The Transformation of Energy and Matter in Ecosystems

Elizabeth Nowak

Students learn at an early age about the need for alternative energy and the need to reduce the use of fossil fuels. They also know that we as animals, depend on plants, but often this is limited to the role of plants in producing oxygen used by animals. Most students (and I would guess most adults) have very little understanding of where our energy comes from, and the role of producers in providing an ecosystem with energy. At the most basic level, students have a difficult time understanding the concept of energy, including the conservation of energy and energy conversions during cellular metabolism, specifically photosynthesis and cellular respiration. I have found that many students confuse matter and energy, even after being introduced to these in middle school and in a freshman physical science course. The goal of my unit is to solidify my students' understanding of matter, energy, and their transformations, while being able to apply these concepts to cellular metabolism (specifically photosynthesis and cellular respiration) and the conversions of matter and energy in ecosystems.

Student Population and Science Sequence

I teach at a vocational/technical high school in New Castle County, Delaware that includes a diverse population of about 1550 students, with 56% of the students qualifying for free and reduced lunch and 30% designated as low income.[1] During the 2015-2016 school year the student population included 36.0% African-American, 32.4% Latino, and 30.0% Caucasian students, with very few from other ethnic groups.[2] (DOE school profiles, 2016) The students come from many different public middle schools all over New Castle County, as well as a few parochial/private schools, so they all have different experiences with science education and come to our school at different levels of scientific understanding. All students take physical science (consisting of an introduction to chemistry, physics and earth science) during their freshman year and biology during their sophomore year. Currently during their junior year the students either take chemistry or integrated science. Chemistry students are typically stronger in math skills and have higher science grades. Many of these students take physics and/or advanced biology in their senior year. Integrated science presently includes concepts from ecology, astronomy, and the fundamental forces of the universe. Because of our vocational focus, no AP or honors science courses are offered at our school.

This unit is designed for the 10th grade biology course at our school. Because biology is taught to all students in the same general biology course (one 90-minute block daily for one semester), there is a wide range of reading and mathematical ability among students in each of my classes. During the 2015-2016 school year special education students made up 14.3% of the student population.[3] Many of the biology classes I have taught have included about 1/3 special education students. Our inclusion classes may include beginning readers and students with learning disabilities, as well as those college-bound students reading well above grade level. This situation presents a challenge, meeting the needs of all our students while teaching all the science concepts required by the Delaware state science standards and the Next Generation Science Standards.

Course Scope, Sequence, and Common Practices

For the past few years our school has used the SEPUP Science and Global Issues (SGI) program as the foundation of its biology curriculum.[4] The three units we have used in the past focus on cell biology, genetics, and evolution. Because we have begun implementing the Next Generation Science Standards at our school, we are in the process of piloting an ecology unit, including some activities from SGI, but focusing on how matter and energy are transformed and/or transferred through an ecosystem. Unfortunately, SGI is not yet completely aligned with NGSS, so we must be selective about which activities we should use, and we must add some activities to fill the gaps. The ecology unit will be the first unit we explore, so this curriculum unit will be taught in the beginning of the course.

Students keep a science notebook (composition book) where they record data, write notes, and paste in papers from class. For every lesson (usually daily), they reflect on the lesson and what they learned from it, by answering the following: What did I do? What did I learn? For the "What did I do?" prompt, they reflect on the science and engineering practices they used in the lesson (obtain information, develop a model, etc.) and show precisely *how* they used the practice in the lesson. For the "What did I learn?" prompt, students reflect on the essential question of the lesson. They answer the question, supporting their answer with evidence from the activities.

Delaware public schools use the learning management system Schoology, which provides a unique opportunity for differentiation as well as blended learning. Students are on Schoology almost daily, using the platform for lesson instructions, videos with embedded questions, discussion boards, assessments and links to computer activities (such as simulations and other interactive activities). Although I have yet to "flip" the lessons (student home internet access is not reliable enough to require students to stream videos at home), our school will be implementing a one-to-one computer initiative next year, and these activities will be more accessible to students. Hopefully students will engage with the material at home, extending the time for learning and allowing for more independent work. (We do mostly paired and group work at school.)

Student Misconceptions

Students come to science class with prior conceptions about how the world works. Several of their misconceptions are related to this unit. They frequently use the terms "matter" and "energy" interchangeably. For example, when my students grow radish seeds in a closed container, observing that the mass of the seedlings increase while the mass of the entire system stays the same, several will often attribute their results to the conservation of energy, not mass. Although most students remember that energy and matter are conserved, they really do not understand what that exactly means in each case (for example, atoms being rearranged into new molecules during a chemical reaction, in the case of matter).

Students also have misconceptions about photosynthesis and cellular respiration. Each year, before teaching photosynthesis and cellular respiration, I use a version of the "Giant Sequoia Tree" formative assessment by Page Keeley.[5] Students are asked to determine what materials a tree needs to grow, and where these materials come from. The options we give them are sunlight, water, soil, oxygen, carbon dioxide, minerals and chlorophyll. Many students choose sunlight, water or soil. Some students who have learned about photosynthesis in middle school will answer chlorophyll, because they remember the pigment is necessary for photosynthesis. Occasionally students will choose oxygen, as they understand it is a requirement for most living things. Very few choose carbon dioxide, and these are students who choose multiple options, refusing to commit to just one option. The fact that many students think sunlight contributes to the mass of a growing plant (rather than being the source of energy that rearranges the atoms of carbon dioxide and water) demonstrates their confusion about energy and matter.

Another misconception that I encounter frequently is that plants perform photosynthesis to provide oxygen to animals, and animals breathe to provide carbon dioxide for plants. When asked why animals need oxygen, students reply "to live" without any further explanation. When probed further, some explain that without oxygen we'd suffocate and die, showing they have little understanding of the role of oxygen during cellular respiration in both plants and animals.

Students also fail to realize that gases such as carbon dioxide and oxygen have mass. In the "Minds of Their Own" series, Kathleen Fisher suggests that this misconception that air has no weight limits students' abilities to truly understand photosynthesis.[6] They don't understand that a gas like carbon dioxide can contribute mass to a growing plant. Even graduates from Harvard and MIT (as shown in the series) hold tight to misconceptions that the mass of the tree comes from light, water, soil, minerals or other nutrients in the soil, and find it hard to believe that carbon dioxide can be responsible for the bulk of the mass of the tree. Using dry ice to show that carbon dioxide has mass or massing an unfilled and filled balloon may help to dispel this misconception.

