# Chapter-II

ECOSYSTEM AND SYSTEM APPROACH TO PROBLEM SOLVING

## 2.1 Ecosystem

### What is an ecosystem?

The complex of a community of organisms and its environment functioning as an ecological unit. (*Merriam Websters*)

An ecosystem is a biological environment consisting of all the living organisms or biotic components, in a particular area, and the nonliving, or abiotic component, with which the organisms interact, such as air, soil, water and sunlight.

Some of the most fascinating reactors imaginable are ecosystems (Vesilind and Morgan, 2004).

Ecosystems are communities of organisms that interact with one another and with their physical environment, including sunlight, rainfall, and soil nutrients. It can be further defined as systems into which matter flows (Davis and Cornwell, 2011).

## 2.2 Key terminologies

- **Habitat** – Place where a population of organisms lives.
- **Population** – Group of organisms of the same species living in the same place at the same time.
- **Community** – a community is an assemblage of two or more populations of different species occupying the same geographical area. The term community has a variety of uses. In its simplest form it refers to groups of organisms in a specific place and/or time, for example, "the fish community of Rara Lake".
- **Biomes** – Complex communities of plants and animals in a region and a climate. These include deserts, tundra, chaparrals or scrubs, and temperate hardwood forests.
- **Biosphere** – It is the sum of all the regions of the earth that support ecosystems. The biosphere is made up of the atmosphere, the hydrosphere (the water) and the lithosphere (the soil, rocks and minerals that make up the solid portion of the earth).
- **Autotroph** – Primary producers obtaining required carbon from inorganic sources such as carbon dioxide ($CO_2$).
- **Heterotroph** – Organisms obtaining required carbon from organic compounds for making cell materials.
- **Phototroph** – Organisms that are able to use sunlight as an energy source. Phototrophic organisms may be either heterotrophic (certain sulfur-reducing bacteria) or autotrophic (algae and photosynthetic bacteria).
- **Chemotroph** – Organisms which obtain required energy from chemical reactions utilizing organic or inorganic compounds. Chemotrophs could be either heterotrophic (protozoa, fungi, and most bacteria) or autotrophic (i.e., nitrifying bacteria).
- **Anabolism** – The biosynthetic reactions by which new cell material is produced.
- **Catabolism** – Metabolic reactions by which substrate is degraded to simpler compounds, yielding energy and usually also building blocks for synthetic reactions.

## 2.3 Why does an engineer need knowledge of Environment/Biology?

**Environment** is a natural science concerned with the study of life and living organisms, including their structure, function, growth, origin, evolution, distribution, and taxonomy. Among the most important topics are five unifying principles that can be said to be the fundamental axioms of modern biology.

1. Cells are the basic unit of life
2. New species and inherited traits are the product of evolution
3. Genes are the basic unit of heredity
4. An organism regulates its internal environment to maintain a stable and constant condition
5. Living organisms consume and transform energy.

Living organisms, particularly the small ones, interact in numerous ways with human activities. On the large scale of the biosphere, which consists of all regions of the earth containing life, microorganisms play a primary role in the capture of the energy from the sun. Their biological activities also complete critical segments of the cycles of carbon, oxygen, nitrogen and other elements essential for life. Microbes are also responsible for many human, animal, and plant diseases. One of the major applications of biology lies with the question of how the microbes can be used for mankind’s welfare and progress. These versatile biological catalysts have served mankind for millennia. Various types of fermentation processes leading to production of ethanol, glycerol and other chemicals have been in practice since ancient times. In the 1940s complementary developments in biochemistry, microbial genetics, and engineering ushered in the **era of antibiotics** with tremendous relief to mankind’s suffering and mortality. This period marks the birth of biochemical engineering, the engineering of processes using catalysts, feedstocks, and/or sorbents of biological origin. Biotechnology began to change from empirical art to predictive, optimized design.

A later generation of **fermentation processes** produced steroids for birth control and for treatment of arthritis and inflammation. Methods for cultivation of plant and animal cells made possible mass production of vaccines and other useful biological agents. Clearly, mankind’s successful harnessing and direction of cellular activities has had many health, social, environmental, and economic impacts on past and contemporary human civilization.

