

Chapter 5

The Biogeochemical Cycles

Introduction

Why the biogeochemical cycles are important is easily illustrated by discussing the importance of O₂ in our atmosphere. Obviously O₂ is essential for most of the familiar life forms, including our own. Everyone knows that green plants produce O₂ and that animals consume O₂. What would happen to the O₂ in the atmosphere if the consumption of O₂ was greater than the production? Obviously it would decrease. It doesn't, but why? The concentration in our atmosphere is about 20% by volume and that is very important. If it was much higher than 20%, say 30%, there would be spontaneous combustion of forests. If it was much lower, say 10%, then most aquatic life would perish and air breathing organisms would be greatly stressed. Then how is it that the concentration is 20%, which happens to be about optimal for life on earth? And how is it that the concentration remains at 20%?

Case Study – Lake Washington

Another, less abstract example is given by the Lake Washington Case Study. Here is an example of how humans raised the inputs of nitrogen and phosphorus by using the lake to dispose of treated wastewater. The connection between human population, ecosystems, and the cycling of elements is very clear. The increased input of N and P proved to be great enough to alter the ecology of the lake in a way that was objectionable to the people of Seattle, and to correct the problem the city of Seattle had to reroute their sewage waste into Puget Sound, which is a much larger water body and better able to assimilate the waste. After this was accomplished in 1968, the water quality of the lake quickly improved. Runoff from an increasingly urbanized watershed around the lake continues to a problem.

5.1 HOW CHEMICALS CYCLE

Life depends on a constant supply of chemical building blocks or essential elements. Life cannot exist even if one of the essential elements is missing. Not only the presence and absence of life, but also its quantity (**production** and **biomass**) also depends on the abundance and supply of essential elements. The essential elements are not uniformly across the planet. For example, some soils are said to be naturally fertile, while others that are deficient in these elements are not. At the other extreme, the abundance of some elements (e.g. selenium) can be so great that they are toxic. First let's consider some basics.

- Biogeochemical Cycles

Our planet can be divided roughly into two parts: one that is living or derived from once living things (termed **biotic**) and one that is non living and not derived from once living things (termed **abiotic**). The biotic part is composed of chemical building blocks derived from the abiotic part. These building blocks just pass repeatedly between the abiotic and biotic environments. The manner in which they pass back and forth between the abiotic environment and living organisms, among organisms, and the way they move about and are distributed spatially and temporally are the subjects of much investigation by ecologists. These transfers or transformations of the elements are collectively referred to as **biogeochemical cycles**. A biogeochemical cycle is the complete path that a chemical takes through the four major parts of the Earth's system: atmosphere, hydrosphere, lithosphere, and biosphere. .

CLOSER LOOK 5.1: MATTER AND ENERGY

The chemical elements are the most fundamental pieces of matter that we will consider in our discussion of biogeochemical cycles. The atoms of all chemical elements are composed of a nucleus of **protons** (+) and **neutrons** (no charge), and a shell of negatively charged **electrons**. The fundamental difference between one element and another is the number of protons in the nucleus. For example, a carbon (C) atom has 6 and only 6 protons, a nitrogen (N) atom has 7 and only 7 protons, and so on. Except for nuclear transformations that will be discussed later, the chemical elements are immutable and are conserved, i.e. neither created nor destroyed. Life is made up of about 24 chemical elements. Most animal and plant matter is composed of C, O, H, N, P, Ca, S, and K and a few others, and the remaining elements (termed **trace nutrients**) are present only in miniscule amounts, but even the trace nutrients are important for life. There are some important differences between the composition of animals and plants, but most animals share the same basic composition and most plants share the same composition.

- Chemical Reactions

Atoms react and combine with one another to form molecules. Molecules also combine with other molecules and with atoms to form new kinds of molecules. The act of atoms or molecules combining is termed a **chemical reaction**, and any particular reaction can be articulated verbally or in terms of symbols. For example, a molecule water combines with a molecule of carbon dioxide to form a molecule of carbonic acid, or in terms of symbols one would write: $\text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{H}_2\text{CO}_3$.

- Here you should explain the meaning of the subscript numbers and the difference between 2CO_2 and CO_2

There are rules that determine which atoms or molecules will react with one another and under what circumstances, and this is the provenance of chemistry, which we will not

delve into. The chemists have discovered these reactions for us and we will leave it at that.

