Photorespiration

Photorespiration is a wasteful pathway that competes with the Calvin cycle. It begins when rubisco acts on oxygen instead of carbon dioxide.

Introduction

Do you have any friends who are awesome people, but who also have some kind of bad habit? Maybe they procrastinate a lot, forget your birthday, or never remember to brush their teeth. You wouldn't stop being friends with them for these reasons, yet from time to time, you might find yourself wishing they would clean up their act.

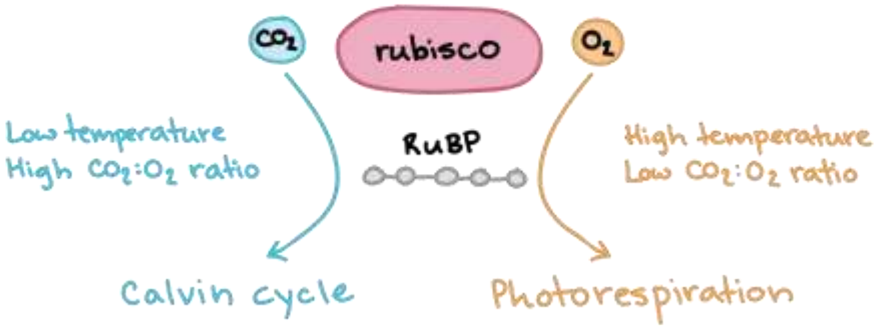
RuBP oxygenase-carboxylase (**rubisco**), a key enzyme in photosynthesis, is the molecular equivalent of a good friend with a bad habit. In the process of **carbon fixation**, rubisco incorporates carbon dioxide (CO_2) into an organic molecule during the first stage of the Calvin cycle. Rubisco is so important to plants that it makes up 30 percent or more of the soluble protein in a typical plant leaf. But rubisco also has a major flaw: instead of always using CO_2 as a substrate, it sometimes picks up O_2 instead.

This side reaction initiates a pathway called **photorespiration**, which, rather than fixing carbon, actually leads to the loss of already-fixed carbon as CO_2. Photorespiration wastes energy and decreases sugar synthesis, so when rubisco initiates this pathway, it's committing a serious molecular *faux pas*.

In this article, we'll explore why photorespiration happens, when it's most likely to take place (hint: think hot and dry conditions), and how it actually works.

Rubisco binds to either CO_2 or O_2

As we saw in the introduction, the enzyme rubisco can use either CO_2 or O_2 as a substrate. Rubisco adds whichever molecule it binds to a five-carbon compound called ribulose-1,5-bisphosphate (RuBP). The reaction that uses CO_2 is the first step of the Calvin cycle and leads to the production of sugar. The reaction that uses O_2 is the first step of the photorespiration pathway, which wastes energy and "undoes" the work of the Calvin cycle.



Rubisco can bind to either carbon dioxide or oxygen depending on environmental conditions. Binding to carbon dioxide and initiation of the Clavin cycle is favored at low temperatures and at a high carbon dioxide-to-oxygen ratio. Binding to oxygen and the initiation of photorespiration is favored at high temperatures and a low carbon dioxide-to-oxygen ratio.

What determines how frequently each substrate gets "chosen"? Two key factors are the relative concentrations of O_2 and CO_2 and the temperature.

When a plant has its stomata, or leaf pores, open CO_2 diffuses in, O_2 and water vapour diffuse out, and photorespiration is minimized. However, when a plant closes its stomata—for instance, to reduce water loss by evaporation—$O2$ from photosynthesis builds up inside the leaf. Under these conditions, photorespiration increases due to the higher ratio of O_2 to CO_2.

In addition, Rubisco has a higher affinity for O_2 when temperatures increase. At mild temperatures, rubisco's affinity for (tendency to bind to) CO_2 is about 80 times higher than its affinity for O_2. At high temperatures, however, rubisco is less able to tell the molecules apart and grabs oxygen more often.

The bottom line is that hot, dry conditions tend to cause more photorespiration—unless plants have special features to minimize the problem. You can learn more about plant "workarounds" in the videos on C4 plants and CAM plants.

