Environmental Impact on Photosynthesis

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All plants ingest atmospheric carbon dioxide and convert it into sugars and starches through the process of photosynthesis but they do it in different ways. The specific photosynthesis method (or pathway) used by each plant class is a variation of a set of chemical reactions called the Calvin Cycle. These reactions impact the number and type of carbon molecules a plant creates, the places where those molecules are stored, and, most importantly for the study of climate change, a plant's ability to withstand low carbon atmospheres, higher temperatures, and reduced water and nitrogen.

These processes of photosynthesis—designated by botanists as C3, C4, and CAM,—are directly relevant to global climate change studies because C3 and C4 plants respond differently to changes in atmospheric carbon dioxide concentration and changes in temperature and water availability.

Humans are currently dependent on plant species that do not thrive in hotter, dryer, and more erratic conditions. As the planet continues to warm up, researchers have begun exploring ways in which plants can be adapted to the changing environment. Modifying the photosynthesis processes may be one way to do that.

C3 Plants

The vast majority of land plants we rely on for human food and energy use the C3 pathway, which is the oldest of the pathways for carbon fixation, and it is found in plants of all taxonomies. Almost all extant nonhuman primates across all body sizes, including prosimians, new and old world monkeys, and all the apes—even those who live in regions with C4 and CAM plants—depend on C3 plants for sustenance.

Species: Grain cereals such as rice, wheat, soybeans, rye, and barley; vegetables such as cassava, potatoes, spinach, tomatoes, and yams; trees such as apple, peach, and eucalyptus

Enzyme: Ribulose bisphosphate (RuBP or Rubisco) carboxylase oxygenase (Rubisco)

Process: Convert CO2 into a 3-carbon compound 3-phosphoglyceric acid (or PGA)

Where Carbon Is Fixed: All leaf mesophyll cells

Biomass Rates: -22% to -35%, with a mean of -26.5%

While the C3 pathway is the most common, it is also inefficient. Rubisco reacts not only with CO_2 but also O_2, leading to photorespiration, a process that wastes assimilated carbon. Under current atmospheric conditions, potential photosynthesis in C3 plants is suppressed by oxygen as much as 40%. The extent of that suppression increases under stress conditions such as drought, high light, and high temperatures. As global temperatures rise, C3 plants will struggle to survive—and since we're reliant on them, so will we.

C4 Plants

Only about 3% of all land plant species use the C4 pathway, but they dominate nearly all grasslands in the tropics, subtropics, and warm temperate zones. C4 plants also include highly productive crops such as maize, sorghum, and sugar cane. While these crops lead the field for bioenergy, they aren't entirely suitable for human consumption. Maize is the exception, however, it's not truly digestible unless ground into a powder. Maize and other crop plants are also used as animal feed, converting the energy to meat—another inefficient use of plants.

Species: Common in forage grasses of lower latitudes, maize, sorghum, sugarcane, fonio, tef, and papyrus

Enzyme: Phosphoenolpyruvate (PEP) carboxylase

Process: Convert CO_2 into 4-carbon intermediate

Where Carbon Is Fixed: The mesophyll cells (MC) and the bundle sheath cells (BSC). C4s have a ring of BSCs surrounding each vein and an outer ring of MCs surrounding the bundle sheath, known as the Kranz anatomy.

Biomass Rates: -9 to -16%, with a mean of -12.5%.

C4 photosynthesis is a biochemical modification of the C3 photosynthesis process in which the C3 style cycle only occurs in the interior cells within the leaf. Surrounding the leaves are mesophyll cells that contain a much more active enzyme called phosphoenolpyruvate (PEP) carboxylase. As a result, C4 plants thrive on long growing seasons with lots of access to sunlight. Some are even saline-tolerant, allowing researchers to consider whether areas that have experienced salinization resulting from past irrigation efforts can be restored by planting salt-tolerant C4 species.

CAM Plants

CAM photosynthesis was named in honor of the plant family in which Crassulacean, the stonecrop family or the orpine family, was first documented. This type of photosynthesis is an adaptation to low water availability and occurs in orchids and succulent plant species from arid regions.

In plants employing full CAM photosynthesis, the stomata in the leaves are closed during daylight hours to lessen evapotranspiration and open at night in order to take in carbon dioxide. Some C4 plants also function at least partially in C3 or C4 mode. In fact, there's even a plant called Agave Angustifolia that switches back and forth between modes as the local system dictates.

Species: Cactuses and other succulents, Clusia, tequila agave, pineapple.
Enzyme: Phosphoenolpyruvate (PEP) carboxylase
Process: Four phases that are tied to available sunlight, CAM plants collect CO2 during the day and then fix CO2 at night as a 4 carbon intermediate.
Where Carbon Is Fixed: Vacuoles
Biomass Rates: Rates can fall into either C3 or C4 ranges.

CAM plants exhibit the highest water-use efficiencies in plants which enable them to do well in water-limited environments, such as semi-arid deserts. With the exceptions of pineapple and a few agave species, such as the tequila agave, CAM plants are relatively unexploited in terms of human use for food and energy resources.

Evolution and Possible Engineering

Global food insecurity is already an extremely acute problem, rendering the continued reliance on inefficient food and energy sources a dangerous course, especially when we don't know how plant cycles will be affected as our atmosphere becomes more carbon-rich. The reduction in atmospheric CO2 and the drying of the Earth's climate are thought to have promoted C4 and CAM evolution, which raises the alarming possibility that elevated CO2 may reverse the conditions that favored these alternatives to C3 photosynthesis.

Evidence from our ancestors shows that hominids can adapt their diet to climate change. Ardipithecus ramidus and Ar anamensis were both reliant on C3 plants but when a climate change altered eastern Africa from wooded regions to savannah about four million years ago, the species that survived—Australopithecus afarensis and Kenyanthropus platyops—were mixed C3/C4 consumers. By 2.5 million years ago, two new species had evolved: Paranthropus, whose focus shifted to C4/CAM food sources, and early Homo sapiens that consumed both C3 and C4 plant varieties.

C3 to C4 Adaptation

The evolutionary process that changed C3 plants into C4 species has occurred not once but at least 66 times in the past 35 million years. This evolutionary step led to enhanced photosynthetic performance and increased water- and nitrogen-use efficiency.

As a result, C4 plants have twice as the photosynthetic capacity as C3 plants and can cope with higher temperatures, less water, and available nitrogen. It's for these reasons, biochemists are currently trying to find ways to move C4 and CAM traits (process efficiency, tolerance of high temperatures, higher yields, and resistance to drought and salinity) into C3 plants as a way to offset environmental changes faced by global warming.

At least some C3 modifications are believed possible because comparative studies have shown these plants already possess some rudimentary genes similar in function to those of C4 plants. While hybrids of C3 and C4 have been pursued more than five decades, due to chromosome mismatching and hybrid sterility success has remained out of reach.

The Future of Photosynthesis

The potential to enhance food and energy security has led to marked increases in research on photosynthesis. Photosynthesis provides our food and fiber supply, as well as most of our sources of energy. Even the bank of hydrocarbons that reside in the Earth's crust was originally created by photosynthesis.

As fossil fuels are depleted—or should humans limit the use of fossil fuel to forestall global warming—the world will face the challenge of replacing that energy supply with renewable resources. Expecting the evolution of humans to keep up with the rate of climate change over the next 50 years is not practical. Scientists are hoping that with the use of enhanced genomics, plants will be another story.

Thank You