11.1: Carbon Cycle

Learning Objectives

- Define the carbon cycle and explain its importance for life on Earth.
- Identify the different carbon reservoirs (atmosphere, oceans, land, living organisms)
- Identify human activities that contribute to increased carbon dioxide levels in the atmosphere (burning fossil fuels, deforestation).

Carbon, just like all other elements, cycles through the environment and is constantly in the process of changing forms and locations. In this section, as in many other pieces of scientific literature, we will periodically refer to carbon by its chemical symbol, C. There is no new carbon in the world, rather, all carbon is continuously recycled from one form to another. All plants, animals (including humans!), fungi, bacteria, and archaea are made of mostly carbon-based molecules such as lipids, carbohydrates, proteins, and nucleic acids. Carbon is also prevalent in soils, rocks and sediments, water bodies (dissolved), and the atmosphere. These locations where carbon resides are known as pools or reservoirs, and the processes that move carbon from one location to another are called fluxes. Figure 7.1.1 shows a simplified version of the global carbon cycle.

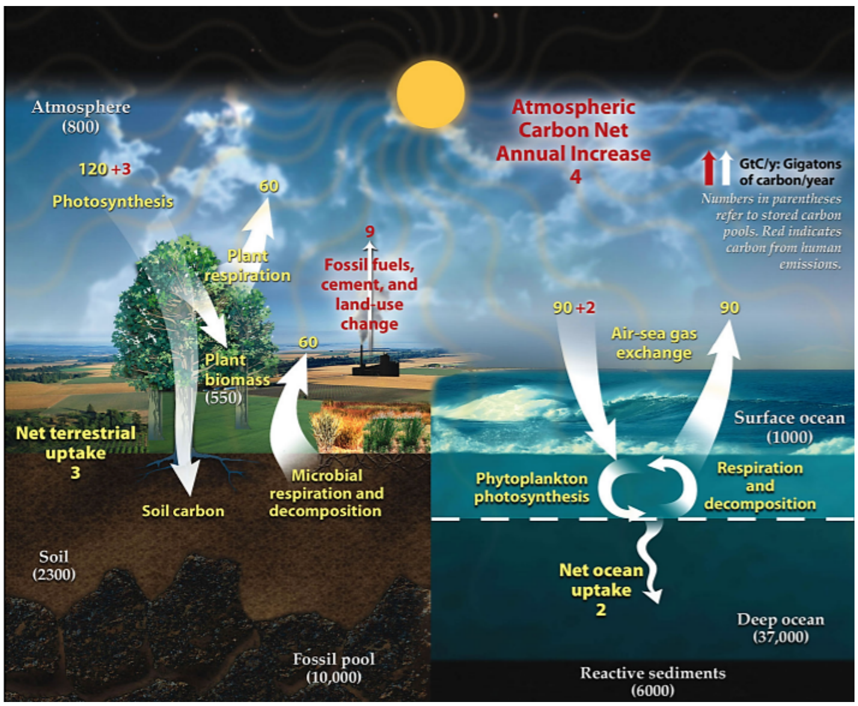

Figure 11.1.1: A simplified carbon cycle. Diagram adapted from U.S. DOE, Biological and Environmental Research Information System.

Some reservoirs hold on to carbon for only a short time. **Aerobic** (oxygen-using) organisms convert carbohydrates created by other organisms into **carbon dioxide** (CO_2) almost instantaneously, which they exhale into the atmosphere. When considering the flux of respiration, living organisms are the **source** of carbon, and the atmosphere is the **sink**. The carbon stays in the reservoir of living organisms for a relatively short time, depending on their life span, from hours and days to years and decades. In contrast, the **residence time** of carbon in the fossil pool is dramatically different. Fossil fuels form over a course of 300-400 million years, forming from ancient plants and animals that decomposed slowly under very specific, **anaerobic** (without oxygen) conditions in wetland environments. Their bodies were gradually transformed by the heat and pressure of the Earth's crust into the fossil fuels that we mine today to provide petroleum oil, natural gas, and coal (see more on this in chapter 4).