Our challenge here is to understand and analyze the process of biotechnology so that we can design and operate them in a rational way. To reach this goal, however, a basic working knowledge of cell growth and function is required. These factors and others peculiar to biological systems usually dominate biochemical process engineering. Living microorganisms can be viewed in an approximate conceptual sense as an expanding chemical reactor which takes in nutrients from the environment, grows, reproduces, and releases products into its surroundings. In instances such as sewage treatment, consumption of nutrients (organic waste) is the engineering objective. When microbes are grown for food sources or supplements, it is the mass of microbial matter produced which is desired. For a sewage treatment process, this microbial matter produced by nutrient consumption constitutes an undesirable solid waste and thus its amount should be minimized. The products formed and released during cellular activity are of major concern in many industrial and natural contexts. The relative rates of nutrient utilization, growth and release of products depend strongly on the type of cells involved and other temperature, composition and motion of their environment. Understanding these interactions requires a foundation built upon biochemistry, biophysics and cell biology. Since study of these subjects is not traditionally included in engineering education, a substantial portion should be dedicated to them.

Whenever possible, the study of qualitative aspects of biological processes should be extended to quantitative mathematical representations. These mathematical models will often be extremely oversimplified and idealized, since even a single microorganism is a very complicated system. Nevertheless, basic concepts in microbiology should serve as a guide in formulating models and checking their validity, just as basic knowledge in fluid mechanics is useful when correlating the friction factor with Reynolds number (Bailey and Ollis, 1986).

A second aspect of the relevance of the study of biology lies with the **pollution effects of anthropogenic activities**. Large scale agricultural operations can result in the release of pesticides, fertilizers, and greenhouse gases (GHGs) to the environment. Dam construction for power generation or water supply can have detrimental effects on river ecosystems. Loss of habitats leading to global extinction of species, introduction of nonnative species in the ecosystem and establishment of built-in areas in the cost of green forests and other ecosystems are issues where engineering is directly or indirectly linked with biology in general or ecosystem in specific.

As illustrated by the **discharge of pollutants into waterways** or other environments, engineering designs often have major impacts on ecosystems. However, with some forethought, engineers can use techniques to minimize negative impacts. Similarly, it is also desirable to know the direct and indirect impacts on ecological resources and surrounding ecosystems while designing a product. Comparing the functional units of similar products and the extent of environmental impacts created by the production and use of the products, we can obtain information to improve processes, support policy and provide a sound basis for informed decisions. This would also help the customers to make their choices.

The **design of new structures or products or services** and the remodelling of existing structures or products or services, offer engineers many opportunities to incorporate energy efficient, water efficient and environmentally friendly materials and devices into their designs. Of course, these types of designs mean that engineers have to work in teams, often with non-engineers, such as biologists and landscape architects.

Thus the **study related to ecosystems** i.e. the domain of plants, animals and their physical environment and the flow of energy and materials in the ecosystem serves as a basis in understanding the advanced concepts in environmental engineering and other cross-cutting disciplines.

## 2.4 Hydrological cycle

The Hydrologic or Hydrological cycle (also termed **water cycle**) is a conceptual model that describes the storage and movement of water between the biosphere, atmosphere, lithosphere, and the hydrosphere (see Fig.1). Water on our planet can be stored in any one of the following major reservoirs: atmosphere, oceans, lakes, rivers, soils, glaciers, snowfields, and groundwater. Water moves from one reservoir to another by way of processes like evaporation, condensation, precipitation, deposition, runoff, infiltration, sublimation, transpiration, melting, and groundwater flow..

