Teacher Preparation Notes for Photosynthesis, Cellular Respiration and Plant Growth

This minds-on, hands-on activity begins with the question of how a tiny seed grows into a giant Sequoia tree. Students analyze data from research on plant molecules and processes and changes in plant biomass. In addition, students conduct an experiment to evaluate changes in CO₂ concentration in the air around plants in the light vs. dark. Students interpret the data to understand how photosynthesis makes an essential contribution to increases in plant biomass, and cellular respiration can result in decreases in plant biomass. This activity counteracts several common misconceptions about plant growth, photosynthesis, and cellular respiration.

This activity will probably require two 50-minute periods, with ~23 hours between these two periods. Teachers or their students will need to begin to grow the plants approximately two weeks before the students will be doing the experiment.

Before beginning this activity, students should have a basic understanding of cellular respiration, ATP and photosynthesis. For this purpose, we recommend these analysis and discussion activities:

- “How do organisms use energy?”
  (https://serendipstudio.org/exchange/bioactivities/energy)
- "Using Models to Understand Photosynthesis"
  (https://serendipstudio.org/exchange/bioactivities/modelphoto)

You can streamline or expand this activity as follows:

- To replace the hands-on part of the activity (questions 10-12), you can substitute a video with questions (https://carbontime.bscs.org/plants/activity-3.1; scroll down to the last item under Resources Provided).
- To reinforce student understanding of how the outputs from photosynthesis are inputs for cellular respiration and vice versa, you may want to add questions 2-6 of “Photosynthesis and Cellular Respiration – Understanding the Basics of Bioenergetics and Biosynthesis” (https://serendipstudio.org/exchange/bioactivities/photocellrespir).
- For additional experimental evidence and a somewhat more complete and sophisticated analysis of where a plant’s mass comes from, you may want to add questions 4-5 and 8-10 from “Where does a plant’s mass come from?” (https://serendipstudio.org/exchange/bioactivities/photocellrespir).²

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¹ By Drs. Ingrid Waldron, Lori Spindler, and Linda Robinson, Department of Biology, University of Pennsylvania, © 2019. These Teacher Preparation Notes and the Student Handout are available at https://serendipstudio.org/sci_edu/waldron/#photobiomass.
² The other questions in these two analysis and discussion learning activities are similar to questions that are included in this hands-on activity.
Learning Goals
In accord with the Next Generation Science Standards:\(^3\)

- Students learn the Disciplinary Core Idea LS1.C. "The process of photosynthesis converts light energy to stored chemical energy by converting carbon dioxide plus water into sugars plus released oxygen…. Cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken”, carbon dioxide and water are formed, and the energy released is used in the production of ATP from ADP and P. Then, the hydrolysis of ATP molecules provides the energy needed for many biological processes.

- Students engage in these Science Practices:
  o Analyzing and Interpreting Data. Evaluate the impact of new data on a working explanation and/or model of a proposed process or system."
  o “Constructing Explanations and Designing Solutions. Apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena…”.

- This activity can help students to understand the Crosscutting Concept: Energy and Matter, Flows, Cycles and Conservation:
  o “Energy drives the cycling of matter within and between systems.”
  o “… without inputs of energy (sunlight) and matter (carbon dioxide and water), a plant cannot grow.”

- This activity helps to prepare students for Performance Expectation: HS-LS1-5. "Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy."


- Many students think that plants get most of their biomass from the soil. In this activity, students analyze results from plants grown without soil, which counteracts this misconception.
- Many students don’t understand the importance of photosynthesis and find it hard to believe that the biomass of plants comes largely from a gas (CO\(_2\)). In this activity, students analyze why an increase in biomass for plants in the light is correlated with a decrease in CO\(_2\) in the surrounding air.
- Many students believe that only animals carry out cellular respiration and plants only carry out photosynthesis. They do not understand that plants also need to carry out cellular respiration to provide ATP for cellular processes. In this activity, the importance of plant cellular respiration is highlighted as students interpret the increase in CO\(_2\) in the air around plants in the dark.

