Study Unit 1.0 BIOGEOCHEMICAL CYCLES

Introduction

The problems faced by the environment today are more chemically complex than ever, yet the environment retains its place as central to human survival. They are intimately intertwined with current events and future developments and have significant impacts on the environment. Therefore there is need to study the interactions among the components of the environment hence the need for looking into biogeochemical cycles as a unit.

Learning outcomes for Study Unit 1

By the end of this unit, students should be able to;

- Describe the biogeochemical cycles

1.1 Introduction to The Biogeochemical cycles

The word biogeochemical comes from two Greek words; ‘Bios’ which refers to living organisms and ‘geo’ to the rock, soil and air.

The cyclic movements of chemical elements of the biosphere between the organism and the environment are referred to as biogeochemical cycles. The atoms of each element such as carbon, hydrogen, oxygen, nitrogen, phosphorous, calcium and the rest are taken from the environment, make a part of some cellular components route involving several other organisms and are returned to the environment to be used over again.

In bio geochemical cycles, there are two phases; the organic / biotic phase and abiotic phase.

The flow of a chemical element through the food chain can be viewed as the organic phase.

The abiotic phases are of critical importance to the ecosystem, as the major reservoirs for all nutrient elements are external to the food chains, and flow in the abiotic phases tends to be much slower than in the organic phase.

There are two classes of abiotic phases in bio geochemical cycle; **a sedimentary phase** which is part of all cycles and **an atmospheric phase** which is possessed by some. Cycles such as nitrogen the atmospheric phase is more important than the sedimentary.

In others such as phosphorous, the atmospheric phase is essentially non-existent. The sedimentary phase is the dominant phase. Biogeochemical cycles that have dominant atmospheric phase are essentially non-existent. Biogeochemical cycles that have dominant atmospheric phases are often called **atmosphere reservoir cycles**; those whose sedimentary phase is dominant are termed as **sediment reservoir cycles**.

There are two types of biogeochemical cycles, the **gaseous** and **sedimentary**.

In gaseous cycles the main reservoirs of nutrients are the atmosphere and ocean.

In sedimentary cycles the main reservoirs are the soil and the sedimentary and other rocks of the earth's crust.

1.2 The Carbon Cycle

Carbon being a basic constituent of all organic compounds is a major element involved in the fixation of energy by photosynthesis. It is so closely tied to energy flow that the two are inseparable.

The source of all the fixed carbon both in living organisms and fossil deposits is carbondioxide CO_2, found in the atmosphere and dissolved in the waters of the earth.

