Natural Biogeochemical Cycles

CHAPTER 5

In all things there is a law of cycles.

—Publius Cornelius Tacitus
(Roman historian)

CARBON CYCLE

Carbon is the basic building block of life and the fundamental element found in carbohydrates, fats, proteins, and nucleic acids (DNA and RNA). Carbon is exchanged among the biosphere, geosphere, hydrosphere, and atmosphere. Although carbon is found in rocks, it is a minor component when compared with the mass of either oxygen or silicon atoms in rocks. Carbon is found in carbon dioxide (CO_2), which makes up less than 1% of the atmosphere.

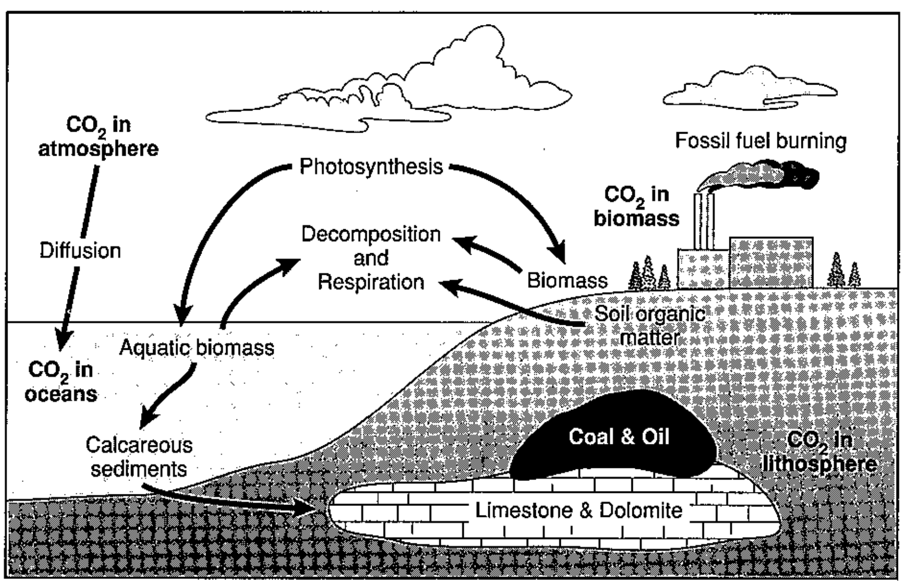

Figure 5.1 The carbon cycle viewed as chemical processes

The major reservoirs or "sinks" of carbon include:

- **Plant matter:** A portion of atmospheric carbon (15%) is removed through photosynthesis by which carbon is incorporated into plant structures and compounds:

$$6CO_2 + 6H_2O + \text{energy (sunlight)} \rightarrow C_6H_{12}O_6 + 6O_2$$

- **Terrestrial biosphere:** Freshwater systems and nonliving organic material are included. Forests store 86% of the planet's above-ground carbon and 73% of the planet's soil carbon. Carbon can be stored up to several hundreds of years in trees and up to thousands of years in soils.
- **Oceans:** Dissolved inorganic carbon in the form of CO_2 and living and nonliving marine biota (i.e., shells and skeletons) are included. The oceans are gaining approximately 2 gigatons (4×10^{12} kg) of carbon each year; however, most of it is not involved with rapid exchanges with the atmosphere. Removing carbon dioxide from water raises the pH, making the water more basic.
- **Sedimentary deposits:** Limestone and carbon trapped in fossil fuels and coal. Limestone is the largest reservoir of carbon in the carbon cycle. The calcium comes from the weathering of calcium-silicate rocks, which causes the silicon in the rocks to combine with oxygen to form sand or quartz (silicon dioxide), leaving calcium ions available to form limestone.

