), cellular respiration became the conceptual focus of the new DRP tasks. In the new tasks, similar to the other EcoSphere tasks, students develop and defend hypotheses related to cellular respiration on an ecosystem level and then test those hypotheses against data provided by the instructor. In the present article, we address the following research question:

> *Does completion of DRP tasks focused on cellular respiration, embedded within the EcoSphere problem set, improve students' understanding of cellular respiration at the ecosystem level?*

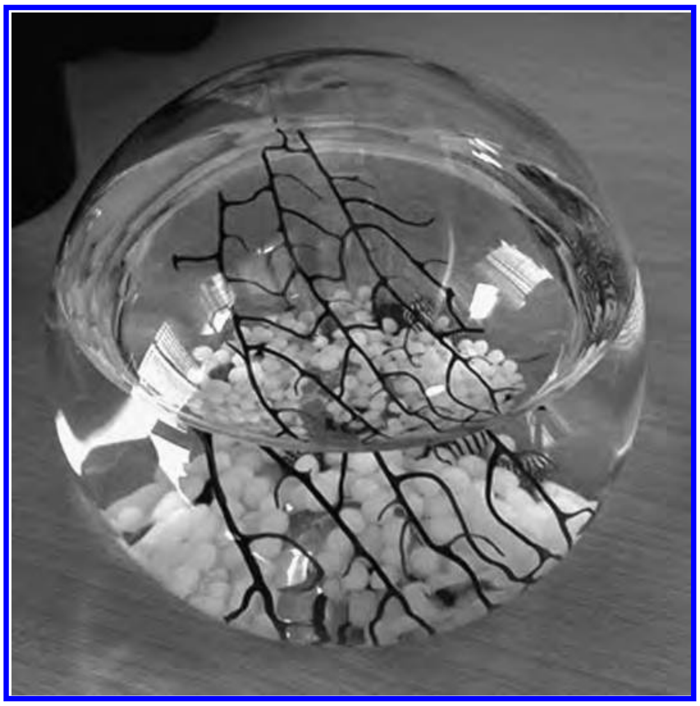

Figure 1. The EcoSpheres used in this module are small, self-contained ecosystems with bacteria, algae, and brine shrimp that survive for several years without human maintenance.

○ Methods

Research Design

The new cellular respiration DRP tasks were implemented in several classes at a comprehensive public high school. The data presented here come from two of these classes that were composed of a majority of low-performing freshman students. Both classes began by completing the original EcoSphere tasks. The experimental class ($n = 31$) then participated in the new cellular respiration DRP tasks, while the control class ($n = 30$) participated in an alternative respiration activity. All 61 students completed a pretest and posttest, and 10 student volunteers (five from each class) were interviewed both before and after the EcoSphere module.

EcoSphere Module Implementation & Pedagogy

The EcoSphere Module (Maskiewicz, 2006) was originally designed to focus on four primary learning objectives related to matter transformation, decomposition, energy transformation, and respiration (see Table 1). The EcoSphere module, along with the new cellular respiration tasks, was embedded in a larger four-week ecology unit that was aligned with the *Next Generation Science Standards* (see Table 1). Below, we provide a brief description of each day, along

Table 1. EcoSphere module learning objectives and alignment.

Instructional Blocks	EcoSphere Task	Learning Objective(s)	*Next Generation Science Standards*	Pretest/Posttest Question Alignment
1	1	Understand the transformation of matter within an ecosystem (matter transformation)	HS-LS1-6 HS-LS2-3 HS-LS2-4	1, 2, 3, 5, 11, 13, 14, 31a, 33a, b, e
	2			
2	3			
	4	Understand the role of decomposers and decomposition within an ecosystem (decomposition)	HS-LS2-3 HS-LS2-4	6, 7, 8, 9, 10, 31b, 33c
	5			
	6	Understand the transformation of energy in an ecosystem (energy transformation)	HS-LS1-5 HS-LS2-3 HS-LS2-4	4, 12, 15, 16, 17, 32, 33d
3	7	Understand the role of cellular respiration in matter cycling (respiration)	HS-LS1-7 HS-LS2-5	18–19, 20–21, 22–23, 24–25, 26–27, 28–29, 30, 31a, 33a, 32

Table 2. Data for cellular-respiration DRP task: EcoSphere water-quality data – algae only, no shrimp or bacteria.