Photorespiration wastes energy and steals carbon

Photorespiration begins in the chloroplast, when rubisco attaches O_2 to RuBP in its oxygenase reaction. Two molecules are produced: a three-carbon compound, 3-PGA, and a two-carbon compound, phosphoglycolate. 3-PGA is a normal intermediate of the Calvin cycle, but phosphoglycolate cannot enter the cycle, so its two carbons are removed, or "stolen," from the cycle5^55start superscript, 5, end superscript.

To recover some of the lost carbon, plants put phosphoglycolate through a series of reactions that involve transport between various organelles. Three-fourths of the carbon that enters this pathway as phosphoglycolate is recovered, while one-fourth is lost as CO_2.

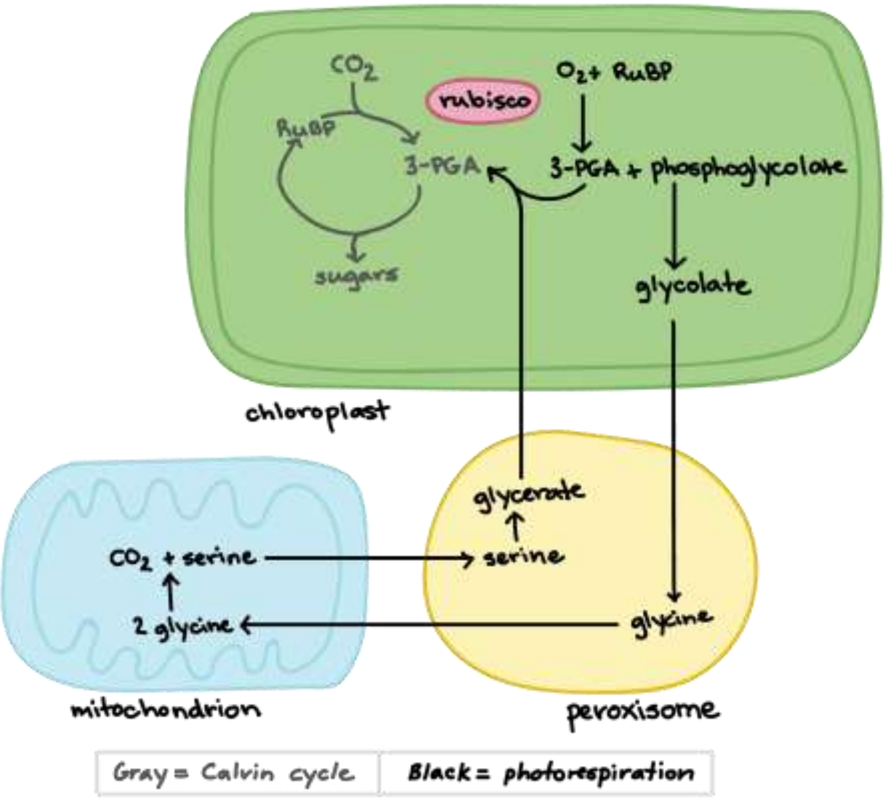


Diagram of photorespiration, showing transport of molecules between organelles.

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Phosphogylcolate is first converted to glycolate inside of the chloroplast. Glycolate then travels to the peroxisome, where it's converted to the amino acid glycine.

Glycine travels from the peroxisome to a mitochondrion. There, two glycine molecules (e.g., from two iterations of the pathway) are converted to the serine, a three-carbon amino acid, in a process that releases one carbon dioxide molecule.

Serine returns to the peroxisome, where it's converted to glycerate. In the chloroplast, glycerate is turned into 3-PGA and can thus enter the Calvin cycle.

How does the photorespiration pathway actually work? To answer this question, let's follow the path of phosphoglycolate, starting when it's just been made in the chloroplast via rubisco's oxygenase.