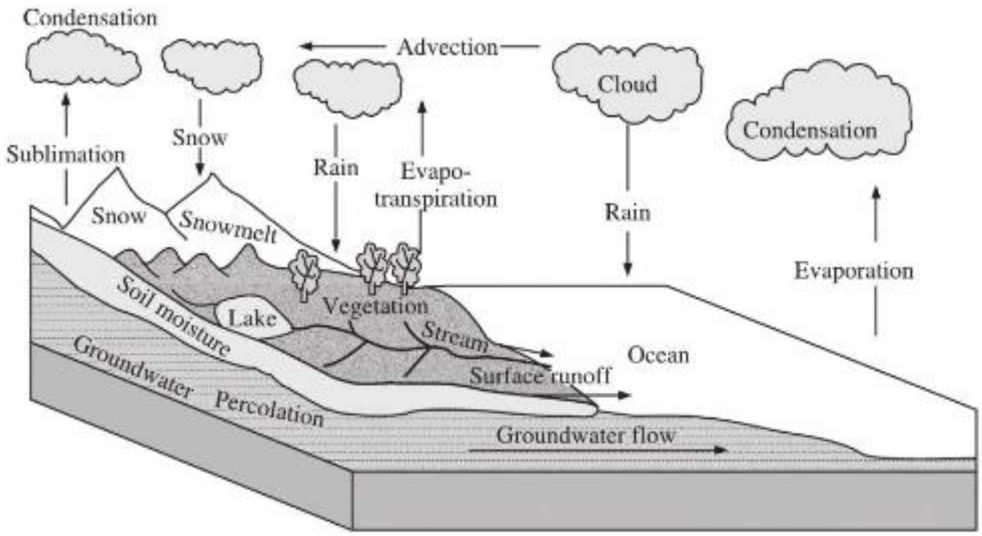



Figure 1 Hydrological cycle

- **Key Hydrological Process:**

1. Precipitation : The process for all moisture produced from clouds and falling on the ground
2. Evaporation: The process by which water changes from liquid to gas or vapor.
3. Transpiration: The evaporation of water into atmosphere from the leaves and stems of the plants.
4. Infiltration: The part of precipitation that enters into the ground and then flows downwards.
5. Runoff: The part of the precipitation that appears in the surface streams, rivers, drains or sewers. This includes both surface and channel runoff.
6. Subsurface flow: The flow of water beneath the earth's surface.

Water balance equation:

The total amount of the water available on the earth is finite and conserved. The water balance equation simply incorporates principles of mass and energy continuity. The water balance equation (often called as water budget equation) for a closed system is

$$\mathbf{\Delta S = P - Q - E} \qquad (2.1)$$

Where P is Precipitation, E is Evaporation; Q is Runoff with the dimensions of volume.

**Catchment area**: The area of land draining into a stream or a water course at a given location is known as catchment area. It is also called drainage basin or area and watershed also. A catchment area is separated from its neighboring areas by a ridge.

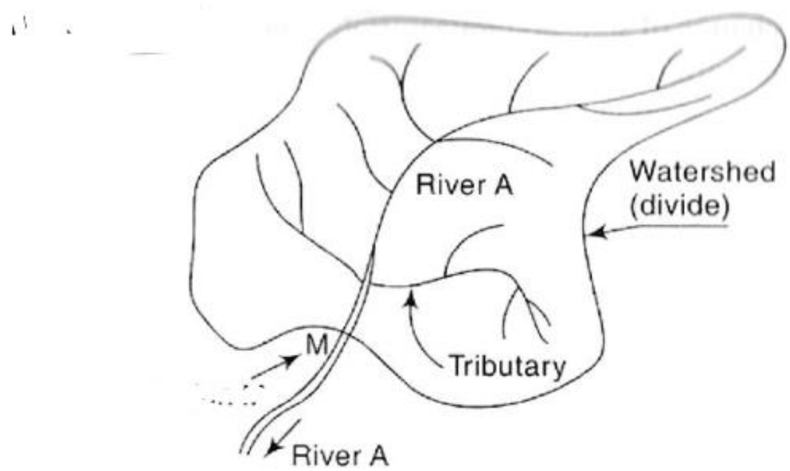



Figure 2 Schematic diagram of Catchment area

**Example 1**: Compute the average annual runoff from the catchment if the average annual precipitation in a 2000 ha catchment is 1400 mm and the corresponding value for the actual evapotranspiration is 800 mm.