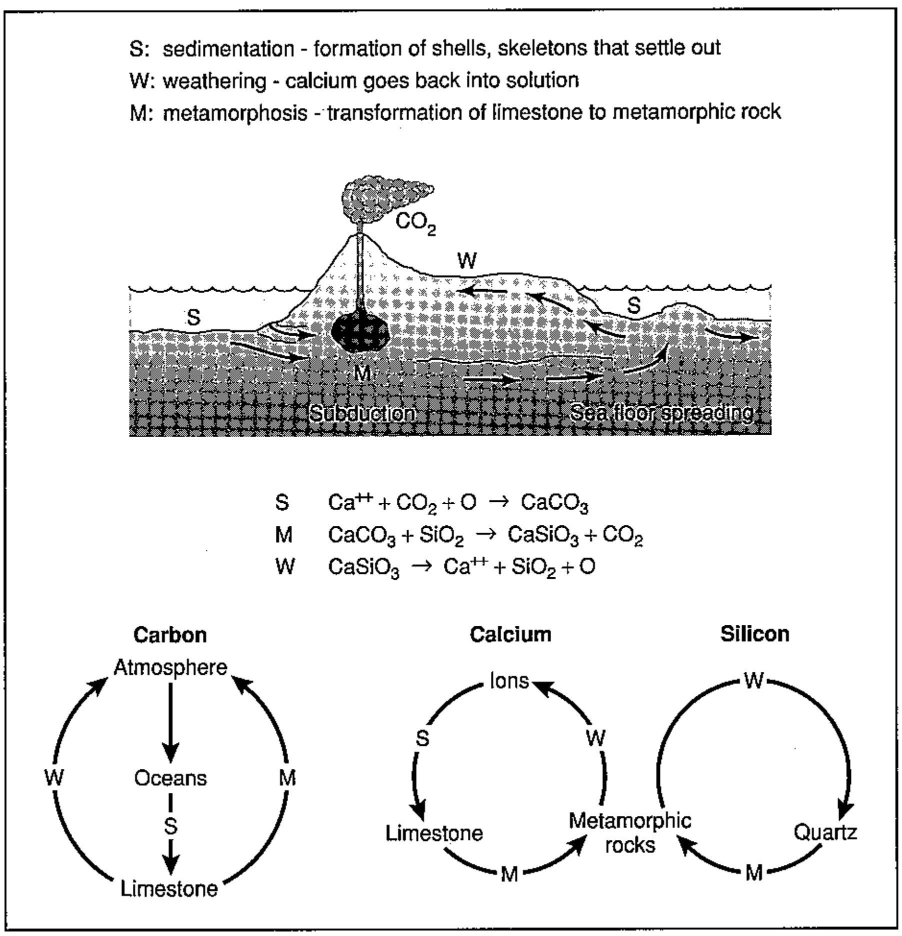

Figure 5.2 Inorganic carbon cycle

Carbon is released back into the atmosphere through:

1. Cellular respiration of plants and animals that break down glucose into carbon dioxide and water: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + energy. When oxygen is not present, anaerobic respiration occurs and releases carbon into the atmosphere in the form of methane (CH_4) (e.g., as marsh gas or flatulence).
2. Decay of organic material by the action of decomposers; if oxygen is present, the carbon is released in the form of carbon dioxide; if oxygen is absent, it is released in the form of methane (CH_4).
3. Burning fossil fuels, wood, coal, and so on.
4. Weatherization of rocks and especially the erosion of limestone, marble, and chalk, which break down to carbon dioxide and carbonic acid (H_2CO_3).
5. Volcanic eruptions.
6. Release of carbon dioxide by warmer ocean waters.

Prior to the Industrial Revolution, transfer rates of carbon dioxide due to photosynthesis and respiration (including decay) were fairly balanced. However, since the Industrial Revolution, more carbon dioxide is being deposited in the Earth's atmosphere than is being removed. This increase is believed to be due to the burning of wood and fossil fuels and deforestation.