Parameter	Acceptable Range	Day 1	Day 10	Day 20	Day 30	Day 100
Turbidity	10–25 NTU	12	13	11	13	12
Dissolved oxygen	>5.0 mg/L	6.5	6.6	6.6	6.5	6.3
Carbon dioxide	>2.5 mg/L	3.1	3.5	3.3	3.3	3.4
Oxides of nitrogen (NOx)	0.050–0.090 mg/L	0.060	0.057	0.053	0.05	0.041*
Organic nitrogen (N)	0.010–0.050 mg/L	0.021	0.026	0.034	0.041	0.052*
Organic phosphorus (P)	0.010–0.050 mg/L	0.015	0.025	0.032	0.043	0.053*
Dissolved phosphates (POx)	0.020–0.090 mg/L	0.050	0.041	0.032	0.021	0.011*

*Outside acceptable range.

with the pedagogical focus of the EcoSphere module for this particular intervention. Because our space here is limited, we only provide examples of some of the new DRP tasks that were implemented. For a full description of the module with all of the tasks, see https://sites.google.com/site/ecospheremodule/home.

Day 1 (~100 minutes)

Students observed an EcoSphere and were provided a short information sheet about bacteria (heterotrophic and nitrifying), brine shrimp, and algae enclosed within the system. Working in cooperative groups and with very little intervention from the instructor, students discussed, constructed a diagram, and then defended their group explanation for why that combination of organisms can survive for an indefinite amount of time (up to 20 years!). As with previous implementations, most of the groups created a circular diagram reflecting only the feeding and gas-exchange relationships between the species in the sphere. Through this introductory task, students engaged in the formation of a model – a hypothesis of relationships – that was later adapted and reformulated through questions asked and data presented during the rest of the module. By the end of day 1, most students had developed incorrect hypotheses that all three organisms are needed to prevent EcoSphere collapse.

Day 2 (~100 minutes)

To challenge their initial hypotheses, students were told that the EcoSphere can survive for several years without the shrimp. Working in groups, they then analyzed existing water-composition data based on experimental changes (i.e., removing one organism at a time) made to the EcoSphere to develop an explanation for how it could survive without shrimp. Through experimental scenarios and data presented in four different tasks, students constructed and defended their own ideas about the ecological roles of the organisms within the EcoSphere. Again, the design of the tasks engages students in the process of hypothesis formation, knowledge construction, and refinement through the analysis of data and development of principled scientific explanations. In this way, students are direct participants in the practice of science, rather than passive recipients of scientific facts. Day 1 and day 2 were identical in both the control and experimental classes.

Day 3 (~100 minutes)

The two classes differed in their activities for day 3, with the experimental group completing the new cellular-respiration DRP tasks. In groups the students discussed task 1:

> *If both bacteria and brine shrimp are removed so that the algae are the only living organisms left in the EcoSphere, the algae will die in a few weeks. Explain in detail why the algae die.*

After some discussion and sharing, students were presented data from an experiment in which the algae are the only living thing in the EcoSphere (see Table 2) and were asked,

> *Do the data in the table support your explanation of why the algae die? Refer to specific parameters (turbidity, dissolved oxygen, carbon dioxide, etc.) in the table to defend your explanation.*

Notice that the data and scenarios in these tasks have no explicit mention of cellular respiration or photosynthesis; however, they are designed to promote student understanding of the role of these processes both at the organismal level, within algae, and at the ecological level as oxygen and carbon cycle through the system. How is this possible? Having the appropriate data (carbon, oxygen, and nitrogen levels) activates students' prior knowledge about cellular respiration and photosynthesis and links that knowledge to organismal and ecological contexts. For example, the third question asks students,

> *Look again at the data on dissolved oxygen and carbon dioxide. In the sphere that contains algae only (no bacteria or brine shrimp), where do the oxygen and carbon dioxide in the EcoSphere come from? Explain in detail and include a drawing/diagram if it aids in your explanation.*

Through cooperative discussions, students formed explanations that accounted for the data, and they eventually (15 min) concluded that these gases came from algae. In this process, the students began to make the connection to cellular respiration in producers. Two additional tasks can be found at https://sites.google.com/site/ecospheremodule/home.