Apply water balance,

ET+R-P=0 or, R= P-ET or, 1400-800 or, R=600mm, R= 0.6m$\times$2000$\times 10^4$=12$\times 10^6$ m$^3$

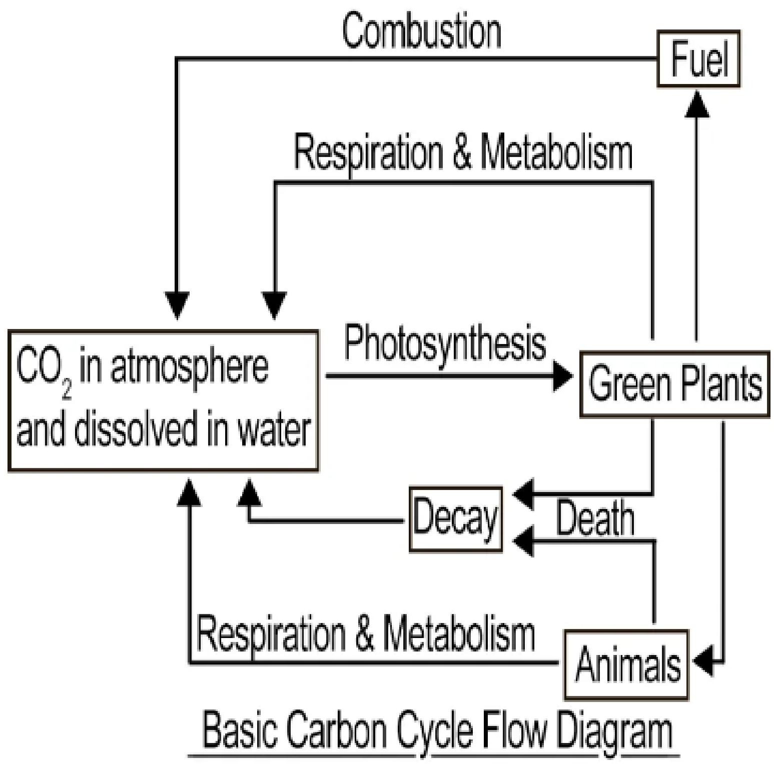
**Global water distribution**

About 96.5% of all the water present on the earth is in oceans as saline water. About 1.7% is in polar ice and another 1.7% is ground water. Only 0.1% is in the surface and atmosphere.

| Location | Water volume in km$^3$ | Percentage of total water |
|---|---|---|
| Oceans | 1338000000 | 96.5 |
| Ice | 24364000 | 1.7 |
| Ground | 23400000 | 1.7 |
| Surface and atmosphere | 220510 | 0.1 |

**2.5 Carbon cycle**

The carbon cycle (Fig. 3.2) is one of the major biogeochemical cycles describing the flow of essential elements from the environment to living organisms and back to the environment again. This process is required for the building of all organic compounds and involves the participation of many of the earth's key forces. The carbon cycle has affected the earth throughout its history; it has contributed to major climatic changes, and it has helped facilitate the evolution of life.