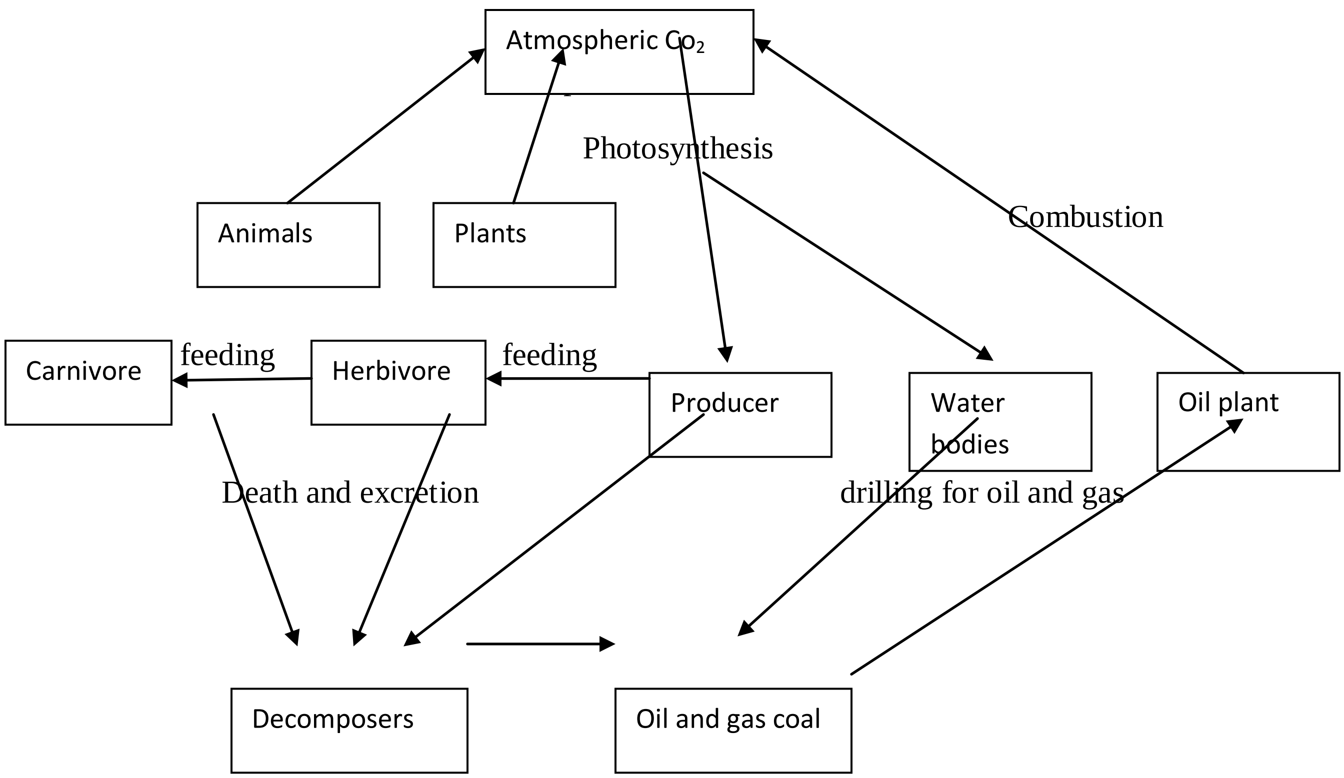
During photosynthesis, carbon from atmospheric, CO_2 is incorporated in the production of the carbohydrate, glucose, $C_6H_{12}O_6$ that subsequently may be converted to other organic compounds such as polysaccharides (sucrose, starch, cellulose etc.), proteins and lipids.

All the polymeric organic compounds containing carbon are stored in different plant tissues as food, and from them carbon is passed on to the trophic levels of herbivores or phytoparasites, or retained by the plant until it serves as food for decay organisms (viz, decomposers) some of the carbon is returned to the atmosphere (for the enveloping aqueous medium) in the form of CO_2, a by-product of plant respiration, in which a considerable portion of glucose is oxidized to yield CO_2 , H_2O and energy as follows.

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

The CO_2 which is released as a byproduct of plant respiration (for metabolic processes) is again used by plants in photosynthesis.

Diagram 1: The Carbon Cycle



Decomposing micro organisms are important in breaking down dead material with the release of carbon back to the carbon cycle.

Similarly, carbon taken up by herbivores or phytoparasites may travel a number of routes. It may be incorporated into protoplasm (assimilation) and stored until the organism dies, where upon it is utilized by decomposers; it may be released through animal respiration: it may serve as food for other organisms; or finally it may be stored in the environment as CO_2.

Similar fates await carbon at the carnivore trophic level. In fact, all the carbon of plants, herbivores, carnivores and decomposers is not respired but some is fermented and some is stored. The carbon compounds that are lost to the food chain after fermentation, such as methane are readily oxidized to Carbondioxide by inorganic reactions in the atmosphere.

As for storage of carbon in sediments, just as deposition works to store materials, erosion may uncover them, and inorganic chemical weathering of rock can oxidize the carbon contained there.

Some carbon is permanently stored in sediments and not uncovered by weathering. It may be replaced by Carbondioxide released from volcanoes.

In modern age, man has greatly increased the rate at which carbon is passing from sedimentary form to Carbondioxide. The combustion of fossil fuels is a significant means of recycling sedimentary carbon much faster than natural weathering.

Small portions of carbon, especially in the sea, are found not as organically fixed carbon but as Carbonate (CO_3^{2-}), especially calcium carbonate ($CaCO_3$). $CaCO_3$ is very commonly used for shell construction by such animals as clams, oysters, some protozoa and some algae. Carbondioxide reacts with water to form carbonate in the following three step reaction.

