The Importance of the Carbon Cycle

Carbon is an element found in all living substances as well as in many inorganic materials. Both diamond and coal are nearly pure carbon, but with different structures. Carbon is a key element for life, composing almost half of the dry mass of the earth’s plants (that is, the mass when all water is removed). The carbon cycle is the exchange of carbon among three reservoirs or storage places: the land, the oceans, and the atmosphere. The amount of carbon in these reservoirs is so large that it is expressed in gigatons (Gt): $10^9$ metric tons (1 metric ton equals 1,000 kilograms or 2,200 pounds).

The atmosphere is the smallest pool of actively cycling carbon, that is, carbon that stays in a reservoir less than a thousand years or so. The land and its plants and animals, which scientists call the terrestrial biosphere, is the next largest reservoir of carbon. The oceans are the earth’s largest active carbon reservoir by far (Figure 1). The carbon budget is the balance of carbon among the three reservoirs.

The carbon cycle is vitally important to life on earth. Through photosynthesis and respiration (see p. 3), it is the way the earth produces food and other renewable resources. Through decomposition, it serves as the earth’s waste disposal system. In addition, the carbon cycle is important because carbon-containing gases in the atmosphere affect the earth’s climate (see “The Greenhouse Effect,” p.2). Increased carbon dioxide ($\text{CO}_2$) in the atmosphere has been responsible for more than half of the climate warming observed in recent decades.

The processes by which carbon moves through the earth’s reservoirs take place on very different time scales. The short-term carbon cycle includes processes that transfer carbon from one reservoir to another in a matter of years, including photosynthesis, plant and animal respiration,

and the movement of $\text{CO}_2$ across the air-sea interface. Other processes, such as the transformation of carbon into limestone and its subsequent release as the rock is weathered, occur very slowly (thousands to millions of years). Scientists call these slower transfers of carbon among reservoirs the long-term carbon cycle.

The carbon cycle is inextricably linked to other chemical cycles, including those of nitrogen, phosphorus, and sulfur, as well as to the global hydrological cycle. Please see the Global Change Instruction Program module Global Biogeochemical Cycles and the Physical Climate System or other works for information on these important topics.

Carbon Reservoirs

Actively cycling carbon in its three reservoirs affects human life every day. Carbon in the atmosphere serves as food for plants (in the presence of sunlight); carbon in the soil serves as energy for the growth of miniature animals called microbes; carbon in plants feeds humans and...
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The Atmosphere

Carbon constitutes much less than 1% of the atmosphere. Even this small percentage adds up to 750 Gt of carbon, which is a lot (although, as noted earlier, much less than in the other two reservoirs). Carbon in the atmosphere occurs almost entirely as CO₂; small amounts of methane (CH₄), carbon monoxide (CO), and chlorofluorocarbons (CFCs) are also present. These gases are all radiatively active, that is, they trap heat near the surface of the earth. So they are also considered greenhouse gases. (See “The Greenhouse Effect,” below.)

The Greenhouse Effect

Like the glass walls of a greenhouse, certain gases trap heat. How do they do this? Shortwave radiation from the sun passes through the earth’s atmosphere and is absorbed by the surface, thereby warming it. Some of this absorbed energy is reradiated back toward space in a different form: as infrared radiation or heat. The greenhouse gases in the atmosphere absorb the heat energy and keep it from escaping back to space (Figure 2). Thus the heat stays in the atmosphere and warms the earth. The greenhouse effect is a natural process that has gone on for millions of years. Without it, life on earth would be impossible, because the earth’s temperature would be about 33°C (60°F) colder than it is today.

Whereas the greenhouse effect is a good thing, an enhanced greenhouse effect might not be. Scientists are concerned that the rapid increase in the amount of CO₂ and many other greenhouse gases in the atmosphere has implications for global climate. Figure 3 shows the relationship between atmospheric CO₂ concentration and temperature over the last 160,000 years. The strong connection suggests—although it alone does not prove—that the level of CO₂ in the atmosphere plays an important role in determining the earth’s temperature. However, there is not a simple linear relationship between the amount of greenhouse gases in the atmosphere and the temperature at the surface of the earth. Complex mathematical models of the earth’s climate system are needed to study potential future consequences of our continued dependence on fossil-fuel energy.