Katerina Svandova's research with misconceptions about photosynthesis demonstrate that misconceptions are not limited to our students. She found the following misconceptions in her study of Czech students:[7]

- Plants produce oxygen in the daytime and nighttime.
- Oxygen release is the main purpose of photosynthesis. (I see this often with my students.)
- Photosynthesis and respiration are the same process, but occur at different times of the day.
- Plants "breathe" through pores, so cellular respiration only takes place in leaves. (I personally have not encountered this misconception, possibly due to the fact that most of my students are unaware that stomata exist.)
- The most important nutrients for plants are water and dissolved substances that plants take up through the roots.

Even as my students progress through the unit, new misconceptions arise. They think carbon dioxide turns into oxygen during photosynthesis, possibly due to the simplified summary equation of photosynthesis that is used in class. They also frequently call carbon dioxide "carbon," leading me to conclude that they do not fully understand the terms atom, element, and molecule. When I ask them to trace the path of a carbon atom in an ecosystem, some students bypass glucose entirely, focusing only on carbon dioxide. They don't realize that bonds are broken and new bonds are formed, producing new molecules with the same atoms.

Ray and Beardsley suggest that in order for students to overcome student misconceptions about photosynthesis, photosynthesis should be taught in the context of natural ecosystems, explaining the role of photosynthesis and photoautotrophs in cycling matter and transferring energy.[8] This is precisely how the Next Generation Science Standards approach the instruction of photosynthesis and cellular respiration.

Hershey lists misconceptions about plants (including photosynthesis) and groups them into categories by the root cause of the misconception.[9] Two of these causes are oversimplification and overgeneralization. He mentions the use of the typical summary equation for photosynthesis used in most textbooks: $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$. Above the arrow is usually written light (and sometimes chlorophyll) to show the conditions necessary for photosynthesis to occur. He suggests that "chloroplasts" should replace "chlorophyll" in the equation, the equation should include several small arrows instead of one. In the past we have written light and enzymes over the arrow, because we only discuss chlorophyll as the pigment that "traps" the energy from the sun needed for photosynthesis, and earlier standards put an emphasis on enzymes and how they catalyze chemical reactions. Additionally, Hershey points out that another common misconception is that photosynthesis is done during the day and cellular respiration is done at night. I have not encountered this much with my students, mainly because they never really considered cellular respiration before. They are only familiar with breathing and often don't realize the purpose of transporting oxygen to cells.

I fear the clarification statements and assessment boundaries of the performance standards of NGSS will lead to the oversimplification and overgeneralization that Hershey mentions. For the physical science standard, the assessment boundary states that students are not required to "calculate total bond energy changes during a chemical reaction from the bond energies of the reactants and products." They are not required to know the biochemical steps of photosynthesis and cellular respiration, but should focus instead on the inputs and outputs of matter and energy transfers and transformations in these processes. I'm afraid that without knowing some of the metabolic pathways involved in these processes, more misconceptions might be created. On the other hand, my students are the future plumbers, cosmetologists, and auto technicians of our society, and delving into the Calvin cycle or oxidative phosphorylation will do nothing to pique their interest. I also need to limit the information presented to keep my students from becoming overwhelmed and missing the big ideas of how matter and energy are transferred and transformed in ecosystems.

Background

It all begins with stars. The original source of matter for any ecosystem on Earth lies in one or more stars that exploded billions of years ago. The original source of energy for almost every ecosystem on Earth is our closest star, the Sun. Although matter can be converted into energy through the nuclear fusion of atoms into new elements, for the purposes of this high school biology course, matter and energy are distinct entities with distinct properties.

Matter is anything that takes up space (has volume) and has mass. Matter is made of atoms and the subatomic particles of which atoms are comprised. This, for the most part, students already know before they come to my biology class. They remember (or can be encouraged to remember) that matter can neither be created nor destroyed, and for a closed and isolated system, mass (the amount of matter) is conserved, but can be changed in form through chemical reactions and radioactive decay. (They balanced equations and studied radioactive decay in the freshman year physical science course at our school.) They've learned that energy is the capacity to do work, can identify different forms of energy, and know that energy also cannot be created or destroyed, but can be transferred and transformed (according to the first law of thermodynamics). Unfortunately, whether it is because of the laws of conservation or some other reason, students often use matter and energy interchangeably.

Although energy cannot be created or destroyed, during an energy transfer or transformation, a portion of the energy is no longer available to do useful work. In cells, much of the energy that is obtained from breaking down organic molecules is lost as heat, which could serve a purpose in maintaining the temperature of the organism, but cannot be used to do the work of the cell.

All the chemical reactions that takes place in the cells of an organism is known as cellular metabolism. These chemical reactions transform matter and energy. They do not usually exist in isolation, but rather as pathways, catalyzed by specific enzymes each step of the way. Catabolic pathways break down organic molecules in the presence of oxygen, releasing energy the cell needs to do work, while anabolic pathways build up larger organic molecules from simpler subunits, such as building up proteins from amino acids. Two of the most important metabolic pathways in cells (and consequently ecosystems) are photosynthesis and cellular respiration, and this is why these processes are highlighted in NGSS.

Photosynthesis

Photosynthesis is the means by which energy from the sun can be harvested and made useful to living things. It uses radiant energy to rearrange the atoms in carbon dioxide and water, converting light energy to the chemical potential energy in sugars, and releasing oxygen gas in the process. It is a complex process, involving two distinct phases, the light reactions and the Calvin cycle. The light reactions are so named because photons are used to drive the energy transfers, resulting in the production of ATP (the immediate source of energy for cellular work) and NADPH (an electron carrier), both of which can be used to drive the Calvin cycle. The energy transfers occur in complexes called photosystems, located in the membrane of thylakoids located in the chloroplasts. Each photosystem consists of a reaction center surrounded by light harvesting centers, and is made up of pigment molecules, proteins, and other small organic molecules. In photosystem II (PSII) the energy absorbed from photons by pigment molecules such as chlorophyll results the splitting of water in the thylakoid space. The formation of oxygen molecules leaves extra protons, forming a proton gradient with a higher concentration of H^+ ions within the thylakoid space. The high energy electrons that result from this process are transferred through a series of electron carrier molecules in an electron transport chain, eventually pumping more protons into the space as they are transferred to a lower energy state, and further increasing the proton gradient. These lower energy electrons are transferred to photosystem I (PSI), which boosts them to an even higher energy level, thanks to the absorption of addition photons. These electrons are used in the reduction of $NADP^+$ to NADPH (adding a pair of electrons and a hydrogen ion) in the stroma of the chloroplast. Meanwhile, the proton gradient powers the conversion of ADP to ATP by ATP synthase. In some cases, excited electrons take an alternative path, cyclic electron flow, using only photosystem I, and generating ATP but no NADPH.