Carbon Sinks

Carbon Sink	Amount (Billions of Metric Tons)
Marine sediments and sedimentary rocks	~ 75,000,000
Ocean	~ 40,000
Fossil fuel deposits	~ 4000
Soil organic matter	~ 1500
Atmosphere	578 (in 1700 C.E.) to 766 (in 2000 C.E.)
Terrestrial plants	~ 580

NITROGEN CYCLE

Nitrogen makes up 78% of the atmosphere. Nitrogen is also an essential element needed to make amino acids, proteins, and nucleic acids. Other nitrogen stores include organic matter in the soil and the oceans (1 million times more nitrogen is found in the atmosphere than is contained in either land or ocean waters).

The natural cycling of nitrogen, in which atmospheric nitrogen is converted to nitrogen oxides by lightning and deposited in the soil by rain where it is assimilated by plants and either eaten by animals (and returned as feces) or decomposed back to elemental nitrogen by bacteria, includes the following processes:

- Nitrogen fixation
- Nitrification

- Assimilation
- Ammonification
- Denitrification

Nitrogen Fixation

Nitrogen fixation is the conversion of atmospheric nitrogen (N_2) to ammonia (NH_3) or nitrate (NO_3^-) ions. Nitrate is the product of high-energy fixation by lightning, cosmic radiation, or meteorite trails. In high-energy fixation, atmospheric nitrogen and oxygen combine to form nitrates, which are carried to Earth's surface in rainfall as nitric acid (HNO_3). High-energy fixation accounts for about 10% of the nitrate entering the nitrogen cycle.

In contrast, biological fixation accounts for 90% of the fixed nitrogen in the cycle. In biological fixation, molecular nitrogen (N_2) is split into two free nitrogen atoms ($N_2 \rightarrow N + N$). The nitrogen atoms combine with hydrogen to yield ammonia (NH_3).

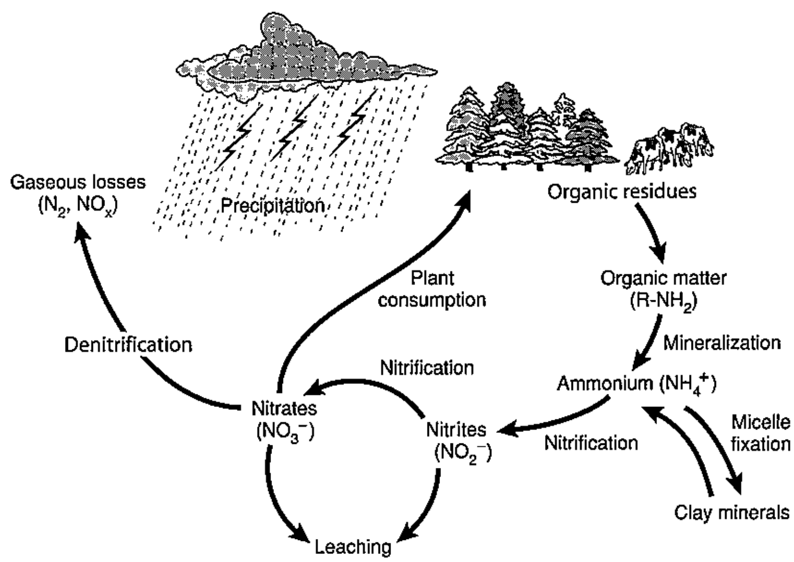

Figure 5.3 The nitrogen cycle

The fixation process is accomplished by a series of different microorganisms. The symbiotic bacteria *Rhizobium* is associated with the roots of legumes. To a lesser extent, some nonleguminous plants also exhibit symbiotic relationships with bacteria. Some free-living aerobic bacteria, such as *Azobacter* and *Clostridium*, freely fix nitrogen in the soil. Finally, blue-green algae (cyanobacteria) such as *Nostoc* and *Calothrix* can also fix nitrogen both in the soil and in water, yielding ammonia as the stable end product.