Reservoirs and fluxes of importance

The two largest reservoirs of carbon on Earth are the oceans, which cover the majority of Earth's surface, and the **lithosphere** (the mineral fraction of Earth: soils, rocks, and sediments). Each of these reservoirs holds more carbon than all of the other reservoirs combined. Much of the carbon stored in these reservoirs, especially deep in the lithosphere or in deep ocean environments, has an extremely long residence time, and does not actively participate in rapid fluxes. The notable exceptions here, of course, are fossil fuels, which are mined by humans and converted into gaseous forms of carbon through combustion.

Biomass, which is biological material derived from living, or recently living organisms, is a much smaller reservoir of carbon. The amount of carbon stored in all of the terrestrial vegetation (550 Gt C) (Gt = gigatonne = 10^9 metric tons = 10^{15} g) is just a fraction of that stored in the oceans (38,000 Gt C) and lithosphere (18,000 Gt C). All of the carbon that is currently stored in all of the vegetation on Earth got there through the process of **photosynthesis**. Plants and other photosynthetic organisms are called **primary producers**, because they "fix" atmospheric CO_2 into organic carbon, such as sugar, a form that is usable by animals and other organisms that need to consume their carbon molecules.

Photosynthetic organisms, such as plants, algae, and cyanobacteria, bring in CO_2 from the atmosphere and, using energy from the sun, convert CO_2 and water into glucose molecules (organic carbon). The products of photosynthesis are oxygen and glucose (Equation 11.1.1). These glucose molecules are simple sugars that **autotrophs** ("self-feeders") can "burn" for energy, or transform into other usable carbon molecules through the process of cellular respiration (described in the next paragraph), or to build plant biomass. Photosynthesis takes place in organelles called **chloroplasts**, shown in Figure 11.1.2. Photosynthesis accounts for 123 Gt of C per year that is removed from the atmosphere and stored in plant biomass. Such a massive amount of photosynthesis occurs on Earth that no other single flux moves as much carbon in the same timeframe.

$$6CO_2 + 6H_2O + \text{solar energy} \rightarrow C_6H_{12}O_6 + 6O_2 \tag{11.1.1}$$

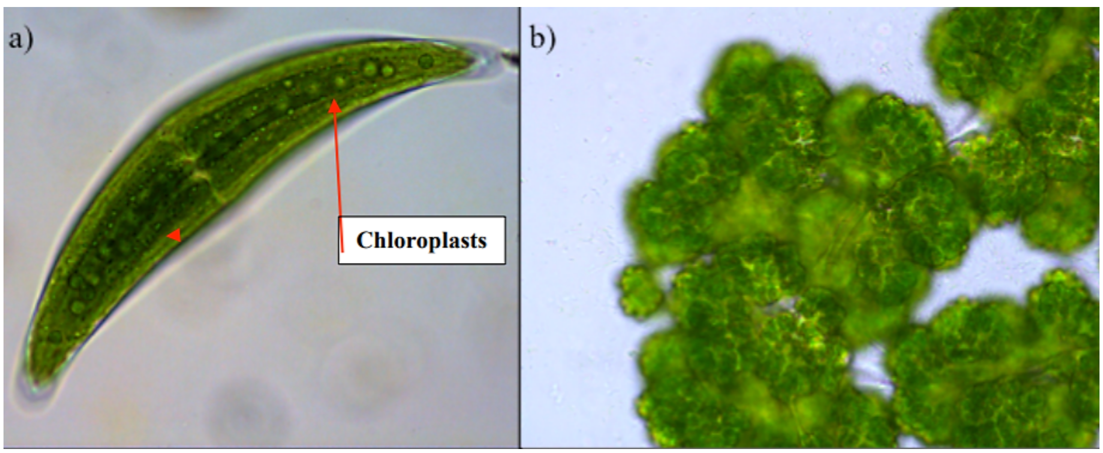

Figure 11.1.2: Chloroplasts visible in freshwater algae. Chloroplasts are green in color due to the chlorophyll a they contain, and are the site of photosynthesis. Chlorophyll a is the green pigment that allows plants, algae, and cyanobacteria to absorb the energy they need for photosynthesis from sunlight. a) Closterium moniliferum Ralfs, (Chlorophyta) green coccoid algae; b) Botryococcus braunii Kützing, (Chlorophyta) green coccoid algae with discoid chloroplasts. Image credit: K. Manoylov, Lake Sinclair, GA