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3 \rightleftharpoons 2H^+ + H\,CO_3^{2-}$$

The precise amount of each of these constituents in the water depends on the PH of the water.

Organisms such as clams can combine bicarbonate or carbonate with calcium dissolved in the water to produce calcium carbonate. After death of the animals, this $CaCO_3$ may either dissolve or remain in sedimentary form.

Certain control mechanisms are inherent in the carbon cycle. The rate of carbon utilization is dependent on its availability. If excessive amounts of carbon are taken up in any one phase of the cycle, other phases of activity may be inhibited or slowed down.

For example, if the pH of water is alkaline, more carbon is tied up in a carbonate and less in solution. If this equilibrium established between the atmospheric and the dissolved carbondioxide changes, the new effect would be a movement of CO_2 into solution until equilibrium is reached.

1.3 The Nitrogen Cycle

Nitrogen is an essential constituent of different biologically significant organic molecules such as amino acids and proteins, pigments, nucleic acids and vitamins. It is also a major constituent of the atmosphere comprising about 78% of it. The paradox is in its gaseous state, $N_{2,}$ abundant though it is, is unavailable to most of life. Before it can be utilized it must be converted to some chemically usable form.

To be used biologically, the free molecular nitrogen has to be fixed and fixation requires an input of energy. In the first step, molecular N_2, has to be split into two atoms.

$N_2 \longrightarrow 2N$

The free nitrogen atoms then must be combined with hydrogen to form ammonia, with the release of some energy.

$2N + 3H_2 \rightarrow 2NH_3$

This fixation comes about in two ways;

One is by high energy fixation such as cosmic radiating, meteoritic trails, and lightening that provide the high energy needed to combine nitrogen with oxygen and hydrogen of water. The resulting ammonia and nitrates are carried to the earth in rain water.

The second method of nitrogen fixation which contributes about 90% of fixed nitrogen of earth is biological. Some bacteria, fungi and blue green algae can extract molecular nitrogen from the atmosphere and combine it with hydrogen to form ammonia.

Some of this ammonia is excreted by the nitrogen fixing organism, and thus becomes directly available to other autotrophs.

Some of these nitrogen fixing organisms may be free living, either in the soil (e.g. bacteria-Azobacter and clostridium) or in water (e.g. blue-green, algae - Nostoc, calothrix and anabaena) and produce vast quantities of fixed nitrogen.

In other cases, certain symbiotic bacteria of genus rhizobium although unable to fix atmospheric nitrogen themselves can do this when in combination with other cells either from the roots of legumes (e.g. peas, beans, clover and alfalfa) and of other angiosperms such as alnus, ceanothus, shepherdia, elaeagnus and myrica, or from the leaves of African genera of rubiacea and pavetta. The bacteria invade the roots or leaves and stimulate the formation of root nodules or leaf nodules, a sort of harmless tumor. The combination of symbiotic bacteria and host cells remains able to fix atmospheric nitrogen and for this reason legumes are often planted to restore soil fertility by increasing the content of fixed nitrogen.

Further, both free soil bacterial (Azobacter, and clostridium) produce ammonia as the first stable product and like the symbiotic bacteria, they require molybdenum as an activator and are inhibited by an accumulation of nitrates and ammonia.

Recently, certain lichens (collema tunae forme and peltigera rufescens) were also implicated in nitrogen fixation. Lichens with nitrogen fixing ability possess nitrogen fixing blue green species as their algal component.

Nitrogen fixed by symbiotic and non symbiotic micro organisms in soil and water is one source of nitrogen. Another source is organic matter. The nitrogenous wastes and carrion of animals are degraded by detritus organisms; nitrogen is converted to amino form (e.g. L-Alanine). The amino group ($-NH_2$) is liberated from organic molecules to form ammonia; this process is called deamination.

Certain specific bacteria, most notably of the genus nitrosomonas can oxidize ammonia to nitrite (NO_2) by the reaction.

$$2NH_3 + 3O_2 \longrightarrow 2NO^-_2 + 2H_2O + 2H^+$$

This reaction takes place in the soil, in lake or sea water or sediments, and whenever ammonia is being released and oxygen is present.