Nitrification

Nitrification is the process in which ammonia is oxidized to nitrite (NO_2^-) and nitrate (NO_3^-), the forms most usable by plants. Two groups of microorganisms are involved in nitrification. *Nitrosomonas* oxidize ammonia to nitrite and water. *Nitrobacter* oxidize the nitrite to nitrate.

Assimilation

Nitrates are the form of nitrogen most commonly assimilated by plants through their root hairs. Nitrogen is used by plants to synthesize amino acids, oils, and nucleic acids. Rains and extensive irrigation can leach soluble nitrates and nitrites into groundwater, which, in high amounts, can interfere with blood-oxygen levels in human infants. Soluble nitrates that run off the land and enter aquatic and wetland habitats result in cultural eutrophication and the destruction of these habitats. Animals assimilate nitrogen-based compounds by consuming plants and other organisms that consume plants.

Ammonification

When a plant or animal dies, or an animal excretes, the initial form of nitrogen is found in amino acids and nucleic acids. Bacteria, or in some cases, fungi, convert this organic nitrogen within the remains back into ammonia (NH_3).

Denitrification

Denitrification is the process in which nitrates are reduced to gaseous nitrogen. This process is used by facultative anaerobes. These organisms flourish in an aerobic environment but are also capable of breaking down oxygen-containing compounds (NO_3^-) to obtain oxygen in anaerobic environments. Examples include fungi and the bacteria *Pseudomonas.*

Effects of Excess Nitrogen

Fossil fuel combustion has contributed to a sevenfold increase in nitrogen oxides (NO_x) to the atmosphere, particularly nitrogen dioxide (NO_2). NO_x is a precursor of tropospheric (lower atmosphere) ozone production and contributes to smog and acid rain and increases nitrogen inputs to ecosystems.

Ammonia (NH_3) in the atmosphere has tripled as the result of human activities since the Industrial Revolution. Ammonia acts as an aerosol and decreases air quality.

Nitrous oxide (N_2O), a significant greenhouse gas, has deleterious effects in the stratosphere, where it breaks down and acts as a catalyst in the destruction of atmospheric ozone. N_2O is in a large part emitted during nitrification (conversion of ammonium to nitrate and nitrite) and denitrification (converting oxides back to nitrogen gas or nitrous oxides for energy generation) processes that take place in the soil. The largest N_2O emissions are observed where nitrogen-containing fertilizer is applied in agriculture.

Human activity has more than doubled the annual transfer of nitrogen into biological available forms through:

- Extensive cultivation of legumes (particularly soy, alfalfa, and clover)
- The extensive use of chemical fertilizers and pollution emitted by vehicles and industrial plants (NO_x)
- Biomass burning
- Cattle and feedlots
- Industrial processes

PHOSPHORUS CYCLE

Phosphorus is essential for the production of nucleotides, production of ATP, fats in cell membranes, bones, teeth, and shells. Phosphorus is not found in the atmosphere but, rather, in sedimentary rocks and does not depend on the action of bacteria. Generally, phosphorus is found in the form of the phosphate ion (PO_4^{3-}) or the hydrogen phosphate ion (HPO_4^{2-}). Phosphorus is slowly released from terrestrial rocks by weathering and the action of acid rain. It then dissolves into the soil and is taken up by plants. It is often a limiting factor for soils due to its low concentration and solubility. Phosphorus is a key element in fertilizer. A fertilizer labeled 6-24-26 contains 6% nitrogen, 24% phosphorus, and 26% potassium.

Humans have impacted the phosphorus cycle in several ways: First, humans have mined large quantities of rocks containing phosphorus for inorganic fertilizers and detergents. Second, clear-cutting tropical habitats for agriculture decreases the amount of available phosphorus as it is contained in the vegetation. Third, humans allow runoff from feedlots, from fertilizers, and from the discharge of municipal sewage plants. The runoff collects in lakes, streams, and ponds. It causes an increase in the growth of cyanobacteria (blue-green bacteria), green algae, and aquatic plants. In turn, this growth results in decreased oxygen content in the water, which then kills other aquatic organism in the food web. Fourth, humans apply phosphorus-rich guano and other phosphate-containing fertilizers to fields.