The next pathway of chemical reactions in photosynthesis, the Calvin cycle, uses the electrons from NADPH and the energy derived from ATP to assemble sugars from carbon dioxide. The resulting sugar is a three-carbon sugar called glyceraldehyde-3-phosphate (G3P). This cycle involves attaching the carbon in CO_2 to a carbon acceptor, the five-carbon sugar ribulose biphosphate (which immediately breaks into two 3-carbon sugars), adding a phosphate group from ATP and reducing the resulting sugars using electrons from NADPH to form G3P. As one G3P is formed, the ribulose biphosphate is regenerated in order to accept another carbon from CO_2. Although only one CO_2 molecule enters the cycle at a time, three carbon dioxide molecules and 3 ribulose biphosphate acceptor molecules (as well as 9 molecules of ATP and 6 molecules of NADPH) are necessary to form one G3P molecule. These are then used to form glucose and other carbohydrates. Figure 1 below shows a simplified diagram of the matter transformations and energy conversions during photosynthesis. For more detailed explanations of the process of photosynthesis, see Cooper[10] and Reese and Campbell.[11]

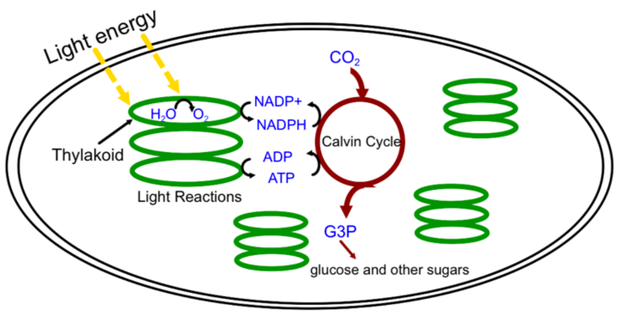


Figure 1. Photosynthesis in the chloroplast of a plant cell.

Cellular Respiration

ATP (adenosine triphosphate) is commonly referred to as the "energy currency of the cell." Energy is stored in ATP molecules by attaching a phosphate group to adenosine diphosphate (ADP). Cellular respiration supplies the energy necessary to generate ATP. The hydrolysis of ATP to ADP and a phosphate group results in a net release of 7.3 kilocalories (30.5 kilojoules) per mole.[12] This energy is used to do the work of the cell, whether it is coupled to endergonic chemical reactions, used for movement or used to transport molecules. This "recharging" process is essential to life, as a typical muscle cell will recycle 10 million ATP molecules per second, and it would be impossible for a cell to build that many ATP molecules from raw materials.[13]

Cellular respiration breaks down the organic molecules produced during photosynthesis and other metabolic processes to generate the ATP molecules needed to do cellular work. The waste products, carbon dioxide and water, can be again used as reactants for photosynthesis, completing the cycle of matter. Aerobic cellular respiration, using oxygen to break down organic molecules, is the most efficient means to generate ATP. Although other organic molecules can be broken down by this process, glucose is the most commonly used example, as it is the molecule most commonly used by cells.[14] This involves redox reactions, and when the electrons from glucose are transferred to oxygen, they are transferred to a lower energy state. The energy that is released becomes available to synthesize ATP molecules. The energy from a glucose molecule is not released all at once, but rather in a step-wise process; otherwise it would be damaging to cells and useless for cellular work. Like photosynthesis, cellular respiration is a complex process that involves many different molecules, including electron carriers. The first part, glycolysis, takes place in the cytoplasm of the cell, while the rest of the process takes place inside the mitochondria. (See Figure 2 below.)

Glucose is broken down into two pyruvate molecules during glycolysis. This occurs in the cytoplasm of the cell, rather than the mitochondria. These pyruvate molecules serve at the raw materials for cellular respiration. Two ATP molecules are required for glycolysis, but 4 ATP molecules are formed by the process, resulting in a net gain of 2 ATP molecules. (Two NADH molecules and 2 hydrogen ions are also made during glycolysis.) Each pyruvate molecule is transported into the mitochondria, converted into acetyl coenzyme A (resulting in a CO_2 molecule and another NADH), and then enters the citric acid cycle. Each turn of the cycle breaks down acetyl CoA into two CO_2 molecules, and generates 1 ATP, 3 NADH (with 3 H^+ ions) and $FADH_2$ (another electron carrier). Thus for each glucose molecule, glycolysis and the citric acid cycle produce 4 ATP, 8 NADH (and 8 H^+ ions), and 2 $FADH_2$, all without molecular oxygen.

If molecular oxygen is present, a complex of proteins and associated molecules embedded in the inner mitochondrial membrane provides the bulk of ATP gained through the breakdown of glucose. These molecules form an electron transport chain. The electrons “fall” to lower energy levels as they are transferred from molecule to molecule in the inner mitochondrial membrane through an electron transport chain. The electrons carried by NADH begin at the higher energy end of the chain, and the electrons carried by $FADH_2$ enter at a somewhat lower point. At the low energy end of the chain, oxygen captures the electrons and H^+ ions, forming water molecules. This electron transport is coupled with the synthesis of ATP from ADP and phosphate, using a H+ gradient that is formed between the intermembrane space and the mitochondrial matrix during the electron transport chain. The electron transport chain and resulting formation of ATP from the chemiosmosis of hydrogen ions together is known as oxidative phosphorylation.

Although not all the energy in glucose is captured in ATP molecules, aerobic cellular respiration is a relatively efficient process, when compared with the burning of gasoline. About a third of the energy from glucose is stored in ATP molecules that are used for cellular work, while only a quarter of the fuel burned in automobiles is actually used to move the car.[15] For more detailed explanations of the process of cellular respiration, see Cooper[16] and Reese and Campbell.[17]

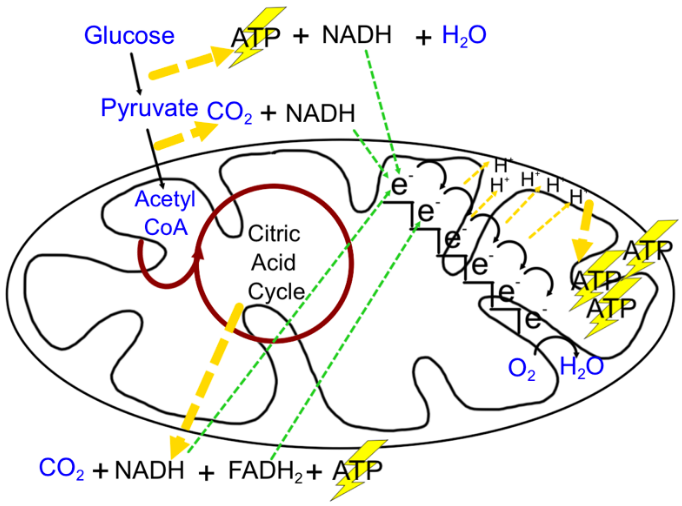


Figure 2. Summary of the steps of cellular respiration.