\(^3\) http://www.nextgenscience.org/sites/default/files/HS%20LS%20topics%20combined%206.13.13.pdf
Supplies and Preparation

Start growing the plants 14-20 days before you plan to do the activity with your students. You may want to start germinating the radish seeds on a Monday morning so students can see the impressive changes during early development, including the sprouting of roots and the cotyledons. For maximum visibility of early plant development and to simplify the interpretation of experimental results, we recommend germinating the seeds on damp paper towels. Students can be enlisted to start the seeds, either in class if you have sufficient class time available or as an extracurricular project.

You can use any of the following methods to estimate how many groups you should plan for.

a. Estimate the number of pairs of groups of approximately four students in each class that you will be doing the activity with. Sum the estimated number of pairs of groups for all of your classes and multiply by two to determine the total number of student groups. This approach will be the most engaging, but also the most expensive, especially the first time you do this activity. The Student Handout is written for this amount of supplies.

b. Estimate the number of pairs of groups of approximately four students in your largest class where you will be doing the activity. Multiply this number by two to determine the total number of student groups. For this version, include the complete procedure on page 4 of the Student Handout only for the class that will set up the containers in the light and in the dark (probably your earliest class); omit procedures steps A, B and D for the other classes. Students will observe the sealed containers and immediately return the sealed containers to their light or dark location for observation by later classes.

c. Purchase the supplies for four groups (so you will have replicates of the plants in the light and the plants in the dark). Take photographs of the plants and indicator before and after each sealed container is put in the light or the dark for ~23 hours. Omit steps A, B and D from the procedure on page 4 of the Student Handout and have students use the photos to complete steps C and E.

Supplies for growing the plants for each group

- 20-30 radish seeds
- disposable 1-pound loaf aluminum pan and plastic wrap to loosely cover it (If you prefer, you can maintain a moist atmosphere around the sprouting seeds and seedlings by inverting the clear plastic containers (see page 5) over the loaf pans; the plastic containers should be propped up to allow airflow.)
- 15 cm length of cotton yarn

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4 This list of supplies and the planting instructions are modified from http://carbontime.bscs.org/sites/default/files/plants/worksheets_assessments/PRE_0.2_PT_Plant_Growth_Investigation_Setup_Worksheet.pdf.
• brown paper towel (must be unbleached brown paper towel, 2-3 sheets per group or a roll, which should be enough for all of your groups)
• 1 L of water for starting the seeds
• 1 L of water with dilute nutrients (e.g. Miracle Grow or Ionic Grow) for use after the seeds sprout (or at least after the cotyledons have turned green)

You will also need one or more large pans or trays to hold the loaf pans and the water to be wicked up into the loaf pans (e.g. https://www.chewy.com/frisco-dog-crate-replacement-pan-22/dp/117380; we recommend that you avoid large disposable aluminum pans, since we had major leakage due to corrosion as a result of interactions between the large and small disposable aluminum pans.)

Unless you have a very sunny place to grow the plants, we recommend supplementing sunlight with artificial light. You can use grow lights or a cheaper alternative such as a compact fluorescent bulb in a clamp lamp with reflector. To provide sufficient intensity, the bulb should be 6-10” from the growing plants, so you may need multiple bulbs/lamps. Seedling growth requires a fluorescent bulb that is full spectrum, daylight or cool/blue. The light should be on for 12-16 hours, alternating with approximately 8-12 hours of darkness; and electric timer is a convenient way to accomplish this. During Experiment 2, you will want to keep each loaf pan of plants in continuous light for ~23 hours or in continuous dark for ~23 hours.

**Planting Instructions**

- Poke a hole through the bottom of each loaf pan (with a pencil, nail or scissors).
- Run the yarn through the hole so that half the yarn falls outside the loaf pan and half is inside.
- Scrunch up 2-3 pieces of brown paper towel and place in the bottom of the loaf pan. Run the yarn wick up over the crumpled pieces of brown paper towel.
- Cut out a piece of brown paper towel big enough to cover the scrunched-up paper towels and a bit up the sides of the loaf pan. You will put the seeds on this piece of paper, and upright edges will prevent the seeds from falling off.
- Put the loaf pans in the large pan(s), add water to the large pan(s), and moisten the paper towels in the loaf pans. You want the paper towels to be damp, but not wet. If the paper towels are too wet, mold may grow. If the paper towels are too dry, few seeds will germinate. In our experience, ~90% of the seeds will germinate if the top piece of paper towel is appropriately damp.
- Place the large pans on a very sunny, warm windowsill and/or under artificial light.
- Count 20 radish seeds per loaf pan and carefully place these seeds on top of the damp paper towel in each loaf pan. Spread them out to give the seedlings room to grow. Cover with a loose piece of plastic wrap or inverted clear plastic container to ensure that the top piece of paper towel stays damp.
- Add water to the larger pan(s) as needed to keep the paper towels damp. Switch to nutrient solution once the cotyledons turn green.