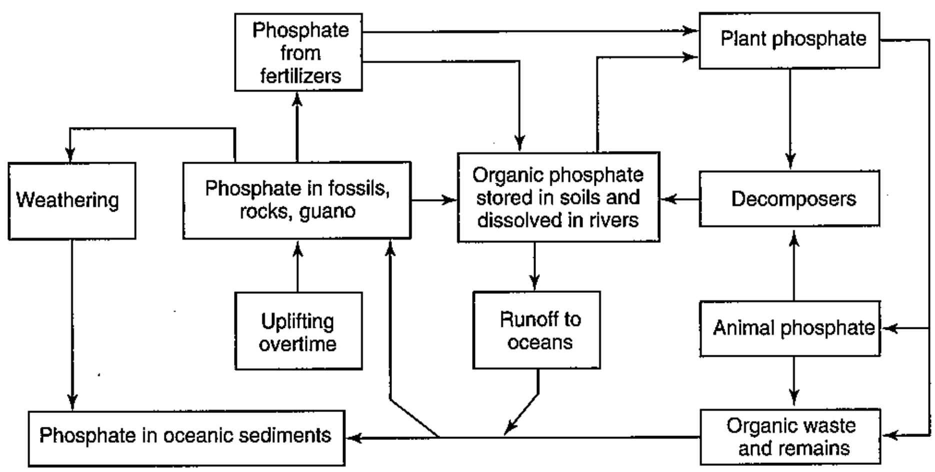

Figure 5.4 The phosphorus cycle

SULFUR CYCLE

Most sulfur is found in underground rocks and deep oceanic deposits. The natural release of sulfur into the atmosphere comes from the weathering of rock and gases released from seafloor vents and volcanic eruptions. Sulfur is released mostly in the form of hydrogen sulfide (H_2S) and sulfur dioxide (SO_2) from these volcanic eruptions. This sulfur dioxide is converted to sulfur trioxide (SO_3) and eventually to tiny droplets of sulfuric acid (H_2SO_4). Sulfuric acid mixes with rain to fall back to Earth and is known as acid rain, acid precipitation, or acid deposition. Sulfate (SO_4^{2-}) salt particles enter the atmosphere from sea sprays, dust storms, and forest fires. These sulfate ions are eventually absorbed by plants, which then incorporate them into proteins. Certain marine algae produce gaseous dimethyl sulfide (DMS), which in the atmosphere also forms tiny condensation nuclei for rain. Humans contribute to adding sulfur to the cycle through refining and burning fossil fuels and by converting (smelting) sulfur-containing metallic mineral ores into free metals such as copper, lead, and zinc.