Carbon dioxide, water vapor, methane, nitrous oxide, and ozone are the greenhouse gases that occur naturally. The concentrations of all of these gases in the atmosphere are increasing as a result of human activities. The chlorofluorocarbons (CFCs) are also greenhouse gases, but they were created by humans; they did not exist in the atmosphere before the 1950s. The CFCs were manufactured for use as aerosol propellants, refrigerants, and solvents. Although their manufacture has been banned, their replacements are also very powerful greenhouse gases.
Photosynthesis and respiration

In the short-term carbon cycle, photosynthesis and respiration are the primary processes that involve the atmosphere. Photosynthesis is the process by which green plants make their food. In this process, plants combine CO₂ and water using light energy to make carbon-containing compounds (sugars and starches, called carbohydrates). Oxygen is produced during the reaction and released to the atmosphere. On land, plants use CO₂ from the atmosphere (Figure 4). In the oceans, phytoplankton use CO₂ dissolved in seawater; much of this dissolved CO₂ also originally came from the atmosphere. Photosynthesis also releases oxygen to the atmosphere.

Thus, thanks to the activity of photosynthetic organisms, all other forms of life on the earth have oxygen to breathe and food to eat—since even carnivores feed on animals that eat plants.

Respiration is the chemical process by which carbon-containing compounds are broken down within cells. It is essentially the opposite of photosynthesis: oxygen and carbohydrates react to produce CO₂ and water, releasing energy during the process. Living organisms use the energy released by respiration to power everything they do. For example, reading this page requires energy, and that energy is supplied by respiration.

Figure 3. Variations in global temperature (bottom line) and atmospheric CO₂ concentration (top line) over the last 160,000 years. The strong pattern of higher temperatures when atmospheric CO₂ levels are high and cooler temperatures when concentrations are lower has been used to suggest that future increases in atmospheric CO₂ concentration could lead to warmer temperatures. From Barnola et al. (1987), p. 410.

Figure 4. The flow of CO₂ into plants via photosynthesis and out of plants and animals via respiration. Photosynthesis removes approximately as much CO₂ from the atmosphere as respiration adds to it. This cycle keeps the atmospheric level of CO₂ fairly constant.
Globally, photosynthesis and respiration tend to be in balance in nature. In other words, photosynthesis takes up about as much CO₂ from the atmosphere each year as is released by respiration. However, extreme weather events—such as prolonged flooding or drought over large areas—or extended periods of unusually hot or cold temperatures can temporarily offset the delicate balance and lead to either a release of CO₂ to the atmosphere or a high uptake of CO₂ from the atmosphere.

**Increases in atmospheric carbon since 1750**

As Table 1 shows, the carbon-containing compounds in the atmosphere have been increasing since the Industrial Revolution (about 1750 AD). At that time, humans began releasing more of these gases into the atmosphere by burning fossil fuels (e.g., gas, coal, oil), cutting down or burning forests to make agricultural land, and other processes. Although scientists have only been able to measure the atmospheric concentrations of these gases for about 40 years, they can estimate the concentrations in earlier periods from growth rings in trees, air trapped in polar ice cores, and other sources. Since 1957, the amount of carbon dioxide in the atmosphere has been measured directly at the South Pole; since 1958, at Mauna Loa, Hawaii; and starting later, at over 20 other locations around the world, including sites in Antarctica, Australia, several maritime islands, and high northern latitudes. (At present, there are no continuous measurement sites in Africa or South America.)

Figure 5 shows the records from these stations. Atmospheric CO₂ has increased about 25% just since 1957, from 315 parts per million in 1957 to 367 ppm in 1999. The increase in atmospheric CO₂ since 1957 is actually greater than the estimated increase over the preceding 200-plus years from 1750 to 1957.