Energy Transfer – From Chemical Reactions to Ecosystems

Gibbs free energy is the portion of the energy of a system that could do work. In molecules, the chemical potential energy results from the arrangement of electrons in the chemical bonds of that molecule. Bond dissociation energy is the amount of energy needed to homolytically break a particular bond, or the amount of energy released when that bond is formed. Chemical reactions involve the breaking and reforming of bonds in new molecules, so they will result in a net increase or decrease of free energy. The change in that free energy is represented by $\Delta G°$. This number is negative when a process occurs spontaneously (not necessarily instantaneously but is thermodynamically downhill), without the need of an input of energy. If this is the case, the products are more stable and store less chemical energy than the starting reactants. Exergonic (downhill) reactions such as this, result in a net release of energy, while endergonic reactions have a positive $\Delta G°$, absorb energy from their surroundings, and result in a net storage of energy in the products (have weaker chemical bonds). In the case of cellular respiration, $\Delta G°$ is equal to -686 kcal (2870 kJ) per mole of glucose broken down under standard conditions, while photosynthesis results in a $\Delta G°$ of +686 kcal per mole of glucose assembled.[18] This means that 686 kcal per mole of glucose are made available to the cell to do work during cellular respiration, while a net 686 kcal per mole are required to perform photosynthesis.

Of course, it's not as simple as that. The energy from glucose when released during cellular respiration is used to produce ATP molecules that store usable energy for the cell. For example, ATP hydrolysis can be coupled with chemical reactions that require energy. For each glucose molecule, up to 38 ATP molecules can be produced through aerobic cellular respiration.[19] The ΔG° of ATP hydrolysis is -7.3 kcal/mole (-30.5 kJ/mole) under standard conditions, but is closer to -13 kcal/mole under conditions typical of the cell.[20] Even if you consider the higher number, one glucose molecule should be able to produce 52 ATP molecules (686 ÷ 13 = 52.8). The process is not 100% efficient, and much of the energy stored in the glucose molecule is lost to the system as heat energy.

Energy flows in an ecosystem through these (and related) processes. The original source of energy for most ecosystems on Earth is the sun. (Thermal radiation supporting life in hydrothermal vents is an exception.[21]) The nuclear fusion of four hydrogen atoms into a helium atom results in the release of a large amount of energy. This seemingly limitless source of energy (at least for the next few billion years) is available to convert into chemical energy through photosynthesis by photoautotrophs. Photoautotrophs (producers) convert light energy from the sun into chemical energy stored in the molecules of carbohydrates. Photosynthesis is responsible for generating an estimated 160 billion metric tons (1.6×10^{14} kg) of carbohydrates each year.[22] Some of the energy in these carbohydrates is converted to ATP during cellular respiration and used by the cell for other cellular processes, while others are stored or used to make other organic molecules, adding to the biomass of the organism.

When a primary consumer eats a producer, both the biomass and the energy stored in the bonds of the food is transferred to the next trophic level, but only a small portion of the energy is transferred to chemical energy stored in the consumer (the rest is used for the organism’s cellular needs or released as heat). The same holds true when a secondary consumer eats a primary consumer. This 10% law is an estimate, but provides a manageable number for students to calculate and a useful tool to understand the transfer of energy.

Models such as food webs and trophic pyramids demonstrate the transfer of energy in ecosystems. In a food web arrows point in the direction of energy flow, so the arrows point from the producers, to primary consumers, to secondary consumers, etc. The trophic pyramid also shows the transfer of energy in ecosystems, but instead demonstrates the relative amounts of energy in each trophic level. It also clarifies for students why there is an upper limit to the number of trophic levels in an ecosystem. With only an estimated 10% of the energy being transferred, there is less and less available energy to support the next trophic level, and eventually there just won’t be enough energy to sustain another. The trophic pyramid also helps explain why biomass and number of individual organisms also decrease with increasing trophic levels.

Classroom Activities

My goal for this curriculum unit is to help students understand how the processes of photosynthesis and cellular respiration transform and transfer matter and energy through organisms in an ecosystem. For most of these activities, students will work in pairs or groups of three or four. Supplemental readings, videos, and other resources will be delivered through activities on Schoology to help students consolidate the information they gather in the following activities. These can also be used to differentiate the activities. Before beginning the ecology unit, students take the “Giant Sequoia Tree” preassessment described in the “Student Misconceptions” section above, to assess what the students already know.

Matter and Energy

Because of the students’ difficulty in differentiating between matter and energy, I have them make a table almost like a Venn diagram, writing everything they know about the similarities and differences between matter and energy. We have a class discussion, correcting any misconceptions, and I have them refer to the table frequently when asking them questions during the unit. My goal is for the students to ascertain whether the question is asking about matter, energy or both, and responding to the question appropriately.

Matter Matters

The first activity is one that we have done every year since I began teaching biology, and has been part of the Delaware recommended curriculum for biology. Students sprout radish seeds in a closed environment (baby food jars sealed with Parafilm with only 10 radish seeds, water, a paper towel, and air inside) to determine where the mass of the growing plants comes from. I have every student group set up one jar in this way so we can collect class data. I also direct them to determine the mass of the 10 radish seeds as well as the mass of the sealed container after everything is added. I encourage them to set up other jars to investigate the effect of a chosen variable on the growth of the seeds (for example, an open system or growing the seeds in the dark) to help them better understand the phenomenon. While the seeds are germinating, we go on to other activities. When we revisit this activity, students should observe that the mass of the sealed container (including its contents) hasn’t changed, but the mass of the seeds increased as the plants grew. I ask students to reflect on their observations to come to a conclusion as to how these plants gained the matter (atoms) they needed to grow and gain mass. After that, I tell the story of van Helmont and his experiment (growing a sapling in 200 pounds of soil, adding only water, then weighing the soil and the tree afterward). I ask the students to interpret the results of his experiment and how it applies to the preassessment they did at the beginning of the unit. Between these two activities, it becomes obvious to students that the soil does not contribute much to the mass of the tree, water is a possible candidate, and that light is needed for the seedling to grow but not to germinate. They will build on these ideas as they progress through the unit, and revisit the phenomenon as an assessment of their understanding.

Science and Global Issues Ecology Activity 7: Energy Flow through an Ecosystem

Part A: Construct a Food Web

In this activity, students are asked to sort 13 cards with information about different organisms in the kelp forest, based on similarities in the information provided. Then they create a food web model to show the transfer of energy through the ecosystem, using the cards and a whiteboard. When their food web has been approved, they transfer that onto poster paper and then color code the producers, consumers, and decomposers.