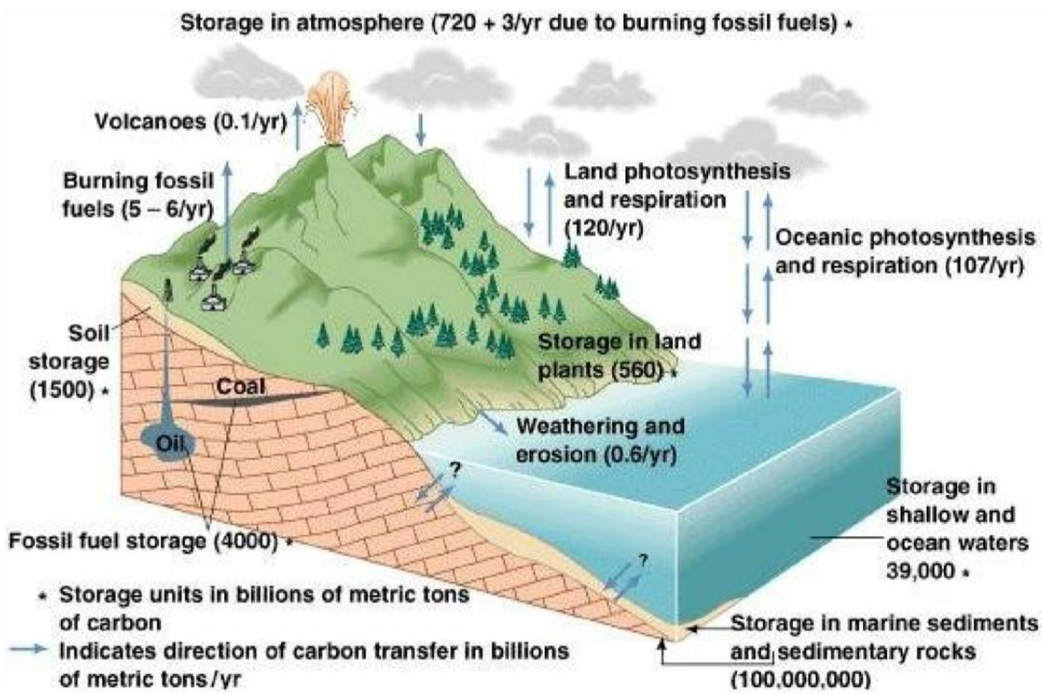




Fig. 3.2 Generalized Carbon cycle

The major driving force underlying the biogeochemical cycle is photosynthesis, which taps solar energy to reduce $CO_2$, bicarbonate, and carbonate, the oxidized forms of carbon, while simultaneously liberating molecular oxygen from water. The amount of carbon fixed per year on land and in the oceans is roughly $1.6 \times 10^{10}$ and $1.2 \times 10^{10}$ tons, respectively. While green plants are the major contributors to the photosynthetic activity on land, photosynthesis occurring in the oceans is almost entirely due to unicellular algae called phytoplankton. Although photosynthesis is the dominant means of $CO_2$ reduction, chemoautotrophs also reduce $CO_2$. Mineralization of organic carbon to $CO_2$ is primarily the consequences of bacterial and fungal metabolic activities.

Carbon is removed or sequestered from the life cycle by several mechanisms. Much of the $CO_2$ released into the atmosphere enters the oceans as bicarbonate ions. There, it can combine with calcium to form calcium carbonate which appears in coral shells and limestone. In this form of carbon is relatively inaccessible, but much of it is ultimately made available by weathering or by attack of acids. Microorganisms participate in the latter process through synthesis of carbonic, sulfuric, nitric, and other acids.

Carbon is sequestered in organic form. Humus, an organic residue derived from microbial resistant plant components, is an important constituent of rich soil. When conditions favor large accumulations of humus, deposits of peat are created which, on a geological time scale, can be transformed into coal. Oil and natural gas are other common forms of sequestered organic carbon. Carbon residing in these forms seems destined for eventual return to the biosphere due to man's apparently relentless demands (Baily and Ollis, 1986).

**2.6 Nitrogen cycle**

The nitrogen cycle represents one of the most important nutrient cycles found in ecosystems. (Figure 3). Nitrogen is a required nutrient for all living organisms to produce a number of complex organic molecules like amino acids, the building blocks of proteins, and nucleic acids, including DNA and RNA. The ultimate store of nitrogen is in the atmosphere, where it exists as nitrogen gas ($N_2$). This store is about one million times larger than the total nitrogen contained in living organisms. Other major stores of nitrogen include organic matter in soil and the oceans. Despite its abundance in the atmosphere, nitrogen is often the most limiting nutrient for plant growth. This problem occurs because $N_2$ gas is not biochemically usable by plants. Plants can only take up nitrogen in the form of ammonium ion ($NH_4^+$), nitrate ion ($NO_3^-$), or, less common, as amino acids. Animals receive the nitrogen they need for metabolism, growth, and reproduction by the consumption of living or dead organic matter containing molecules composed partially of nitrogen.

In most ecosystems nitrogen is primarily stored in living and dead organic matter. This organic nitrogen is converted into inorganic forms when it re-enters the biogeochemical cycle via decomposition. Decomposers chemically modify the nitrogen found in organic matter to ammonium ion ($NH_4^+$). This process is known as mineralization and it is carried out by a variety of bacteria and fungi.