Biomass in the carbon cycle, including plants and animals, is the reservoir of carbon that we are most likely most familiar with, and also the reservoir that is most readily available to us. We all participate in the flux of **consumption** of carbon when we eat food. All of our food is simply plant and/or animal biomass. Our body takes the carbon molecules contained in this biomass, and uses them, along with the oxygen we breathe in, for **cellular respiration** to create the adenosine triphosphate (ATP) we need for energy. The products of cellular respiration include the CO_2 we exhale, water, and energy that is stored in ATP (Equation 11.1.2). Our bodies also builds additional biomass out of the carbon molecules in this food, allowing us to create new cells for growth or replenishment. This is the only way we, and all other **heterotrophs** ("other-eaters"), can bring in the carbon we need to build and maintain our bodies. Remember, you are what you eat!

$$C_6H_{12}O_6 + CO_2 \rightarrow 6CO_2 + 6H_2O + \text{energy} \tag{11.1.2}$$

Cellular respiration is an important flux in the carbon cycle, and one that contributes carbon to the atmosphere. Remember that animals and other heterotrophs complete cellular respiration using the carbon molecules that they bring in through their food. Plants and other photosynthetic autotrophs complete cellular respiration using the carbon molecules they formed from CO_2 through photosynthesis. Any carbon molecules that are left over after the organism has acquired sufficient energy through cellular respiration make up the biomass of the plant. As plants and animals die and decompose, their bodies are consumed by decomposer organisms such as fungi and bacteria. Through the flux of **decomposition**, some decaying biomass is converted into atmospheric carbon by the decomposers, while most of the biomass is buried into the soil, contributing to soil carbon. In oxygen-rich environments, decomposers rapidly consume dead and decaying biomass using the same process of aerobic cellular respiration described above. In oxygen-deficient environments, decomposers complete other metabolic pathways, and very slowly consume the organic matter. Some of the gases produced from anaerobic decomposition include **methane** (CH_4), **nitrous oxide** (N_2O), and the foul-smelling hydrogen sulfide (H_2S).

The biomass reservoir of the carbon cycle is also important to us as a source of energy. Through the flux of **combustion**, we convert the **potential energy** held in biomass into heat energy that we can use, and release carbon dioxide in the process. If you have ever burned logs on a campfire, or even burned food on the stove, you have completed this flux of biomass combustion. Of course, this happens naturally as well, the best example being natural forest fires caused by lightning strikes. The chemical reaction for combustion is identical to the chemical reaction for cellular respiration. The difference is that in cellular respiration, energy is released in a controlled fashion, and captured in ATP molecules. In combustion, all of this energy is released rapidly in the form of light and heat.

As all of the fluxes we've discussed so far involve the atmosphere, we have not yet discussed the flux that connects the atmosphere to the oceans. Carbon can enter the oceans through two primary fluxes: first through photosynthesis by algae or cyanobacteria (also called phytoplankton in Figure 11.1.1), and second through the chemical reaction of **ocean-atmosphere exchange**. The ocean, as with all surface water bodies, always contains some dissolved CO_2. This CO_2 is in **equilibrium** with the CO_2 in the air. Some atmospheric CO_2 is constantly dissolving into the ocean, while some dissolved CO_2 is constantly diffusing into the atmosphere. Under normal conditions, these two fluxes will be happening at equal rates. As you can see in Figure 11.1.1, however, this is no longer the case. In the section Human impacts on the carbon cycle, we will discuss why this is the case.

Activity: Better understanding the carbon cycle

To further review the carbon cycle, and better understand the human impacts on it, use this interactive graphic from Woods Hole laboratories: http://www.whoi.edu/feature/carboncycle/. As you will see, the information described in this text is only a small portion of the total carbon cycle on Earth. Finally, complete Table 11.1.1 as a way to review the sink/source relationship within this cycle. See if you can correctly identify the source and sink of carbon for each of these important fluxes in the carbon cycle.

Table 11.1.1: Practice understanding the sink/source relationship with cycles

Carbon flux	Carbon source	Carbon sink
Cellular respiration	Carbohydrates in living organisms	CO_2 in the atmosphere
Photosynthesis		
Consumption		
Combustion		
Decomposition		
Ocean/atmosphere exchange		
Fossil fuel formation		