For each group for investigating the indicator solution (question 11)

- 2 small beakers or clear plastic cups
- 1 or more straws
- 1 syringe or 1 mL pipette
- indicator solution (You will need enough indicator solution per group to half fill the two beakers, as well as the petri dish for the experiment. Prepare the indicator solution as a 10X stock in distilled water. For use, dilute the 10X stock solution to 1X with distilled water.)
For 100 ml 10X stock solution:

Mix in beaker:
- distilled or deionized water 97.99 ml
- ethanol 1.72 ml (Carolina #861281)
- 2-propanol 0.10 ml (100 ul) (Carolina #884890)
- Methanol 0.09 ml (90 ul) (Carolina #874950)

Add and stir into solution:
- Sodium bicarbonate 0.08g (80 mg) (pure baking soda from grocery store)
- Thymol blue 0.02 g (20 mg) (Sigma Aldrich # 114545-5G)
- Cresol red 0.01g (10 mg) Sigma Aldrich #114472-5G)

For 1X Solution: Dilute 10X stock solution 1:10 using distilled or deionized (not tap) water.

For each group for the experiment with plants in light vs. dark (Procedure on bottom of page 4 of the Student Handout)
- petri dish + indicator solution to half fill the petri dish
- loaf pan of plants
- a clear plastic container, big enough to hold a loaf pan of plants and a petri dish + a lid or plastic wrap to seal the container (e.g. 2-quart size clear plastic food storage container, https://www.katom.com/144-2SFSCW441.html)
- sunny location and/or artificial light for half the groups’ containers; dark closet or a large, dark plastic bag or a box with no holes or cracks for each container from the other half of the groups
- color chart to interpret changes in indicator color (http://www.biorad.com/webroot/web/pdf/lsr/literature/10049348.pdf)

Instructional Suggestions and Background
To maximize student participation and learning, I recommend that you have students work on groups of related questions in pairs or individually before having a class discussion of their answers.

In the Student Handout, numbers in bold indicate questions for the students to answer and letters in bold indicate steps in the experimental procedure for the students to do.

If you use the Word version of the Student Handout to make changes for your students, please check the PDF version to make sure that the formatting in the Word version is displaying correctly on your computer.

A key is available upon request to Ingrid Waldron (iwaldr@upenn.edu). The following pages provide instructional suggestions and additional background information – some for inclusion in your class discussions and some to provide you with relevant background that may be useful for your understanding and/or for responding to student questions.

First Page of Student Handout
The videos suggested at the beginning of the Student Handout will help your students develop a vivid understanding of the very impressive growth of a tiny seed into a huge giant Sequoia. The figure below provides another way to convey how very large a tree can become. For additional information about giant sequoias, see https://en.wikipedia.org/wiki/Sequoiadendron_giganteum.
As your students work in pairs to answer question 1, you may want to circulate around the room asking open-ended, probing questions. Class discussion of student answers to question 1a should set up hypotheses to explore in subsequent sections of the activity. To preserve student interest in subsequent sections, please do not try to teach definitive answers during this introductory discussion. In discussing student answers to question 1b, probe for how each proposed investigation would help scientists understand where the mass of a giant Sequoia comes from.

Question 2 introduces hydroponics (https://www.fullbloomhydroponics.net/hydroponic-systems-101/). This provides a dramatic counterexample to the common misconception that most of a plant’s mass comes from the soil. To preserve student interest, please do not try to teach definitive answers at this time.

Experiment 1 – Changes in Biomass for Seedlings Grown in Light vs. Dark
This section introduces experimental results and analysis and discussion questions to help students understand that:

- Plants can gain biomass in the light, but plants lose biomass in the dark.
- In the light, photosynthesis produces sugar molecules which serve as precursors for the synthesis of other organic molecules in the plant. ⁵ (This figure provides additional information.)