During these activities, the instructor motivates the groups to work together using the data to test their ideas but does not overtly guide the groups to the answer. Thus, the pedagogical role of the instructor in the DRP tasks is more supportive than directive. In these tasks, the data take center stage and provide the basis and evidence for student claims. Rather than teacher notes or textbook facts, the students rely on logical reasoning to analyze data and form conclusions.

On day 3 in the control class, instead of participating in the new tasks, students developed a hypothetical EcoSphere experiment, predicted the data they would expect to observe, and then discussed the reasons for the observed data. The control activity was designed to give the control class an opportunity to activate prior knowledge in any of a number of related topics, including cellular respiration or photosynthesis. It also provided the control class with an equitable amount of time in the EcoSphere module without participation in the new respiration DRP tasks.

The DRP tasks are designed to engage students in questioning, hypothesis-formation, cooperative problem solving and presentation of ideas, peer evaluation and critique, and argumentation strategies. The implementation of these tasks is not prescribed; rather, the specific pedagogical approach to the content is left to the discretion of the teacher. Because this module is similar to a "dry lab," it does not require any expensive lab equipment for implementation; thus, it can easily be adopted in any classroom (even the EcoSphere is not required – images can be used). The module was designed such that student–student interaction and discussion are important factors in learning and engagement.

Student Learning Gains

The pretest and posttest included questions that were compiled from validated assessments adapted from Haslam and Treagust (1987) and diagnostic question clusters used by Maskiewicz et al. (unpublished data). Qualitative analysis was based on four open-ended questions included in the pretest and posttest along with more detailed interview results from 10 student volunteers, selected because of their availability to participate. We chose the four open-ended questions on the basis of their relevance to the EcoSphere module in general and their ability to elicit student understanding about the process of cellular respiration in producers. We used Mohan et al.'s (2009) coding scheme to analyze the interview and short-answer responses for differences in "levels of achievement" between the pretest and posttest. Mohan et al. (2009) identified four levels of achievement based on patterns in student thinking about carbon cycling in ecological systems, from the most simplistic thinking (level 1) to the most complex and scientific (level 4). Descriptions of each level are shown in Table 3. By adopting a similar framework as Mohan et al., the first author developed the remaining descriptions of levels of achievement (levels 1–4) for decomposition, energy transformation, and respiration (Table 3).

○ Results

Pretest & Posttest

Results from an unpaired t-test show a significant difference ($P < 0.001$; Table 4) between the mean pretest and posttest scores of both the control class and the experimental class, which suggests that the EcoSphere module was effective in promoting learning for this particular group of students, just as it was shown to be effective in previous studies (e.g., A. C. Maskiewicz et al. unpublished data). However, for the present study, we were interested in the effect of the new DRP tasks, and so we sorted the 30 questions (1 point each) by concept focus area and analyzed them separately. In the control class, in which students did not participate in the respiration DRP tasks, the paired t-test scores for the pretest and posttest revealed significant improvements on questions focused on matter transformation and decomposition. In the experimental class, which included the new respiration DRP tasks, the results showed significant gains in all four of the concept focus areas, including respiration. The experimental class also showed higher gains in $\bar{g}$ value (mean of normalized gains) than the control class in all four concept focus areas, but especially in the areas of decomposition, energy transformation, and respiration (Table 4).

Qualitative Open-ended Written Response Results

The written responses from the open-ended questions in the pretest and posttest showed gains in student levels of achievement in all four focus areas. In addition, 3 of the 30 students (10%) in the experimental class provided evidence of level 4 achievement in at least one of the concept focus areas. Level 4 responses are complex descriptions in which students account for the flow of all matter or energy in a system through various chemical changes within biological or chemical processes according to conservation laws. The following example is from one of these level 4 responses:

> *[G]lucose is broken down in cellular respiration. CO_2 is the by product [sic] and is released.… The glucose is broken down in cell respiration & the energy transfers to bond energy in ATP. The ATP is used to power the leg muscle in a coyote. Eventually, the bond energy will be released as heat energy into our atmosphere.*

Notice how this student accounts for all matter and energy transformations, including the ultimate release of energy as heat (a shorthand way of talking about thermal energy). This type of complexity is similar to that observed in the other level 4 responses in matter transformation, decomposition, and energy transformation. However, level 4 written responses were observed in only 10% of the analyzed open-ended responses.