Nitrogen in the form of ammonium can be absorbed onto the surfaces of clay particles in the soil. The ammonium ion has a positive molecular charge and is normally held by negatively charged soil colloids. This process is sometimes called micelle fixation. Ammonium is released from the colloids by way of cation exchange. When released, most of the ammonium is often chemically altered by a specific type of autotrophic bacteria (bacteria that belong to the genus Nitrosomonas) into nitrite ($NO_2^-$). Further modification by another type of bacteria (belonging to the genus Nitrobacter) converts the nitrite to nitrate ($NO_3^-$). Both of these processes involve chemical oxidation and are known collectively as nitrification. Unlike ammonium, nitrate is negatively charged and, therefore, does not absorb onto negatively charged clay surfaces. Consequently, nitrate is very mobile in soil and it is easily leached. Some of this leached nitrate flows through the hydrologic system until it reaches the oceans where it can be returned to the atmosphere by denitrification. Denitrification is also common in anaerobic soils and is carried out by heterotrophic bacteria. The process of denitrification involves the metabolic reduction of nitrate ($NO_3^-$) into nitrogen ($N_2$) or nitrous oxide ($N_2O$) gas. Both of these gases then diffuse into the atmosphere, thus removing nitrogen from the soil, accounting for the name, denitrification.

Almost all of the nitrogen found in any ecosystem originally came from the atmosphere. Significant amounts enter the soil in rainfall or through the effects of lightning. The majority, however, is biochemically fixed in ecosystems by specialized micro-organisms, all of which are bacteria of various types, including a variety of Gram-positive and Gram-negative bacteria, actinomycetes, and cyanobacteria. Members of the bean family (legumes) and some other kinds of plants form mutualistic symbiotic relationships with certain types of nitrogen-fixing bacteria. In exchange for some nitrogen, the bacteria receive from the plants carbohydrates and special structures (nodules) in the roots where they can exist in a protected environment. Scientists estimate that biological fixation globally adds approximately 140 million metric tons of nitrogen to ecosystems every year.

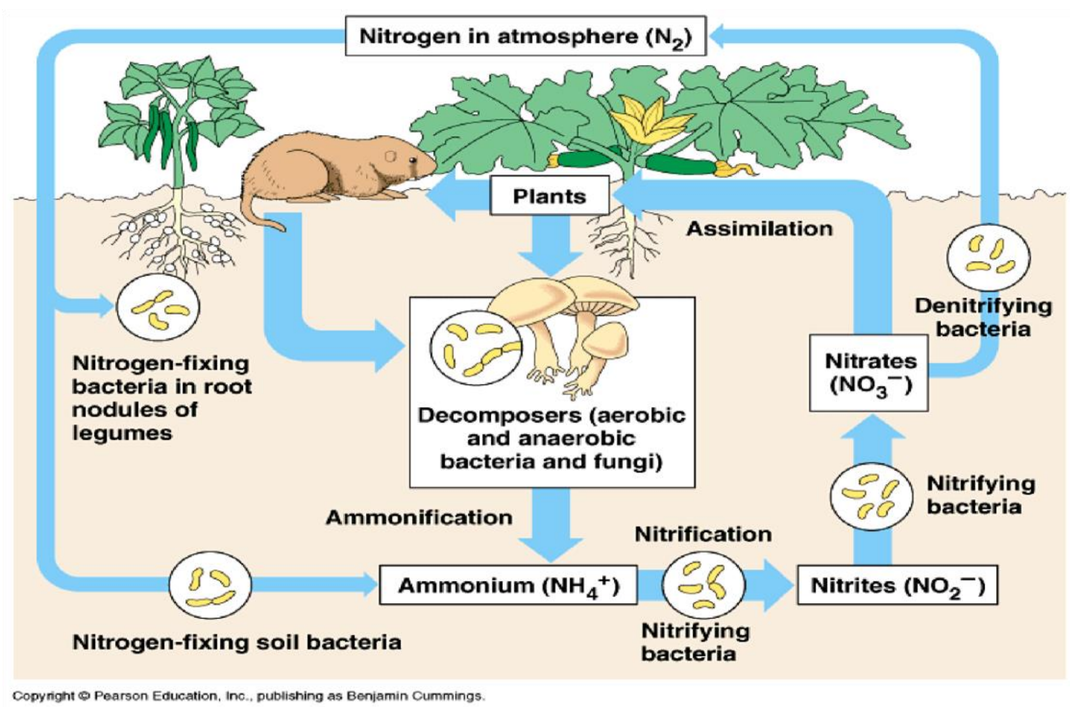



**Fig 3.3 Generalized Nitrogen Cycle in the environment**

Humans now fix approximately as much nitrogen industrially as does natural nitrogen fixation, thus dramatically altering the nitrogen cycle. Some of the major processes involved in this alteration include:

- The application of nitrogen fertilizers to crops has caused increased rates of denitrification and leaching of nitrate into groundwater. The additional nitrogen entering the groundwater system eventually flows into streams, rivers, lakes, and estuaries. In these systems, the added nitrogen can lead to eutrophication and associated hypoxia.