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⁵ To synthesize amino acids, nucleotides, and phospholipids, plants also need nitrogen and phosphorus, typically obtained from soil water. If you want to include this point, please see pages 10-11 for suggestions.
The three-part figure in the middle of page 2 of the Student Handout shows how a plant is made up of cells which contain chloroplasts which make sugars which are converted to other organic molecules in a plant’s cells. The Student Handout figure includes an edited version of the figure shown below in a larger size. The detail shown in the figure below is not discussed in this activity. If you want to introduce your students to the multiple reactions involved in photosynthesis, you can use the discussion and analysis activity “Using Models to Understand Photosynthesis” ([https://serendipstudio.org/exchange/bioactivities/modelphoto](https://serendipstudio.org/exchange/bioactivities/modelphoto)). Similarly, if you want to introduce your students to the multiple reactions involved in cellular respiration, you can use the discussion and analysis activity “Using Models to Understand Cellular Respiration” ([https://serendipstudio.org/exchange/bioactivities/modelCR](https://serendipstudio.org/exchange/bioactivities/modelCR)).

The following evidence supports the conclusion that atoms from CO₂ are the primary source of the mass of the glucose molecules produced by photosynthesis. Since CO₂ and H₂O are the inputs for photosynthesis, the carbon atoms in glucose must come from CO₂. Experiments using isotopes of oxygen have shown that the oxygen atoms in the sugar molecules produced by photosynthesis come from CO₂, while the oxygen atoms in the O₂ produced by photosynthesis come from H₂O ([https://www.howplantswork.com/2009/02/16/plants-dont-convert-co2-into-o2/](https://www.howplantswork.com/2009/02/16/plants-dont-convert-co2-into-o2/)). Note also that carbon and oxygen have much higher atomic weights than hydrogen, so most of the mass of glucose is due to the carbon and oxygen atoms. (See table below.)
<table>
<thead>
<tr>
<th>Atom</th>
<th>Atomic weight</th>
<th>Percent of molecular weight of glucose</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>12.0</td>
<td>40%</td>
</tr>
<tr>
<td>O</td>
<td>16.0</td>
<td>53%</td>
</tr>
<tr>
<td>H</td>
<td>1.0</td>
<td>7%</td>
</tr>
</tbody>
</table>

To help students understand that the gas, CO₂, actually has mass, you can use either or both of the following demonstrations.

- Have a student who is wearing a suitable protective glove hold some dry ice. He or she should notice the weight of the dry ice and also how it gives off CO₂ gas. Discuss how the same molecules/atoms are present in both the solid and gas, but are more spread out in the gas.
- Have the students measure the weight of a bottle or cup of carbonated soda immediately after removing the cap, and then several other times over a class period as more and more of the CO₂ bubbles off.

To help your students understand how water and CO₂ reach the chloroplasts, you may want to use the figure below.

![Leaf Structure labeled](https://www.carlsonstockart.com/images/sl/Leaf-Structure_labeled.jpg)

During your discussion of question 6, you may want to include this question:

Can light be converted to mass?

In question 7, students use the information from page 2 of the Student Handout to revise their models of where the giant Sequoia’s mass comes from.

The figure in the bottom half of page 3 of the Student Handout shows glucose as the sugar produced by photosynthesis. Photosynthesis directly produces a three-carbon sugar glyceraldehyde-3-phosphate which is used to synthesize glucose and fructose. Some of the glucose and fructose are used to make sucrose, which is transported to other parts of the plant. As you discuss this figure, students should understand two important points:

- Cells can not directly use sunlight or glucose to provide the energy for most biological processes. Therefore, all organisms (including plants) need to make ATP which can...
provide energy in the form needed to carry out many cellular processes (e.g. pumping substances into and out of cells and synthesis of organic molecules).

- Most organisms carry out cellular respiration to produce ATP. The important point that plants need to carry out cellular respiration contrasts with some diagrams of the carbon cycle in ecology which show photosynthesis occurring in plants and erroneously show cellular respiration occurring only in animals.