Part B: Use a Food Web to Predict the Impact of Actions and Events on an Ecosystem

Students are given ecosystem event description cards and are asked to predict short-term and long-term effects on the ecosystem, based on their food webs.

Part C: Construct an Energy Pyramid

Student construct an energy pyramid model of the kelp forest ecosystem using the information from their food web. This leads to a class discussion of energy transfers in ecosystems, and students practice calculating the amount of energy available at each trophic level. I also give them additional work calculating biomass and discuss the pyramid of numbers as well. They come to understand why there are many more prey organisms than there are predators.

Science and Global Issues Ecology Activity 8: Carbon Cycle

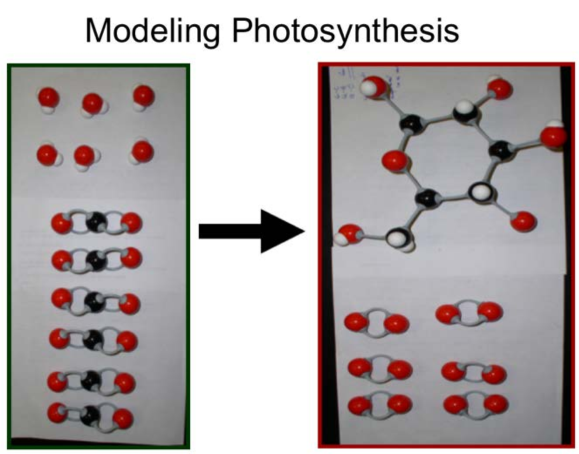
This activity makes the transition from energy to matter in an ecosystem. It uses a computer simulation to focus on the cycling of carbon in an ecosystem between different carbon reservoirs. The activity provides information about the amount of carbon in different reservoirs before and after the industrial revolution, and students look at how different processes (including photosynthesis, cellular respiration and burning fossil fuels) transfer carbon between these reservoirs. They come to the conclusion that although the amount of carbon in some reservoirs increases, the amount in others decreases, and the overall amount of matter (carbon) stays the same.

Science and Global Issues Ecology Activity 9: The Photosynthesis and Cellular Respiration Shuffle

This activity uses both a computer simulation and cards to demonstrate the relationship between photosynthesis and cellular respiration, showing both the cycling of matter and transfer of energy in an ecosystem. Students first sort cards with diagrams of different steps of photosynthesis and cellular respiration, dividing the cards into the two processes and putting them in order, based on the inputs and outputs of these processes. They check their work with the simulation, and then write captions for each of the cards. NGSS asks students to focus on the inputs and outputs of these processes rather than the details described above, so this activity is appropriate for all students. Students requiring more of a challenge can visit the animations listed in “Additional Resources” to gain a better understanding of these processes.

What Does It Take? Modeling Photosynthesis and Cellular Respiration

This is another activity that was part of the Delaware recommended curriculum for biology prior to NGSS. Students use molecular models such as the ones in Figure 3 below to investigate the conservation of matter in chemical reactions. They are given molecular models of the reactants of photosynthesis, are asked to act as enzymes during photosynthesis to rearrange the atoms of the molecules to form glucose and oxygen molecules, then simulate cellular respiration to form the original molecules of carbon dioxide and water. Along the way they are asked questions relating to the equations and conservation of matter. This is when I introduce the summary equations of photosynthesis and cellular respiration and review balancing equations. I also use this activity to introduce chemical potential energy, as they will need to understand the concept before the next activity.



$$6H_2O + 6CO_2 \xrightarrow[\text{enzymes}]{\text{light}} C_6H_{12}O_6 + 6O_2$$

Figure 3. Using molecular models to model photosynthesis

Calculating Bond Energies to Demonstrate Conservation of Energy

In this activity, students calculate the bond energies involved in cellular respiration (and later photosynthesis), based on the summary equations for each process. (See bond energy worksheets in “Additional Resources.”) Kilocalories are used rather than kilojoules because students are familiar with the idea of Calories in food being a measure of energy in that food, and our culinary arts and health career students use units of Calories in their career areas. First they calculate the change in free energy during cellular respiration, using the table in Figure 4.[23] They add up the total bond energy in a glucose molecule (2182 kcal/mole) and the six oxygen gas molecules (6 x 116 = 696 kcal/mole) for a total bond energy of 2878 kcal/mole in the reactants. The same is done for the products of cellular respiration. The free energy in six carbon dioxide molecules is 2244 kcal/mole, while the free energy in six water molecules is 1320 kcal/mole, resulting in a total energy of 3564 kcal/mole in the products. By subtracting the total amount of energy in the products from that of the reactants, the net free energy change is -686 kcal/mole, the negative sign indicating a net release of energy.

Students are then asked to develop a model showing that the release or absorption of energy from this chemical reaction system depends upon the total bond energy (almost verbatim from the NGSS performance standards). A colleague and I did this activity with our students this semester for the first time, and we found that students needed some prior instruction on energy diagrams before tackling this task. I used the combustion of hydrogen and electrolysis of water as examples to review chemical reactions and demonstrate energy diagrams with the students. Many students still struggled, however, because they were not sure how to display the total bond energy of the reactants and the products. Many wanted to plot the reactants at 2878 kcal/mole and the products at 3564 kcal/mole, when conceptually, the amount of bond energy in the reactants is the energy that is needed to break the bonds and get them to the transition state. The amount of energy released when new bonds are formed in the products is the difference between the transition state and the products. So the net energy change is the difference between the stored energy of the products and the transition state subtracted from the difference between the stored energy of the reactants and the transition state. Drawing the model this way shows a net release of energy of -686 kcal/mole of glucose. A sample model is shown in Figure 4 below.

Average Bond Energies

Bond Type	kcal/mol	kJ/mol
C-H	98	410
O-H	110	460
C-C	80	335
C-O	78	326
O=O	116 (2x58)	485 (2x242.5)
C=O	187* (2x93.5)	782* (2x391)
(*as found in CO2)		

Source: Kimball's Biology Pages, 2010 (kJ/mol calculated using 4.184 kJ per kcal conversion factor). Bond energy estimates are somewhat variable, depending on source, but these estimates work for the purposes of this activity.