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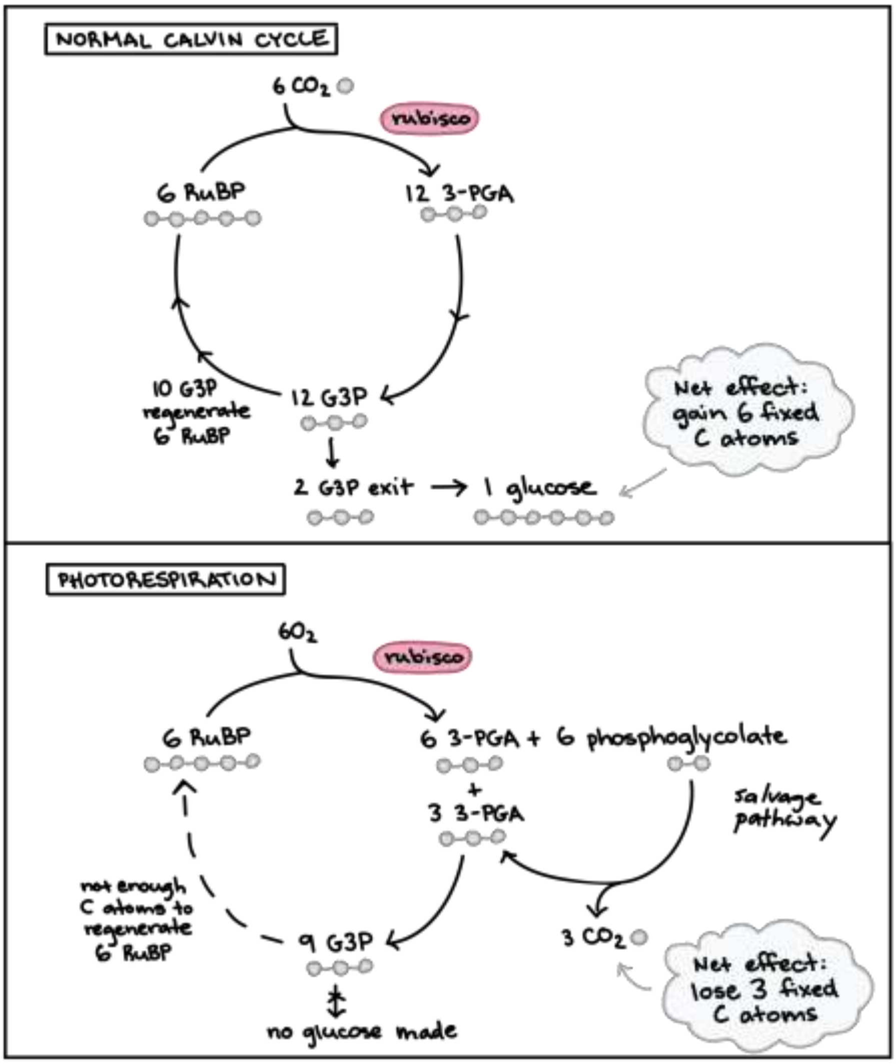
- Glycine travels from the peroxisome to a mitochondrion. There, two glycine molecules (e.g., from two iterations of the pathway) are converted to serine, a three-carbon amino acid. This releases one CO_2 molecule.
- Serine returns to the peroxisome, where it's converted to glycerate. In the chloroplast, glycerate is turned into 3-PGA and can thus enter the Calvin cycle.

In the diagram below, you can see a comparison between photorespiration and the normal Calvin cycle, showing how many fixed carbons are gained or lost when either 6 CO_2 or 6 O_2 molecules are captured by rubisco. Photorespiration results in a loss of 3 fixed carbon atoms under these conditions, while the Calvin cycle results in a gain of 6 fixed carbon atoms.



Comparison of Calvin cycle and photorespiration pathways.

In the Calvin cycle, 6 CO_2 molecules combine with 6 RuBP acceptors, making 12 3-PGA molecules. These are converted into 12 G3P sugars. 2 leave the cycle to make 1 glucose, while 10 are recycled to make 6 RuBPs. The cycle can begin again.

In the photorespiration pathway, 6 O_2 molecules combine with 6 RuBP acceptors, making 6 3-PGA molecules and 6 phosphoglycolate molecules. The 6 phosphoglycolate molecules enter a salvage pathway, which converts them into 3 3-PGA molecules and releases 3 carbons as CO_2. This makes for a total of 9 3-PGA molecules. These can be converted into 9 G3P sugars. This is not enough for any to exit the cycle as glucose. In fact, it is not even enough to regenerate the 6 RuBP acceptors. Instead, only 5 RuBP acceptors can be regenerated, with 2 leftover carbon atoms. The 3 carbons released as CO_2 have been "stolen" from the cycle.

Photorespiration is definitely not a win from a carbon fixation standpoint. However, it may have other benefits for plants. There's some evidence that photorespiration can have photoprotective effects (preventing light-induced damage to the molecules involved in photosynthesis), help maintain redox balance in cells, and support plant immune defenses.