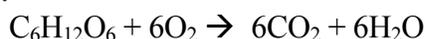
- Here you may want to define ions, cations and anions.

CLOSER LOOK 5.2: A GENERIC BIOGEOCHEMICAL CYCLE

A cycle can be visualized as a box and arrow diagram showing the flux of an element or compound from one compartment to another. This diagram also shows the mass balance of the cycle. The arrows generally show the flow rate or flux rate and the boxes show the amount of the element in that particular compartment. From these amounts and fluxes it is possible to calculate the residence times. Take for example a lake with a volume of $3 \times 10^6 \text{ m}^3$ and flows into and out of the lake of $3,000 \text{ m}^3/\text{day}$. The residence time of water in the lake would be the volume divided by the flux, or 1000 days.

CLOSER LOOK 5.3: PHOTOSYNTHESIS AND RESPIRATION

Another reaction that is vitally important is the reaction between carbon dioxide and water to form carbohydrate or sugar. This is the reaction known as **photosynthesis**: $6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$ (see Photosynthesis and Respiration a Closer Look) We had talked about oxygen earlier, this is where it comes from. Now we can talk about a biogeochemical cycle as coupled reactions that result in a closed cycle of elements. Using carbon as an example, the carbon atoms in CO_2 are combined with water molecules to form sugar, but there must be a way to transfer the carbon in sugar back into CO_2 , or else all the carbon on the planet would end up in a colossal heap of sugar, there would be no CO_2 left for plants to photosynthesize, and life would end. Fortunately there is a way to liberate the carbon from sugar and it is termed **respiration**:



Notice that is the same reaction as photosynthesis, but reversed. Photosynthesis requires energy in the form of sunlight to operate, and some of the solar energy is captured and stored in the sugar molecule. When the sugar molecule is converted back into CO_2 and H_2O , that stored energy is released and that is the energy that allows living things to accomplish the work that is needed to survive.

5.2 ENVIRONMENTAL QUESTIONS AND BIOGEOCHEMICAL CYCLES

The actual details of how the essential elements cycle is more complex than this simple example. The cycles are influenced by biological, geological, atmospheric and hydrological factors. The cycles interact, they are intentionally and unintentionally modified by people, sometimes with positive results and sometimes with negative results. We intentionally modify the cycles to increase food production, for example, by

supplying extra nutrients, like nitrogen. But this has unintentional side effects like harming the ecology of lakes and rivers. We can reduce the impact of people on the environment by properly managing these cycles, and that can only be done by understanding them. Major questions can be broken down into those that are primarily biological, geological, atmospheric and hydrological. Examples (p. 81 and 82) include biological questions, such as: What chemicals necessary for life place limits on the abundance and growth of organisms? Can the cycles of these be altered by people to increase production of desired species or limit the production of nuisance species; geological: What physical and chemical processes control the movement and storage of chemicals in the environment? Atmospheric: What determines the concentrations of chemicals in the atmosphere? Hydrological: How do biogeochemical cycles affect the productivity of a water body, and how can they be managed?

5.3 BIOGEOCHEMICAL CYCLES AND LIFE: LIMITING FACTORS

The abiotic environment consists of about 103 elements, while the biotic environment requires about 24 of these elements. These are divided into macronutrients and micronutrients. The macronutrients consist of C, H, N, O, P and S. The growth rate of organisms (**biological production**) is dependent on the supply rates of these essential nutrients. More specifically, biological production is limited by the one element (termed the **limiting factor**) that is least available relative to the need or the demand. In most natural environments and in agriculture, the elements that are most commonly limiting (the elements that usually limit the rate of production) are N and P. That is why farmers use so much N and P fertilizer to make their crops grow faster.

Elemental composition of some organisms and organic compounds (% of dry weight):

Element	Corn	Man	Carb.	Fat	protein
O	44	15	51	11	24
C	44	56	42	77	52
H	6	7	6	12	7
N	2	9			16
K	1	1			
Ca	<1	5			

5.4 GENERAL CONCEPTS CENTRAL TO BIOGEOCHEMICAL CYCLES

Some elements like O, H and C discussed above cycle between the air, water, soil and living things. N and S also cycle as gases. Most other essential elements do not exist in a gaseous form, and they do not cycle through the air. Most importantly, every biogeochemical cycle is closed. There are no dead ends. The product of every reaction is the substrate of another reaction!

