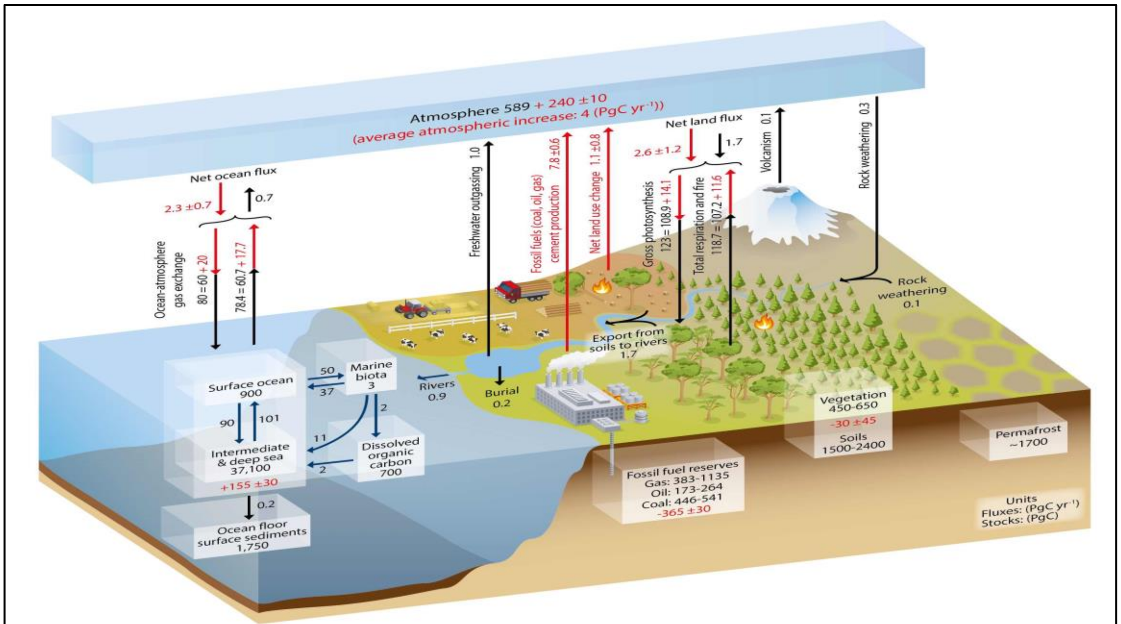
TEACHER BACKGROUND:
THE GLOBAL CARBON BUDGET

The cycling of carbon through photosynthesis and respiration is only part the global cycling of carbon. Geochemical processes also contribute to carbon cycling. Biological processes transfer carbon between organisms and the environment; geochemical processes transfer carbon between sedimentary rocks and the atmosphere, oceans and living organisms. Biological processes are relatively short term, occurring over years to hundreds of years while geochemical processes work on a time scale of millions of years.

Carbon occurs primarily as carbon dioxide (CO_2) in air and water, organic carbon in living and dead organisms, and carbonate ions (CO_3^{-2}) in water, rocks, shells, and bones. To understand how these are connected in a cycle, it is useful to think in terms of ***sources, sinks, and fluxes***. ***Sources*** are carbon emitters; ***sinks*** are carbon absorbers; ***fluxes*** are flows of carbon between sources and sinks. A source may also be a sink. For example, the atmosphere is a source of carbon dioxide for photosynthesis, but it is also a sink for carbon released during respiration, burning, and decay.



The carbon cycle from IPCC 2013

The ***carbon budget*** is an estimate of the maximum amount of greenhouse gases that can be released into the atmosphere over time and still keep warming limited to a specified level. In many cases, carbon budgets are pegged to holding the average global temperature increase below 2° C compared with the beginning of the Industrial Age in the 18th Century. Accelerated burning of fossil fuels over the past 2.5 centuries has poured billions of tons of carbon into the atmosphere, causing global surface air temperatures to warm already by an average of 0.8 degrees C. Scientists have estimated that a 2 °C warming would trigger a host of more drastic changes in the climate, including effects that would be irreversible.

CARBON RESERVOIRS

The Earth's carbon reservoirs can be grouped into any number of different categories. The four categories that have the greatest relevance to the overall carbon cycle are explained below.

- **Lithosphere:** The largest amount of carbon on Earth is stored in sedimentary rocks within the planet's crust. These rocks were produced either by the hardening of mud (containing organic matter) into shale over geological time, or by the collection of calcium carbonate particles, from the shells and skeletons of marine organisms, into limestone and other carbon-containing sedimentary rocks. The sedimentary rocks on Earth store the largest amount of carbon, while another sizeable amount is stored in the Earth's crust as hydrocarbons formed over millions of years from ancient living organisms. These hydrocarbons are commonly known as ***fossil fuels***.

- **Oceans:** The Earth's oceans as a whole contain a large pool of carbon, most of which is in the form of dissolved inorganic carbon stored at great depths, where it resides for long periods of time. A much smaller amount of carbon is located near the ocean surface. This carbon is exchanged rapidly with the atmosphere through both physical processes, such as CO_2 gas dissolving into the water, and biological processes, such as the growth, death and decay of plankton. Although most of this surface carbon cycles rapidly, some of it can also be transferred by sinking to the deep ocean pool where it can be stored for a much longer time.