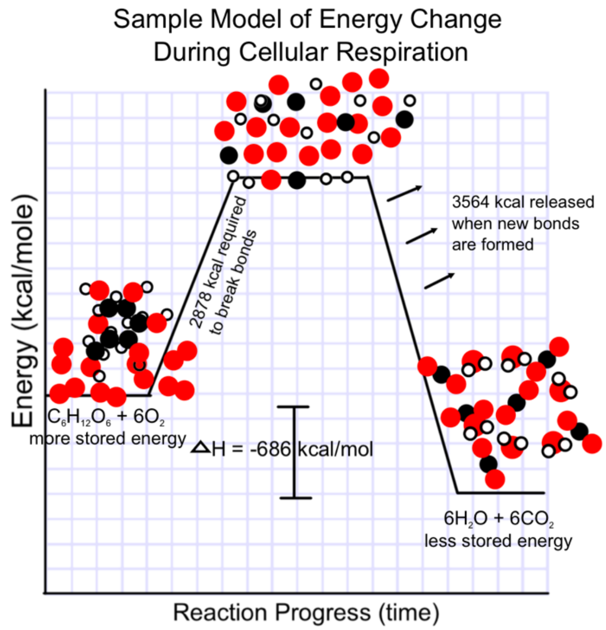


Figure 4. Table of average bond energies and sample model of energy change during cellular respiration

Finally, we asked the students to repeat the process for photosynthesis, which took much less time since almost all the calculations were already done. They still struggled with the model, but when the new model was completed and they were asked to compare the two models, many of the students had an "aha" moment when they realized that the amount of energy stored during photosynthesis was exactly the same as the amount released during cellular respiration. At the end of this activity, students were given the amount energy released in removing a phosphate group of an ATP molecule during ATP hydrolysis under cellular conditions, and then asked to calculate how many ATP molecules could be generated from one molecule of glucose. They then realize that not all the energy in glucose is converted into energy in ATP, and conclude that the process is not 100%, some of the energy being lost to the system as heat. I have them apply this knowledge to the trophic pyramid they constructed in SGI Activity 7 (described above), and construct an explanation of why only about 10% of the energy is stored in each trophic level.

Burning Gummy

This engaging demonstration has proven to be useful in student understanding of the necessity of ATP for cellular activities. I add 5 grams of potassium chlorate to a heat resistant (Pyrex) test tube large enough to easily drop a gummy bear. I then melt the potassium chlorate using a butane torch, while discussing the main ingredients of a gummy bear (corn syrup, sucrose, and dextrose), noting that all of these ingredients contain glucose and/or fructose. A thermocoupler can be used to measure the heat released from the reaction, or a simple Styrofoam calorimeter could be constructed to note the temperature change in the water (which would help students understand the definition of a calorie).[24] Students get a very clear picture of the energy released and exactly how much energy is contained in very few Calories (kilocalories). Releasing all the energy in glucose could be damaging to cells, so ATP is utilized to safely release energy as it is needed by the cell. (Note: Follow all safety precautions, especially the use of goggles and a shield, as the reaction is highly exothermic. Although I have never had a test tube shatter when doing this demonstration, it is quite possible. If you are unable to perform the demonstration, many similar videos can be accessed on youtube.com. I have included one in the "Additional Resources" section.)

Factors that Affect the Rate of Photosynthesis

For this activity, we use the Gizmo called "Photosynthesis Lab" at explorelearning.com.[25] In this simulation, students vary the temperature, color of light, amount of light, and amount of carbon dioxide, observing the effects on the amount of oxygen produced by a plant. Students are able to record data in the simulation, and display their data as a graph. This activity requires a subscription. Instead of using the student exploration sheet provided with the activity, I have students explore on their own, first changing one variable at a time and then two or more variables. They record their data and draw graphs of their results in their student notebooks. I then ask them to find the best combination of variables to maximize photosynthesis, making it a class competition.

Factors that Affect the Rate of Cellular Respiration

The Respiring Biomass Activity is based on Science and Global Issues (SGI) Ecology Activity 10. In this activity students use lima beans and phenol red to design experiments that test the effect of different factors on the rate of cellular respiration. During cellular respiration, two hydrogen atoms (two protons and two electrons) are removed from glucose. Two electrons and one proton are transferred to NAD^+, reducing it to NADH. The extra H^+ causes the pH of the solution to decrease, making it more acidic, and changing the color from orange to yellow. Having very little luck with using phenol red as an indicator in this study, I chose instead to use bromothymol blue (BTB) to determine the amount of carbon dioxide produced through cellular respiration.

If using the SGI Ecology Activity 10, in addition to the information provided in the teacher's guide, I would suggest the following:

1. Use BTB instead of phenol red for quicker results.

2. If the cups in the kit are not available, add two large lima beans to 5 mL of BTB in large test tubes (one for each condition). Wrap the test tubes in Parafilm to seal them. This gave us much quicker results than the cups.
3. Be prepared to soak the beans for one extra day. The SGI teacher's guide recommends one day of soaking and one day on wet paper towels. An additional day on wet paper towels may have improved our results. Only use those beans that have a visible hypocotyl.

Because the Next Generation Science Standards embed photosynthesis and cellular respiration in an ecological context, I felt it would be beneficial to use radish seeds, measuring the biomass of the seeds instead of counting them. The students have already learned about biomass in the context of trophic pyramids, and they were familiar with radish seeds from their Matter Matters activity. In order to make the activity more quantitative, I decided to change the data collection. Instead of noting color change, which can be gradual, we used a spectrophotometer to measure color change in the BTB over 10, 20 and 30 minutes. A sample procedure is given below:

1. Measure 3 grams of radish seeds into four large glass test tubes. Add 10 mL BTB solution (approximately 0.005%) and immediately seal the tube with stoppers or Parafilm and place into the following conditions:
    a. Ice water bath
    b. Room temperature water
    c. Warm (40°C) water bath
    d. Hot (80°C) water bath
2. After 10 minutes, gently swirl the solution in each test tube and add one mL of the BTB solution from each test tube to the spectrophotometer cuvettes, resealing the test tubes immediately after taking each sample.
3. Use the spectrophotometer to measure the absorbance of each solution and record the absorbance at the large peak of the solution (approximately 620 nanometers). A control with the stock BTB solution should also be measured.
4. Repeat steps 2 and 3 after 20 and 30 minutes.

Sample results are shown in Figure 5 below.