Qualitative Interview Results

Averages of pre- and post-instruction interview responses in each of the four concept focus areas are presented in Table 5. Not only are all average pre- and post-instruction gains larger for the experimental class, but all average post-instruction levels are higher in the experimental class (Table 5).

One student's (Lucy's) interview responses provide a representative example of the types of gains seen in levels of achievement that occurred for students in the experimental class. In one interview question, students were asked to explain how a carbon atom can get from Grandma Johnson's dead body into a coyote's leg. At one point in the semistructured interview, Lucy was asked to elaborate on the release of a CO_2 molecule that she mentioned. In her pre-instruction interview, she provided a typical Level 1 response:

> *Well plants produce oxygen, so maybe [carbon dioxide] is released because [the plant] has too much carbon dioxide.*

Table 3. Scoring rubric showing descriptions of levels of achievement for open-ended and interview questions.

Description of Levels of Achievement in Concept Focus Area				
Level	Matter Transformation (Mohan et al., 2009)	Decomposition	Energy Transformation	Cellular Respiration
1	Explanations in terms of separate objects and events, rather than connected biological and chemical processes.	Attempt to explain decomposition without a decomposer, or explanations that include organisms (e.g., "bacteria") and actions (e.g., "break down"), rather than connected biological and chemical processes.	Explanations of energy in separate objects and organisms, rather than in terms of flow through an ecosystem. No explanation of biological or chemical processes involved. Students may explain energy as being in living organisms only.	Explanations of natural phenomena in terms of separate organisms and actions (e.g., "breathing" "taking in") rather than actions connected to biological processes like cellular respiration.
2	Explanations of cause-and-effect sequences of events with hidden, underlying mechanisms for macroscopic events.	Cause-and-effect explanations with hidden, underlying mechanisms for macroscopic decay. Decomposers only accelerate decomposition.	Explanation of energy in terms of flow through ecosystem, with hidden processes, but without respect to transformation.	Cause-and-effect explanations of respiration as an energy-related process in animals, but not necessarily in plants. Respiration as alternative to photosynthesis, occurring only at night, or a gas-conversion process.
3	Explanations of sequences of events with descriptions of chemical change as underlying mechanisms for macroscopic events. Generally traced matter, but converted matter to energy and reluctant to attribute mass gain or loss to gases.	Cause-and-effect explanations with biological and chemical mechanisms for macroscopic decay. Generally included biological processes in explanation, but readily converted matter to energy and vice versa.	Explanation of energy transformation through various forms via biological or chemical processes within a system. Generally traced energy, but converted between matter and energy and/or attempted to explain energy as cyclical within the ecosystem.	Cause-and-effect explanations of respiration as an energy- or matter-transformation process occurring in plants, animals, and decomposers. Included description of chemical change. Readily converted between matter and energy without respect to conservation laws.
4	Descriptions of chemical changes constrained by physical laws like conservation of matter or energy, and complex explanations of key cellular and metabolic processes, and natural mechanisms.	Complex descriptions of decomposition included cellular respiration that are constrained by physical and natural laws such as matter and energy conservation.	Description of energy transformations in various forms and through various processes that are constrained by law of conservation. Accounted for all energy in the system, including that lost as heat.	Description of respiration as an energy- and matter-transformation process constrained by conservation that occurs in all living organisms.

Table 4. Changes in student understanding by concept focus, based on pretest and posttest scores, following EcoSphere module implementation in control class and experimental class.

	Control Class				Experimental Class			
Concept Focus	Mean Pretest Score	Mean Posttest Score	P	ḡ	Mean Pretest Score	Mean Posttest Score	P	ḡ
Matter transformation	2.74	4.16	<0.001*	0.26	2.80	4.80	<0.001*	0.47
Decomposition	2.06	2.64	0.01*	0.08	2.13	3.07	<0.001*	0.28
Energy transformation	1.87	2.32	0.10	0.05	1.97	2.97	0.001*	0.25
Respiration	4.90	6.03	0.06	0.08	5.13	8.10	<0.001*	0.38

Notes: *Significant ($P < 0.05$); ḡ values indicate mean of normalized gain.

Table 5. Summary table of averages of qualitative pre- and post-instruction interview gains in levels of achievement (see Table 3 and text) in student responses in all four concept areas from students in both control and experimental classes.