If you want to reinforce these points, you could use either or both of these questions:

8a. For each of the three processes shown, label the box with:
- L if this process only occurs in the light
- D if this process only occurs in the dark
- L + D if this process occurs in the light and in the dark
- No if the process does not occur in plants

8b. Cells in plant leaves have both chloroplasts and mitochondria. If plant cells can carry out photosynthesis to produce sugars, why do plant cells need mitochondria?

When you discuss how photosynthesis converts light energy to chemical energy, you should observe the following cautions. Chemical energy should not be thought of as stored in high-energy molecules such as glucose. Energy is not released when chemical bonds are broken. Energy can only be released when new chemical bonds are formed as molecules react to form other molecules. Therefore, it is more accurate to think of energy as stored in a system (e.g. the system of glucose and O₂ reactants), rather than in individual molecules or chemical bonds. (For a more complete discussion, see “Cellular Respiration and Photosynthesis – Important Concepts, Common Misconceptions and Learning Activities”; https://serendipstudio.org/exchange/bioactivities/cellrespiration)

As you know, hydrolysis refers to a chemical reaction in which a molecule is split into smaller molecules by reacting with water. Students may be less familiar with this term and may need help to recall this definition. This figure shows the hydrolysis of ATP.

(http://umdberg.pbworks.com/w/page/79788248/ATP%20hydrolysis)
Question 10 asks students to propose a hypothesis about how seedlings lose biomass in the dark. Their hypotheses will be tested in the next section.

Experiment 2 – Changes in CO₂ in the Air around Plants in the Light vs. Dark

Question 11 is intended to get students thinking about the hands-on experiment they will do in this section. During discussion of student answers to questions 10 and 11, you can encourage students to challenge others’ ideas and defend their ideas, but please save the “correct answers” for your discussion of questions 13-15.

Question 12 will help students to interpret the color changes of the CO₂ indicator solution; it will also provide the opportunity for students to remember that human cells carry out cellular respiration, so our exhaled air is rich in CO₂. A good discussion of the indicator used in this experiment is available on page 10 of http://www.bio-rad.com/webroot/web/pdf/lse/literature/10000066050.pdf; this source also presents a possible alternative, more sophisticated hands-on activity suitable for AP or college students.

As you discuss question 14, some students may benefit from a review of basic concepts. For this purpose, we recommend the video available at https://carbontime.bscs.org/plants/activity-3.1 (scroll down to the last item under Resources Provided).

If you want to introduce your students to additional aspects of plant growth you can use the following questions.

This figure summarizes how molecules and ions move in a plant.

15. Explain how the carbon and oxygen atoms from a CO₂ molecule in the air can become part of a cellulose molecule in the cell wall of a root cell. Be specific about the multiple steps needed.

To answer this question correctly, students need to understand that sugars are water-soluble, but cellulose is not. The figure in this question shows how NO₃⁻ and other minerals are absorbed from the soil through the roots and transported to other parts of the plant. If you want your students to learn that these minerals are used to synthesize organic molecules, you can use the following questions.

15b. Proteins are made up of amino acids which contain nitrogen atoms. How does a leaf cell in a plant get the nitrogen it needs to make proteins?
16a. Circle each of the five inputs to the tree shown in this figure.

16b. Explain why the tree needs each of these inputs.

The distinction between changes in biomass and changes in total mass discussed in question 16 in the Student Handout is observed in nature when plants in the dark gain total mass due to substantial uptake of water (http://plantsinmotion.bio.indiana.edu/plantmotion/movements/leafmovements/pumpkingrowth/pumpkin.html).

At the end of this section, we recommend that you discuss the Crosscutting Concepts:
• “Energy drives the cycling of matter within and between systems.”
• “without inputs of energy (sunlight) and matter (carbon dioxide and water), a plant cannot grow”. (This activity focuses on how cells grow; plant growth also depends on cell division.)

At the end of this section, you may also want to discuss how preventing forest destruction and growing new forests can reduce atmospheric CO₂ concentration, which can reduce global warming. However, you should be aware that these benefits are counteracted to varying degrees by other effects of trees (e.g. trees’ secretion of volatile organic compounds and the greater absorption of sunlight by leaves compared to more sunlight reflected by snow or light sand) (https://www.nature.com/articles/d41586-019-00122-z).