- **Atmosphere:** Most of the carbon in the atmosphere is in the form of CO_2, with much smaller amounts of methane (CH_4) and various other compounds. The carbon in the atmosphere is of vital importance because of its influence on the greenhouse effect and climate. The relatively small size of the atmospheric carbon pool also makes it more sensitive to disruptions caused by an increase in the sources or sinks of C from the Earth's other pools. In fact, the present-day value is substantially higher than that which probably occurred before the onset of fossil fuel combustion and deforestation. The amount contained before these activities began, is believed to be the normal upper limit for the Earth under natural conditions.

- **Terrestrial Ecosystems:** Terrestrial ecosystems contain carbon in the form of plants, animals, soils and microorganisms. Of these, plants and soils contain the largest amounts. Unlike the Earth's crust and the oceans, most carbon in terrestrial ecosystems exists in organic forms. Most of the carbon in soils enters in the form of dead plant matter that is broken down by microorganisms during decay. The decay process also releases carbon back to the atmosphere, as these microorganisms eventually break most of the organic matter all the way down to CO_2.

CARBON FLUXES

The movement of any material from one place to another is called a ***flux.*** We typically think of a carbon flux as a transfer of carbon from one pool to another. Fluxes are usually expressed as a rate with units of an amount of some substance being transferred over a certain period of time (Gt C/yr). For example, the flow of water in a river can be thought of as a flux that transfers water from the land to the sea and can be measured in gallons per minute or cubic kilometers per year.

Photosynthesis: During photosynthesis, plants use energy from sunlight to combine CO_2 from the atmosphere with water from the soil to create. In this way, carbon is removed from the atmosphere and stored in the structure of plants. Because some plants can live to be tens, hundreds or even thousands of years old, carbon may be stored, or ***sequestered***, for relatively long periods of time.

Plant Respiration: Plants also release CO_2 back to the atmosphere through the process of respiration. Respiration occurs as plant cells use carbohydrates, made during photosynthesis, for energy. Plant respiration represents approximately half of the CO_2 that is returned to the atmosphere in the terrestrial portion of the carbon cycle.

Litter fall: Living plants also shed some portion of their leaves, roots and branches each year. Because all parts of the plant are made up of carbon, the loss of these parts to the ground is a transfer of carbon (a flux) from the plant to the soil. Dead plant material is often referred to as litter (leaf litter, branch litter, etc.) and once on the ground, all forms of litter will begin the process of decomposition.

Soil Respiration: The release of CO_2 through respiration is not unique to plants, but is something that all organisms do. When dead organic matter is broken down or decomposed, CO_2 is released into the atmosphere at an average rate of about 60 GtC/year globally. Because it can take years for plants to decompose carbon, it is temporarily stored in organic matter in soil.

Ocean-Atmosphere Exchange: Inorganic carbon is absorbed and released at the interface of the oceans' surface and surrounding air, through the process of ***diffusion***. Once in a dissolved form, CO_2 goes on to react with water in relatively simple chemical reactions in which H_2O and CO_2 join to form H_2CO_3, also known as ***carbonic acid***. The formation of ***carbonate*** in seawater allows oceans to take up and store a much larger amount of carbon than would be possible if dissolved CO_2 remained in that form. Carbonate is also important to a vast number of marine organisms that use this mineral form of carbon to build shells.

In addition, carbon is cycled through the ocean by the biological processes of photosynthesis, respiration, and decomposition of aquatic plants. Because ocean plants don't have large, woody trunks that take years to breakdown, the process happens much more quickly in oceans than on land—often in a matter of days. For this reason, very little carbon is stored in the ocean through biological processes. The total amount of carbon uptake and carbon loss from the ocean is dependent on the balance of organic and inorganic processes.

Fossil Fuel Combustion: The modern-day carbon cycle also includes several important fluxes that stem from human activities. The most important of these is combustion of fossil fuels: coal, oil and natural gas. Because the main byproduct of fossil fuel combustion is CO_2, these activities can be viewed as a new and relatively rapid flux to the atmosphere of large amounts of carbon. In 2013, fossil fuel combustion represented a flux to the atmosphere of approximately 10 GtC/year.

Land Cover Change: Another human activity that has caused a flux of carbon to the atmosphere is land cover change, largely in the form of ***deforestation***. With the growth of human population, a considerable amount of the Earth's land surface has been converted from native ecosystems to farms and urban areas. Because forests and other native ecosystems generally contain more carbon (in both plant tissues and soils) than the cover types they have been replaced with, these changes have resulted in a net flux to the atmosphere of about 1.5 GtC/year.

Geological Processes: Geological processes represent an important control on the Earth's carbon cycle over time scales of hundreds of millions of years. They include the formation of sedimentary rocks and their recycling via plate tectonics, weathering and volcanic eruptions. These processes convert carbon that was initially contained in living organisms into sedimentary rocks within the Earth's crust. The geological cycle moves so slowly that these fluxes are small on an annual basis and have little effect on a human time-scale. Scientists think that organic carbon stored in the geosphere can possibly remain there for millions of years.

The carbon budget grew out of a series of scientific studies that established a clear link between the accumulation of greenhouse gases in the atmosphere and changes in mean surface air temperatures. Researchers found that temperatures increased 1.8 degrees C for each 3.7 trillion metric tons of additional CO_2 in the atmosphere. Emissions are expressed in metric tons, each of which is equal to 1.1 U.S. tons, or 2,205 pounds. The method for estimating volumes of CO_2 and other gases that are constantly moving into and out of the atmosphere have improved. Those emissions are both naturally occurring and man-made. That led to complex equations aimed at predicting carbon gas exchanges involving plants and oceans, as well as shifts in emissions from human activities, such as burning fossil fuels and destroying forests that would otherwise absorb CO_2.