As fast as nitrate is produced, other bacteria, such as nitrobacter, can combine nitrite with oxygen to form nitrate (NO_3^-) by the reaction.

$$2NO^-_2 + O_2 \longrightarrow 2NO_3^-$$

Both of those reactions which are performed by two nitrifying bacteria nitrosomonas and nitrobacter, are the parts of a single biological process called nitrification. In the nitrification process thus, ammonia is oxidized to nitrate and nitrite, yielding energy. This energy is used by the bacteria to make their organic materials directly from Carbondioxide and water. Nitrate can be taken up by autotrophs at the beginning of food chains.

Under certain circumstances, nitrate is either not produced in the nitrogen cycle or it is degraded before it can be utilized by autotrophs. Degradation of nitrate is called denitrification, and may be important when oxygen concentration is low. Denitrifying bacteria such as pseudomonas can use the energy of the nitrate ion to drive their metabolism and in so doing; they break the nitrate down to nitrite, ammonia or molecular nitrogen.

$$C_6 H_{12} O_6 + 12NO_3^- \longrightarrow 12NO_2^- + 6CO_2 + 6H_2O$$

$$C_6H_{12}O_6 + 8NO_3^- \longrightarrow 4N_2 + 2CO_2 + 4CO_3^{2-} + 6H_2O$$

$$C_6H_{12}O_6 + 3NO_3^- \longrightarrow 2NH_4 + {}_6CO_2 + 3OH^-$$

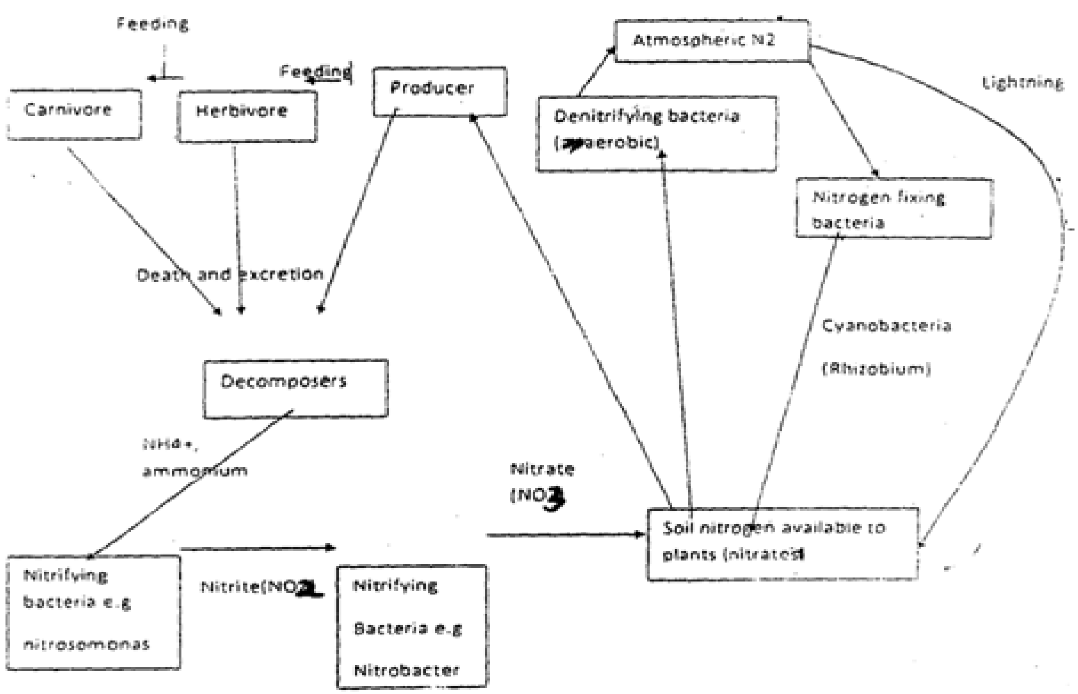
If denitrification is significant in an ecosystem, nitrite is transitory and is also degraded into either ammonia or molecular nitrogen.