Effects of Photosynthesis and Cellular Respiration on Changes in Biomass
This figure shows some research evidence relevant to question 17. (Dry mass is very close to biomass.) The line that trends downward shows the decrease in biomass due to cellular respiration for peas germinating in the dark. The line with the slight uptick at the end shows the trends for peas germinating in the light. Biomass begins to increase once photosynthesis in the seedlings produces more sugars than the seedlings’ cells are consuming in cellular respiration.
Question 18 refers to starch in seeds as a source of glucose that can be used for cellular respiration and to synthesize other organic molecules for the seedling while it is growing underground. Seeds also contain oils that are used for these purposes, and many seeds also contain some sugar. Seeds also contain proteins, DNA and phospholipids.

Question 19 can be used for formative assessment and review of all the major concepts covered. We recommend that you have students prepare a draft of their summary posters individually. Then, they should meet in small groups to discuss their individual summary posters and make a consensus summary poster that reflects the group’s thinking. As the groups work, you can circulate around the room, asking probing questions of each group. Each group summary poster can be prepared on poster board or on a whiteboard. Then, a whole-class discussion of the different diagrams and charts can help to correct any remaining misconceptions and reinforce accurate understanding of the effects of photosynthesis and cellular respiration on changes in plant biomass.

6 For this purpose you would want one whiteboard per student group in your largest class. To obtain whiteboards, you can go to Home Depot and ask them to cut a 8’ x 4’ whiteboard (e.g. EUCATILE Hardboard Thrifty White Tile Board) into six pieces with the dimension 32” x 24”. They should have a power saw rig that allows their employees to cut the pieces very easily. They should not charge to cut them and the product cost is reasonable.

Some important tips for using whiteboards:
- Coat the white boards with Endust (or similar product) before using. Every once in a while, wipe them clean and reapply Endust.
- Do not use markers that are old or almost empty. The ink from these are more difficult to erase.
- Black markers are easiest to erase. To prevent stains, erase right away, especially red or green markers. Do not use markers that are old or almost empty, since the ink from these is more difficult to erase. Recommended brands are Expo markers and Pilot BeGreen markers. To clean up stains you can use Windex or Expo Whiteboard Cleaner.
- Teacher and/or students can take a picture of the information on the board if they want to save it.


To begin, students view a video about the trophic cascade that resulted when wolves were reintroduced to Yellowstone. To better understand this trophic cascade, students learn about food webs and construct and analyze a food web for Yellowstone National Park. Next, students learn that the biosphere requires a continuous inflow of energy, but does not need an inflow of carbon atoms. To understand why, students analyze how the carbon cycle and energy flow through ecosystems result from photosynthesis, biosynthesis, cellular respiration and the trophic relationships in food webs. In the final section, students use the concepts they have learned to understand trophic pyramids and phenomena such as the relative population sizes for wolves vs. elk in Yellowstone. Thus, students are introduced to several ecological phenomena which they interpret as they learn about relevant processes at the cellular-molecular, organismal, and ecological levels. (NGSS).

Possible alternatives to this hands-on activity include:
- “Photosynthesis Investigation” (https://serendipstudio.org/exchange/bioactivities/photocellrespir), which presents a semi-quantitative, but technically more difficult method for measuring the rate of photosynthesis. The last section gives instructions for student-designed investigations of factors that may influence the rate of photosynthesis (NGSS);

Sources of Student Handout Figures
- Figure of giant Sequoia on pages 1 and 3 – https://www.pngkey.com/png/detail/94-945686_are-giant-sequoia-trees-succumbing-to-drought-giant.png
- Figure of Experiment 1 on the top of page 2 and the bottom of page 5 – From Ebert-May et al., Disciplinary Research Strategies for Assessment of Learning, BioScience 53:1221-8, 2003
- Figure of plant, plant cell and chloroplast on page 2 – constructed using edited images from https://www2.estrellamountain.edu/faculty/farabee/biobk/leaf1.gif https://i.pinimg.com/originals/97/c8/07/97c8077bb24aaaf8d9ee569c37e0cc57a.gif and https://classconnection.s3.amazonaws.com/114/flashcards/433114/jpg/picture21330823222426.jpg
- Figure of plant energy processes on page 3 – modified from https://sites.google.com/site/lmwhitebiology/_/rsrsrc/1443747840357/energy/photosynthesis-cellular-