5.5 THE GEOLOGIC CYCLE

Nature consists of many different kinds of cycles that operate on different time scales. The geologic cycle or rock cycle is a cycle that also involves a cycle of elements, but it operates on time scales longer than the biogeochemical cycles. Geologic cycles literally churn the elements by consuming and renewing the earth's crust. Liquid rock spews out of volcanoes, hardens to form igneous rock, igneous rock is twisted and compressed under great pressure to form metamorphic rock, metamorphic and igneous rock both are eroded and deposited to form sedimentary rock, and all are eventually drawn again into the interior of the earth and converted into magma.

- The Tectonic Cycle – involves the creation and destruction of the solid outer layer of Earth, the lithosphere. Here you can launch into a discussion of plate tectonics, subduction zones, and spreading centers, including earthquakes, volcanism, the speed at which the plates move, Pangea, and the San Andreas fault. Show illustrations of the earth's plate boundaries (Fig. 5.7), the position of the continents over time and give some sense of the time. You also can talk about the importance of continental drift to biogeography (biogeography is discussed in greater detail later), and you can talk about the discovery of life around thermal vents and how those ecosystems actually operate on chemical energy, not solar energy. Show pictures. Thermal vent communities are significant scientifically because they suggest how the earliest ecosystems probably operated billions of years ago in the ocean when the atmosphere was devoid of oxygen.

- The Hydrological Cycle -
Include here as an example of yet another kind of cycle, but give the details in the lecture(s) that address water resources.

- The Rock Cycle – Tectonic processes form igneous rock, which are weathered by wind, water and acids into sand, silt and clay. Weathered materials accumulate in basins and can be compacted by overlying sediment to form sedimentary rock. Under intense heat and pressure, sedimentary rock will form metamorphic rock. See Fig. 5.9.

5.6 BIOGEOCHEMICAL CYCLING IN ECOSYSTEMS

- Ecosystem Cycles of a Metal and a Nonmetal

The calcium cycle (Fig. 5.12) is typical of that for a metal, the sulfur cycle (Fig. 5.13) is typical of a nonmetallic element. An important distinction between the two is that sulfur forms a gas (several in fact), while calcium does not.

- Chemical Cycling and the Balance of Nature

The chemical composition of life forms is remarkably uniform. For the most part, living things (the biota) are all composed of the same chemical elements. For all practical purposes, the abundance of each of the basic elemental building blocks is fixed, they neither increase nor decrease over time. This is referred to as **conservation of mass**.

Conservation of mass is an important concept. The example of what happens to the mass of a piece of wood or paper when it burns will serve as a nice illustration. Of course the solid $C_6H_{12}O_6$ is converted into CO_2 and H_2O , the mass of elements in wood is conserved, they are just converted into gas. What follows is a discussion of several of the major biogeochemical cycles (N, C, P) and how they operate, why they are important, and how humans are affecting the cycles.

5.7 SOME MAJOR GLOBAL CHEMICAL CYCLES

● Carbon (Fig. 5.14)

The inventory: atmosphere 750 bMt; soil 1580; fossil fuel 4000; shallow ocean 38,000. Cycling through the atmosphere is very fast. Plants absorb carbon as carbon dioxide (CO_2) during the process of photosynthesis and from organic molecules (definition: **organic matter** is a molecule that contains both C and H atoms). Organic molecules containing C, synthesized by plants, are passed along to animals, and from animal to animal.

The organic C molecules in plants and animals are eventually degraded or decomposed by microbes (bacteria and fungi) and the organic matter converted to CO_2 , completing the cycle. Over geologic time scales, some of the organic C has been preserved in deposits, buried, and converted into coal, gas, and petroleum (fossil fuel).

We have excellent measurements of how much fossil fuel is used annually on a global scale, and we have excellent measurements of how much CO_2 is accumulating in the air. A large fraction of the CO_2 produced by burning fossil fuel does not remain in the atmosphere. A large part is absorbed by the ocean, but there is a sizable fraction that is unaccounted for and this has led to a spirited debate among scientists about where it is going. If the missing fraction is not going into the ocean (which we think we know) or atmosphere (which we know with certainty), then it must be going into the vegetation. Therein lies the controversy. The biogeochemical carbon cycle is one that humans are modifying to a degree that is sufficient to modify global climate.... we think.