1.3.1 Cycling of nitrogen in the ecosystem

The sources of inputs of nitrogen under natural conditions are the bacterial fixation of atmospheric nitrogen, addition of inorganic nitrogen in rain from volcanic activities, ammonia absorption from the atmosphere by plants and soil, and nitrogen accretion from windblown aerosols, which contain both organic and inorganic forms of nitrogen. In terrestrial ecosystems, nitrogen, largely in the form of ammonia and nitrates is taken up by plants which convert it into amino acids and proteins. Animals (primary macro-consumers) may eat the plant and utilize the amino acids from the plant proteins in the synthesis of their own proteins and other cellular constituents. When animals and plants die, the decay bacteria convert the nitrogen of their proteins and other compounds into ammonia. Animals excrete several kinds of nitrogen containing wastes; urea, uric acid, creatinine and ammonia and the decay bacteria convert these wastes to ammonia. Ammonia may be lost as a gas to the atmosphere, may be acted upon by nitrifying bacteria, or may be taken up directly by plants. The nitrates may be utilized by plants, immobilized by microbes, stored in decomposing humus or leached away. This material is carried to streams, lakes, and eventually the sea, where it is available for use in aquatic ecosystems. There, nitrogen is cycled in a similar manner, except that the large reserves contained in the soil humus are largely lacking. Life in the water contributes organic matter and dead organisms that undergo deposition and subsequent release of ammonia and ultimately nitrates.

In aquatic ecosystem, atmospheric nitrogen is fixed by numerous blue green algae. Under natural conditions, nitrogen lost from ecosystems by denitrification, volatilization, leaching, erosion, windblown aerosols, and transportation out of the system is balanced by biological fixation and other sources.

1.3.2 Summarized diagram showing the nitrogen cycle



1.4 The water cycle

Living organisms, atmosphere and the earth maintain between them a circulation of water and moisture, which is referred to as water cycle or hydrological cycle.

Water forms a very significant factor of the environment and without the cycling of water, biogeochemical cycles (i.e. gases and sedimentary) could not exist, ecosystems could not function and life could not be maintained. Water is important for an ecosystem for several reasons and these include:- It is the medium by which nutrients are introduced into autotrophic plants, it serves as a means of thermal regulation for both plants and animals, it is a means by which sediments, a prime source of mineral nutrients, are removed from or added to local ecosystems, it covers the great majority of the earth's surface and it is the dominant feature of all aquatic ecosystems.

Box 1: Definition of hydrological cycle

Hydrological cycle can be defined as an alteration of evaporation and precipitation, with the energy used to evaporate the water being dissipated as heat in the atmosphere as the water condenses.

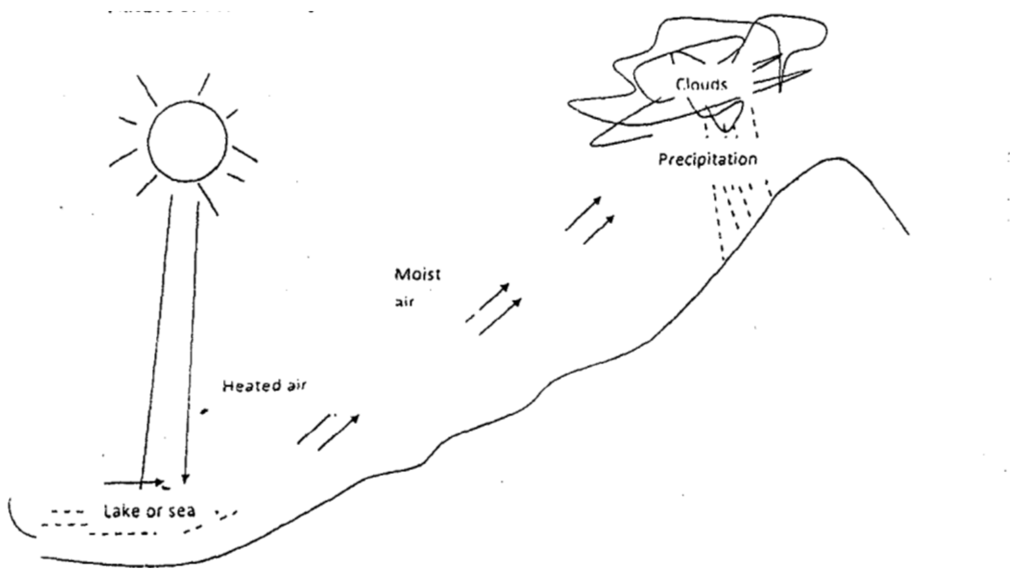
The hydrological cycle is driven by solar energy and gravity. More than 80% of the total insolation that is not lost immediately as electromagnetic radiation goes to evaporate water. The hydrologic cycle over the oceans or seas (water bodies) is extremely simple. Here, the water surface is heated by the sun's rays and evaporates into the atmosphere as water vapor which eventually forms the clouds.