Concept Focus Area	Average of Experimental Class (DRP Task) Pre-instruction Levels	Average of Experimental Class (DRP Task) Post-instruction Levels	Average of Control Class (No DRP Task) Pre-instruction Levels	Average of Control Class (No DRP Task) Post-instruction Levels
Matter transformation	1.25	2.33	1.56	2.25
Decomposition	1.50	2.38	1.50	2.00
Energy transformation	1.75	2.63	1.67	2.00
Cellular respiration	1.13	2.38	1.00	2.00

In her post-instruction interview response to the same question, but in the context of decomposition, she was able to trace carbon from carbohydrates in Grandma Johnson's decomposing remains to carbon dioxide being released by decomposers during cellular respiration:

> *Well [decomposers] could decompose the plant… and so they would have the carbohydrate they decomposed. Then through cellular respiration in their body they would let off carbon dioxide.*

Here, Lucy's explanation bears the hallmarks of level 3 understanding because respiration is described as a chemical process of matter transformation that occurs in plants and decomposers (earlier in the same interview, she explained that plants release CO_2 "through cellular respiration").

○ Discussion

Our results provide further evidence of the effectiveness of the EcoSphere module in promoting students' qualitative and quantitative achievement gains and depth in levels of understanding in matter transformation, decomposition, and energy transformation. In cellular respiration, however, only students from the experimental class who participated in the respiration DRP tasks made gains on quantitative posttests and provided qualitative evidence of deeper levels of achievement. Findings from both qualitative and quantitative data collected in the present study are consistent in supporting the validity of the data and showing the effectiveness of the respiration DRP tasks in improving low-performing freshman high school students' understanding of cellular respiration at the ecosystem level.

Interestingly, along with significant gains in cellular respiration, the experimental class made larger gains than the control class in the other three non-respiration-focus concept areas. We propose that when one understands the role of cellular respiration in an ecosystem, this knowledge facilitates understanding in other concepts. For example, if a student understands the conversion of glucose to carbon dioxide and water during cellular respiration, she is likely to have a better way to contextualize the law of conservation of matter that involves transformations. And if a student understands the transformation of bond energy occurring during cellular respiration, she is more likely to be able to understand that energy transformation through an ecosystem is constrained by energy conservation laws. This *overflow* effect, whereby understanding of one concept focus (i.e., cellular respiration) leads to increased understanding of another concept, speaks to the need for similar curricular bridges between physical and biological sciences noted by others (Carlsson, 2002a, b; Mohan et al., 2009)

It is noteworthy that the gains in the present study were observed in classes with a high population (67.2%) of low-achieving ninth-grade students. These results suggest that the EcoSphere module, along with the embedded cellular-respiration tasks, can be very effective in promoting student achievement within a wide range of student performance levels and educational contexts.

Our results are limited, however. Although evidence of level 4 reasoning was observed in the open-ended posttest written responses in every concept focus area, only 3 of 30 students in the experimental class reached such a high level of achievement. These results parallel those of Mohan et al.'s (2009) study, which also found that only 10% of high school students could provide level 4 explanations post-instruction. This suggests that although student understanding improved, student gains were modest and did not result in learning that was scientifically complex and free from alternative conceptions. Reasons for these modest gains may be varied and complex and point to the importance of additional research in this area.

○ Conclusions & Implications

The *Next Generation Science Standards* and AAAS's *Vision and Change* ring in a new era in education marked not only by new ways of teaching, but by new ways for students to demonstrate learning. No longer is it simply expected that "students *know*…" (NCLB California Science Standards), but it is expected that "students who demonstrate understanding *can* [insert verb]…" (NGSS Lead States, 2013). This shift represents an important refocusing of the role of educators to cultivate in students the intellectual and experiential capital with which to demonstrate their understanding. Because the *Next Generation Science Standards* challenge students to understand matter and energy conservation within biology, curriculum design must integrate domains of science that have classically been separate. The curriculum presented here shows that students can learn a biological concept like cellular respiration, presented in an ecological context, with an emphasis on physical science concepts.

Biological concepts such as cellular respiration, shown to be difficult for learners both in high school and at the undergraduate level, are attainable when educators design interdisciplinary experiences that engage students in the process of socially constructed knowledge formation. Giving students data to analyze and hypothesize about, rather than simple direct instruction, enabled them to take control of their own knowledge formation and refinement and improve their scientific understanding of the world around them.

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