● Carbon-Silicate (Fig. 5.18)

Over geological time scales, the cycling of carbon and silicon are linked. CO_2 in water forms a weak acid (carbonic acid or H_2CO_3). This helps to weather rock and dissolve calcium and silicate ions. These carbonates, silicates and calcium move in surface and ground water to the ocean where diatoms and other organisms make their shells from these materials. When they die, these shells sink to the bottom and make vast deposits of carbonate-rich sediments, such as limestone.

● Nitrogen

The nitrogen cycle (Fig. 5.19) is one of the most complex because it involves several steps that are uniquely accomplished by microbes. Plants absorb nitrogen as ammonium

Chapter 5

(NH_4) or nitrate (NO_3). Ammonium is a cation, while nitrate is an anion. These molecules behave much like table salt. When paired with a molecule with an opposite charge they will form a solid that looks like salt, but when placed in water the compound dissolves (the anion separates from the cation). Animals require their N in organic form. It must have been converted first by a plant into organic molecules (proteins).

The N in both plants and animals is returned to the soil where the organic matter decays and the organic P is once again converted back into inorganic NH_4 by microorganisms (fungi and bacteria). There are specialized bacteria that will convert NH_4 into NO_3 ; this process is termed **nitrification**. It is a process that requires oxygen. There are specialized bacteria that will convert NO_3 into N_2 gas; this process is termed **denitrification**. It is a process that happens only in the absence of oxygen. Such environments are found in waterlogged soils like find in wetlands and some other restricted places.

There are other specialized bacteria that will convert N_2 into ammonium (NH_4); this process is termed **nitrogen fixation**. There are nitrogen fixing bacteria that live in the roots of some plants (legumes) and supply the plant hosts with N, and there are other nitrogen fixing bacteria that live freely in the soil and in aquatic environments.

Nitrogen used in agriculture (as well as munitions) is manufactured using the Haber-Bosch process. This is a process that uses natural gas to fix atmospheric N_2 . Prior to the discovery of this process in the early 20th century, nitrogen was obtained from deposits of guano.

Here you could test your students grasp of the concept of recycling by diagramming the N cycle and omitting the N-fixation step. Ask them what would happen.

• Phosphorus

P is one of the many elements that does not have an important gaseous phase. P is absorbed by plants as orthophosphate or PO_4 . PO_4 is taken up by plants in ionic form, it is converted by plants into organic P compounds (amino acids, ATP, etc.).

Animals require their P in organic form. It must have been converted first by a plant.

The P in both plants and animals is returned to the soil where the organic matter decays and the organic P is once again converted back into inorganic PO_4 by microorganisms (fungi and bacteria), completing the cycle. Some PO_4 is lost from terrestrial ecosystem because it leaches from the soil into ground water and moves slowly to lakes and streams and eventually into the ocean. The lost PO_4 is replaced by P that dissolves slowly from rocks. PO_4 for agriculture is derived from phosphate mines. Note that phosphate mines represent a nonrenewable resource, and this could limit agricultural production in the future.

Topics for Class Discussion—Thinking Critically

IF THERE WERE NO BACTERIA OR FUNGI, COULD LIFE EXIST?

Practically speaking, no. Microbes are necessary to convert organic molecules back into their inorganic constituents. Fire accomplishes the same function and in some ecosystems, periodic fires are necessary for the regeneration and maintenance of communities, but obviously fire does not really substitute for microbes and in aquatic environments does not function at all.

CRITICAL THINKING: HUMAN ALTERATION OF THE NITROGEN CYCLE

Humans now fix annually as much NH_4 by the Haber-Bosch process as the global rate of nitrogen fixation by microbes. Here is a major biogeochemical cycle that humans alter on a global scale. How will this change as the human population grows? Does this affect the global carbon cycle? Does this change the ecology of the environment on regional or global scales?

Web Resources

<http://www.eos-ids.sr.unh.edu> A NASA site that documents and tracks changes in the Earth's biogeochemical cycles.

<http://www.whrc.org/science/carbon/carbon.htm> A site at the Woods Hole Research Center with many excellent graphics and facts on the global carbon cycle.

http://www.wri.org/biodiv/pubs_content_text.cfm?cid=1412 A World Resources Institute publication with facts about human contributions to the global nitrogen cycle.

You can find many excellent resources on the WRI web site: www.wri.org and <http://www.earthtrends.wri.org>