Clouds are formed by warm air containing water vapor rising up becoming cooled and reaching a dew point where the atmospheric vapors produced condense around particles of dust and other particulates in the atmosphere often called **nucleation particles**. As evaporation continues, the water droplets (condensed atmospheric vapors) accumulate within these clouds. The atmosphere possesses a limited capacity for holding water vapor thus the droplets formed by this means, when heavy enough, fall as precipitation, with the energy used to evaporate the water being dissipated as heat in the atmosphere as the water condenses.

As rain falls on the earth's surface (precipitation), water is not evenly distributed throughout the earth for instance.

Almost 95% of the total water on earth is chemically bound into rocks and does not cycle. Of the remaining water, about 97.3% is in the oceans or seas. About 2.1 % exists as ice in polar caps and permanent glaciers. The rest is fresh water present in form of atmospheric water vapor, ground water or inland surface water.

1.4.1 Illustration of the water cycle



Several routes are open to precipitation that falls on land. These include direct evaporation, transpiration, entry of water into ground water, systems and run off. Consequently, the routes of hydrologic cycles on land can be divided into three main categories. These include:-

The rapidly cycling portion (evapotranspiration) which includes evaporation and transpiration. The less rapidly cycling water/ surface run off.

Very slowly cycling ground water that seeps into the soil can end up in any of the following three categories:-

1.4.2 Evapotranspiration

This includes evaporation and transpiration. Evaporation refers to water that is evaporated directly from any surface other than a plant welt as a lake, soil surface or animal skin. In most cases, the main effects of direct evaporation are:

To moderate the temperature of the local area.

To show the hydrologic cycle to continue

In some ecosysystems evaporation also leads to a concentration of salts in the water of soil which may be a critical environmental factor. Transpiration is water that evaporates from the surface of leaves of plants. Transpiration acts to move the bio geochemical cycles for all minerals nutrients that enter the food chain via the roots of plants.

1.4.3 Surface runoff

If transpiration is related to tire mechanism of nutrient uptake, the gross movement of soluble solid panicles in the ecosystem is accomplished largely by runoff Nutrients that have accumulated in sediments or soils can be eroded by steams and removed altogether by a local ecosystem, or soluble water, where they are removed front tire area. Streams may carry sediment particles which can be chemically altered through additional weathering so that the nutrient elements they contain may be utilized by organisms. Finally, moving water acts as an agent of erosion which removes soil and allows weathering of the underlying rock to make their nutrients available to plants.

1.4.4 Ground water

Ground water is water that saturates either sediment or rock below the water table. In general is not trapped by plant for transpiration and it too deep to be directly evaporated from the soil surface. It is an exceedingly important reservoir for water which moves from one place together under the influence of gravity. The area where the net water movement is from the surface into the ground water system is termed as a catchment area; areas where ground water reaches the surface and runs off are termed as sprints. A rock body through which ground water flows is called an aquifer. A well drilled into an aquifer that has sufficient hydrostatic pressure to force water up into it is called an artesian well.

In summary, the hydrologic cycle on land thus includes evapotraspiration of water from earth surface and lead surface formation of clouds, precipitation, surface run off, accumulation of water as ground water return of water to sea via streams or direct evaporation and cloud formation and so on.