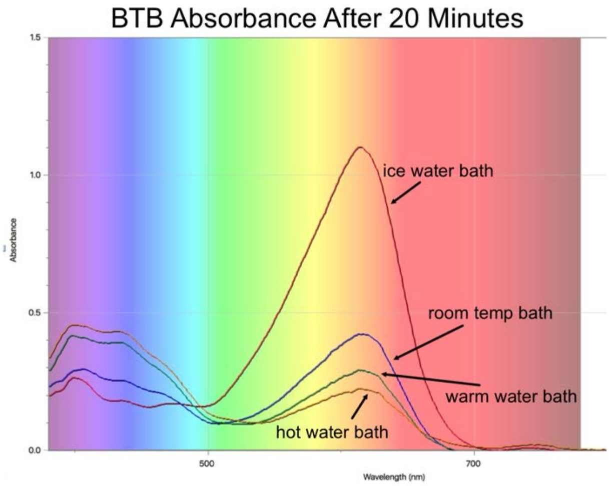


Figure 5. Sample results from the Respiring Biomass activity

Students may choose to test other factors besides temperature, and may analyze and display the data in a number of ways. I felt it important for the students to understand the meaning of results from the spectrophotometer, so they were assigned activities on Schoology to better understand light, color, and how a spectrophotometer works. This provides an opportunity to differentiate, since students are able to design their experiments and analyze their data in many different ways. Struggling students had a hard time understanding the relationship between absorbance and the rate of cellular respiration, so I would recommend they design their experiments to collect qualitative data, focusing on the color change.

Assessment

In addition to traditional assessments, I use performance assessments to test students' mastery of performance standards. The first performance assessment is given midway through the unit. Students read an article about a Delaware ecosystem, the dunes of Cape Henlopen State Park, to gather information about the interactions between organisms in that ecosystem. They then use the information they obtain to construct a food web. I also give them data on biomass at the different trophic levels of the ecosystem, and they calculate the percent of biomass transferred to each trophic level. They then construct an energy pyramid and discuss the energy conversions in the ecosystem.

The end of unit performance assessment begins with a reading of gross and net primary production (something they have not yet been exposed to). They gather information about these terms and relate the new information to what they have studied in this unit. They also gather information about the NPP, amount of sunlight, and temperature in different biomes from tables and maps. They then construct an explanation demonstrating which biome will provide the most NPP to secondary consumers, using all they have learned in the unit. Next they look at a Keeling Curve showing the increase in atmospheric carbon dioxide over time, explain the cyclical rise and fall of CO_2 levels each year, and make a claim whether this overall rise in CO_2 would result in an increase or decrease in NPP over time, providing evidence from the reading and figures, as well as the information learned in this unit.

Additional Resources

Sample Bond Energy Student Worksheet (https://drive.google.com/file/d/0B2Ehdy7-GZSkM1dEYTkwOU9zMGs/view?usp=sharing)

Gizmos (www.explorelearning.com)

Gizmos are interactives that help students explore scientific concepts. There are Gizmos for almost every topic, but few that specifically meet the standards in this unit. Each Gizmo comes with a teacher guide, vocabulary sheet, and student exploration worksheet. The following Gizmos could be used with this unit.

Cell Energy Cycle

Although I think the name is inappropriate, this Gizmo is a good interactive for the basic inputs and outputs of both photosynthesis and cellular respiration. Students add reactants to the chloroplasts (and later mitochondria) and observe the outputs, the equation, and then the balanced summary equation. It also shows simple energy transfers, and shows glycolysis happening outside the mitochondria, while the rest of cellular respiration takes place inside the mitochondria. I use this as remediation because it is very easy to follow, and the students can usually complete the student exploration sheet independently without any trouble. This Gizmo also shows the energy transfers during photosynthesis and cellular respiration in a very simplified way.

Photosynthesis Lab

This Gizmo is useful for investigating the effects of different variables (carbon dioxide concentration, light intensity, color of light and temperature) on the rate of photosynthesis and thus the production of oxygen. This is useful because it is more open ended - the students choose the settings and then record their data in their science notebooks.

Other Interactives/Animations/Videos

I have found the following links useful, either in preparing students for activities, or using as enrichment or remediation with students.

- Vernier Spectrovis Plus training video: www.vernier.com/training/videos/play/?video=163 (Shows how to use the Spectrovis Plus, including fluorescence settings.)
- "Gummy Bear Experiment" with molten potassium chlorate: https://www.youtube.com/watch?v=7Xu2YZzufTM (Video showing Burning Gummy demonstration for students who are absent.)
- Bioman Photosynthesis and Respiration Game: https://biomanbio.com/GamesandLabs/PhotoRespgames/phorespgame.html (Mainly to help review the basics. There are also quizzes students can take.)
- Johnson Exploration: Photosynthesis: http://mhhe.com/biosci/genbio/biolink/j_explorations/ch09expl.htm (Interactive that reviews the process of photosynthesis.)
- Amoeba Sisters Youtube channel: https://www.youtube.com/user/AmoebaSisters (Short engaging videos on various science topics, especially useful for struggling students.)
    - "Cellular Respiration and the Mighty Mitochondria"
    - "Photosynthesis and the Teeny Tiny Pigment Pancakes"
    - "Food Webs and Energy Pyramids"
    - "Carbon and Nitrogen Cycles"

Appendix

Standards Alignment

Delaware has adopted the Next Generation Science Standards (NGSS)[26], so our biology curriculum includes all three dimensions of learning in science: Science and Engineering Practices, Crosscutting Concepts, and Disciplinary Core Ideas. I have found that making the practices and concepts apparent to the students is an important step towards understanding the core ideas in biology as well as the scientific process.

The main Science and Engineering Practices used in this unit are the following:

2. Developing and Using Models
5. Using Mathematics and Computational Thinking
8. Obtaining, Evaluating, and Communicating Information

The main Crosscutting Concept used in this unit is the following:

5. Energy and Matter: Flows, Cycles and Conservation

This unit also includes the following performance standards from the Disciplinary Core Ideas. Note that one of the standards taught in the biology curriculum comes from a physical science standard. Although the curriculum being developed for the state of

Delaware is still a work in progress, at present time these performance standards are to be included in the biology course:

> HS-PS 1-2 Develop a model to illustrate that the release or absorption of energy from a chemical reaction system depends upon the changes in total bond energy.
> HS-LS 1-5 Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy.
> HS-LS 1-7 Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in new compounds are formed resulting in a net transfer of energy.
> HS-LS 2-3 Construct and revise an explanation based on evidence for the cycling of matter and flow of energy in aerobic and anaerobic conditions.
> HS-LS 2-4 Use mathematical representations to support claims for the cycling of matter and flow of energy among organisms in an ecosystem.
> HS-LS 2-5 Develop a model to illustrate the role of photosynthesis and cellular respiration in the cycling of carbon among the biosphere, atmosphere, hydrosphere, and geosphere.

Bibliography

Cooper, Geoffrey M. *The Cell: A Molecular Approach*. Washington, D.C.: ASM Press, 1997.

Delaware Department of Education. "Delaware DOE School Profiles." Accessed August 12, 2016. http://profiles.doe.k12.de.us/schoolprofiles/School/Default.aspx?checkSchool=80.