**Atmospheric CO₂ records of the past**

Measurements of CO₂ concentrations in air extracted from polar ice cores are currently the best means to extend the CO₂ record through the geologically “recent” past (last 200,000 years). The transformation of snow into ice traps air bubbles that are used to record the atmospheric CO₂ concentration. Provided that the cores are extracted carefully from well-chosen sites and the analysis is done correctly, the ice record provides reliable information on past atmospheric CO₂ concentrations.

The ice-core record reveals an average value of 280 ppm in the level of atmospheric CO₂ over the 1,000 years before the Industrial Revolution, with fluctuations up to 10 ppm. The largest of

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**Table 1**

Atmospheric concentrations of important carbon-containing gases

<table>
<thead>
<tr>
<th>Gas</th>
<th>Estimated pre-Industrial Revolution concentration (ca. 1750)</th>
<th>Current concentration (1999)</th>
<th>Percentage of increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>280 ppm*</td>
<td>367 ppm (773 Gt)</td>
<td>31%</td>
</tr>
<tr>
<td>Methane</td>
<td>0.7 ppm</td>
<td>1.8 ppm (5.1 Gt)</td>
<td>157%</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>~0.05 ppm</td>
<td>0.05 ppm (0.1 Gt)</td>
<td>——</td>
</tr>
</tbody>
</table>

*ppm = parts per million by volume; out of 1 million molecules in the atmosphere before the Industrial Revolution, 280 molecules were carbon dioxide.
Why the Zigzags?

The zigzag pattern of increase shown in Figure 5 reflects the seasonal uptake and release of CO₂ by plants. Levels of CO₂ are high when plants are respiring more than they are photosynthesizing (winter) and are low when photosynthesis exceeds respiration (summer). Since Northern and Southern Hemisphere winters and summers occur at opposite times of the year, you might expect the opposing patterns from the two hemispheres to cancel each other out in the global record. However, the pattern for the midlatitude Northern Hemisphere prevails because its larger land masses support more seasonally active photosynthesis. In the seasonless tropics, photosynthesis goes year round.

The size of the zigzag, that is, the height of each peak (its amplitude), has generally increased over the past few decades. We are not sure why this is, because the trend is not well correlated with the increase in atmospheric CO₂ concentration. The change could reflect either increased photosynthesis or increased respiration.

The Oceans

The oceans absorb and store about 39,000 Gt of carbon—more than 60 times as much as the atmosphere (see Figure 1). Over 95% of oceanic carbon is in the form of dissolved inorganic carbon (dissolved CO₂ and bicarbonate and carbonate ions); the remainder comprises various forms of organic carbon (living organic matter and particulate and dissolved organic carbon). Scientists differentiate between the inorganic and organic forms of carbon because the two forms go...
through different chemical reactions and also are affected in different ways by physical ocean processes. The physical, chemical, and biological processes that affect carbon in the oceans are described in Chapter 2.

**The Terrestrial Biosphere**

Within this reservoir, the largest pool of carbon (roughly 65.5 million Gt) is in sedimentary rocks—mostly limestone, a carbonate rock, and also organic sediments that contain fossil fuels. However, aside from human use of these fuels (which will be discussed in the next chapter), rocks do not play a role in the short-term carbon cycle. Carbon storage in plants and soils is more important. Plants and soils store and release carbon on time scales ranging from seasons to thousands of years, and they contain about 2,200 Gt carbon (C)—almost three times as much total carbon as the atmosphere and more organic (but not more total) carbon than in the oceans (Figure 7).

Not only is the amount of carbon in the terrestrial biosphere large, but it is readily modified by human activity. Therefore this reservoir may be thought of as the most active part of the global carbon cycle. It is difficult, however, to pin down the role of the terrestrial biosphere in the global carbon cycle because of the complex biology underlying carbon storage, the great heterogeneity of vegetation and soils, and the somewhat unpredictable nature of human land use and land management. We will discuss some of these concerns in the next chapter.

Figure 7. Comparison of the land and oceanic carbon pools that are important in the short-term carbon cycle.