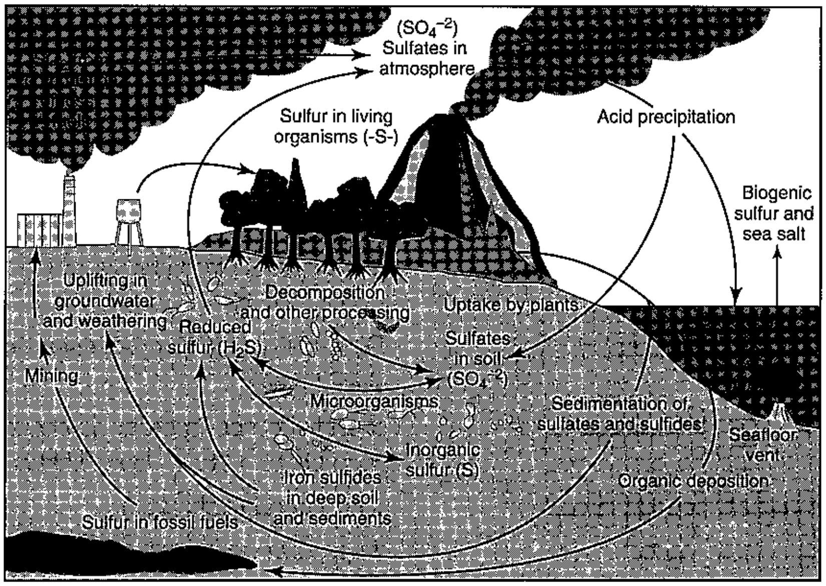

Figure 5.5 The sulfur cycle

WATER CYCLE

The water cycle is powered by energy from the sun. Solar energy evaporates water from oceans, lakes, rivers, streams, soil, and vegetation. The oceans hold 97% of all water on the planet and are the source of 78% of all global precipitation. Oceans are also the source of 86% of all global evaporation, with evaporation from the sea surface keeping Earth from overheating. If there were no oceans, surface temperatures on land would rise to an average of 153°F (67°C).

The water cycle is in a state of dynamic equilibrium by which the rate of evaporation equals the rate of precipitation. Warm air holds more water vapor than cold air. Processes involved in the water cycle include evaporation, evapotranspiration, condensation, infiltration, runoff, and precipitation.

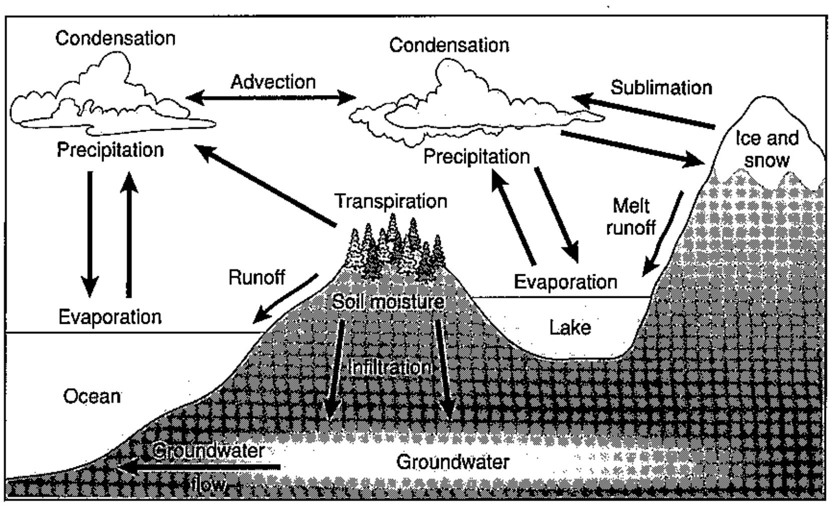

Figure 5.6 The water cycle

Human Impact on Water Cycle

Human Activity	Impact on Water Cycle
Withdrawing water from lakes, aquifers, and rivers	Groundwater depletion and saltwater intrusion
Clearing of land for agriculture and urbanization	Increased runoff Decreased infiltration Increased flood risks Accelerated soil erosion
Agriculture	Runoff contains nitrates, phosphates, ammonia, etc.
Destruction of wetlands	Disturbing natural processes that purify water
Pollution of water sources	Increased occurrences of infectious agents such as cholera, dysentery, etc.
Sewage runoff, feedlot runoff	Cultural eutrophication
Building power plants	Increased thermal pollution

CONSERVATION OF MATTER AND ENERGY

The law of conservation of matter states that during an ordinary chemical change, there is no detectable increase or decrease in the quantity of matter. The total quantity of matter and energy available in the universe is a fixed amount and is never any more or less. The law of conservation of energy states that energy cannot be created or destroyed but can change its form. Conversion of one type of matter into another is always accompanied by the conversion of one form of energy into another. Usually heat is either given off or absorbed, but sometimes the conversion involves light or electrical energy in addition to heat.