Explore Learning. "Photosynthesis Lab Gizmo." Accessed October 21, 2016. https://www.explorelearning.com/index.cfm?method=cResource.dspDetail&%3BResourceID=395&%3BClassID=0.

Govenar, Breea. "Energy Transfer through Food Webs at Hydrothermal Vents: Linking the Lithosphere to the Biosphere." *Oceanography* 25 (2012): 246–255. Accessed November 13, 2016. http://dx.doi.org/10.5670/oceanog.2012.23.

Harvard-Smithsonian Center for Astrophysics. "Lessons from Thin Air." Vol. 2 of *Minds of our own*. Washington, DC: Annenberg Media. 1997. Accessed October 1, 2017. http://www.learner.org/vod/vod_window.html?pid=77 .

Hershey, David R. "Avoid Misconceptions when Teaching about Plants." August 2004. Accessed November 8, 2016. http://www.actionbioscience.org/education/hershey.html

Helmenstine, Anne Marie, PhD. "Coffee Cup Calorimetry and Bomb Calorimetry." About.com Education. December 04, 2015. Accessed January 19, 2017. http://chemistry.about.com/od/thermodynamics/a/coffee-cup-bomb-calorimetry.htm.

Keeley, Page, Francis Eberle, and Joyce Tugel. "Giant Sequoia Tree." In *Uncovering Student Ideas in Science*. Arlington, VA: NSTA Press, 2007.

Kimball, John W. "Bond Energy." Kimball's Biology Pages. December 29, 2010. Accessed September 30, 2016. http://www.biology-pages.info/B/BondEnergy.html.

Quinn, Helen, Heidi Schweingruber, and Thomas Keller, eds. *Framework for K-12 Science Education*. Washington, D.C.: National Academy Press, 2011.

Ray, Andrew M., and Paul M. Beardsley. "Overcoming Student Misconceptions about Photosynthesis: A Model- and Inquiry-Based Approach Using Aquatic Plants". *Science Activities: Classroom Projects and Curriculum Ideas.* 45 (2008): 13-22.

Reece, Jane B., and Neil A. Campbell. *Campbell Biology*. 9th ed. Boston: Benjamin Cummings, 2011.

SEPUP. *Science and Global Issues: Biology*. Rondonkoma, NY: Lab-aids, 2011.

Song, Kim, and Donald Le. "Bond Energies." Chemistry LibreTexts. October 14, 2016. Accessed December 30, 2016. http://chem.libretexts.org/Core/Physical_and_Theoretical_Chemistry/Chemical_Bonding/General_Principles_of_Chemical_Bonding/Bond_Energies.

Svandova, Katerina. "Secondary School Students' Misconceptions about Photosynthesis and Plant Respiration: Preliminary Results." *Eurasia Journal Of Mathematics, Science & Technology Education* 10 (February 2014): 59-67. *Education Source*, EBSCO*host* Accessed November 8, 2016.

Vasta, Rita. "DTHS Stats." E-mail message to author. August 9, 2016.

---

1 Rita Vasta, "DTHS Stats," E-mail message to author, August 9, 2016.
2 "Delaware DOE School Profiles," accessed August 12, 2016. http://profiles.doe.k12.de.us/schoolprofiles/School/Default.aspx?checkSchool=80
3 Vasta, 2016.
4 SEPUP. *Science and Global Issues: Biology* (Rondonkoma, NY: Lab-aids, 2011).
5 Page Keeley, Francis Eberle and Joyce Tugel, "Giant Sequoia Tree," in *Uncovering Student Ideas in Science* (Arlington, VA: NSTA Press, 2007).
6 Harvard-Smithsonian Center for Astrophysics, "Lessons from Thin Air," Vol. 2 of *Minds of Our Own* (Washington, DC: Annenberg Media, 1997), accessed October 1, 2017, http://www.learner.org/vod/vod_window.html?pid=77.
7 Katerina Svandova, "Secondary School Students' Misconceptions about Photosynthesis and Plant Respiration: Preliminary Results." *Eurasia Journal of Mathematics, Science & Technology Education* 10 (2014): 59-67, *Education Source*, EBSCO*host*, accessed November 8, 2016.
8 Andrew M. Ray and Paul M. Beardsley, "Overcoming Student Misconceptions about Photosynthesis: A Model- and Inquiry-Based Approach Using Aquatic Plants," *Science Activities: Classroom Projects and Curriculum Ideas*, 45 (2008): 13-22.
9 David R. Hershey, "Avoid Misconceptions when Teaching about Plants," accessed November 8, 2016, http://www.actionbioscience.org/education/hershey.html.
10 Geoffrey M. Cooper, *The Cell: A Molecular Approach* (Washington, D.C.: ASM Press, 1997), 404-415.
11 Jane B. Reece and Neil A. Campbell, *Campbell Biology*, 9th ed. (Boston: Benjamin Cummings, 2011), 184-203.
12 Cooper, *The Cell: A Molecular Approach*, 63.
13 Reece and Campbell, *Campbell Biology*,151.
14 Reece and Campbell, *Campbell Biology*, 164.
15 Reece and Campbell, *Campbell Biology*, 176-177.

[16] Cooper, *The Cell: A Molecular Approach*, 389-404.
[17] Reece and Campbell, *Campbell Biology*, 163-183.
[18] Cooper, *The Cell: A Molecular Approach*, 65.
[19] Cooper, *The Cell: A Molecular Approach*, 68.
[20] Reece and Campbell, *Campbell Biology*, 150.
[21] Breea Govenar, "Energy Transfer through Food Webs at Hydrothermal Vents: Linking the Lithosphere to the Biosphere," *Oceanography* 25 (2012): 246–255, accessed November 13, 2016, http://dx.doi.org/10.5670/oceanog.2012.23.
[22] Reese and Campbell, *Campbell Biology*, 203.
[23] John W. Kimball, "Bond Energy," Kimball's Biology Pages, December 29, 2010, accessed September 30, 2016, http://www.biology-pages.info/B/BondEnergy.html.
[24] Helmenstine, Anne Marie, PhD, "Coffee Cup Calorimetry and Bomb Calorimetry," About.com Education, December 04, 2015, accessed January 19, 2017. http://chemistry.about.com/od/thermodynamics/a/coffee-cup-bomb-calorimetry.htm.
[25] Explore Learning, "Photosynthesis Lab Gizmo," accessed October 21, 2016, https://www.explorelearning.com/index.cfm?method=cResource.dspDetail&%3BResourceID=395&%3BClassID=0.
[26] Helen Quinn, Heidi Schweingruber and Thomas Keller, eds, *Framework for K-12 Science Education* (Washington, D.C.: National Academy Press, 2011).