- Increased deposition of nitrogen from atmospheric sources because of fossil fuel combustion and forest burning. Both of these processes release a variety of solid forms of nitrogen through combustion and contribute to acid rain.
- Livestock ranching. Livestock release large amounts of ammonia into the environment from their wastes. This nitrogen enters the soil system and then the hydrologic system through leaching, groundwater flow, and runoff.
- Sewage waste and septic tank leaching. ( TEE, 2012)

### 2.7 Phosphorus cycle

The phosphorus cycle is the biogeochemical cycle which characterizes the transport and chemical transformation of phosphorus through the geosphere, hydrosphere and biosphere. Unlike many other biogeochemical cycles, the atmosphere does not play a significant role in the movement of phosphorus, since phosphorus and phosphorus-based compounds are typically solids at the normal ranges of temperature and pressure found on Earth. Therefore most of the phosphorus remains within rock, sediments, sand, and the ocean floor, with a fraction in living biomass. Phosphorus moves among trophic levels in an ecosystem by plant growth, herbivory and carnivory.

Phosphorus in the Earth's crust generally occurs in its maximally oxidized state, such as inorganic phosphate rocks. Phosphates are liberated from rocks in the weathering process of the natural environment. The small phosphorus losses in a terrestrial system caused by leaching through the action of rain are countered by gains from weathering rocks. In soil, phosphate is absorbed on clay surfaces and organic matter particles and becomes incorporated.

Plant species dissolve ionized forms of phosphate and take the mineral into their system. Herbivores obtain phosphorus by consuming plant biomass, and carnivores by consuming herbivores. Herbivores and carnivores excrete phosphorus as a waste product in urine and feces. Phosphorus is then released back into the soil when plants or animal matter decomposes and the cycle repeats. Phosphorus is an essential nutrient for plants and animals in the form of ions, including phosphate-->phosphate, $PO_4^{3-}$ and hydrogen phosphate, $HPO_4^{2-}$.

Phosphates are effective fertilizers, but they also cause pollution problems in lakes streams. Because phosphorus is often the nutrient in limited supply, even a small increase in availability can cause a significant effect. Over-enrichment of phosphate can lead to algae blooms. This excess of algae causes increased consumption by bacteria, which then leads to even higher bacterial concentrations. In the process the bacteria use up much of the dissolved oxygen in the water during cellular respiration and thereby cause the death of fish due to oxygen deprivation. The primary biological importance of phosphates is as a component of nucleotides, which serve as energy storage within cells (Adenosine triphosphate [ATP]) or, when linked together, form the nucleic acids deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). Phosphorus, primarily in the form of hydroxyapatite, $Ca_5(PO_4)_3OH$, is a key structural component of animals. Approximately 80% of the phosphorus in vertebrate animals is in their bones and teeth. This element is also an important constituent of phospholipids, which are in all biological membranes. Anthropogenic influence

Human influences in the phosphorus cycle arise chiefly from the introduction of synthetic fertilizers. Use of fertilizers mainly has significantly altered both the phosphorus and nitrogen cycles. Vegetation may not be able to utilize all of the phosphate fertilizer applied; as a consequence, much of the phosphate applied as fertilizer is lost from the land through water surface runoff. The dissolved phosphate in surface runoff is eventually precipitated as sediment at the bottom of the water body. In certain lakes and ponds, this phosphate may be dissolved and recycled, often as an excessive nutrient. Animal wastes or manure are also be applied to land as fertilizer, particularly in developing countries.

If misapplied on frozen ground during the winter, much of the fertilizer may be lost when ice melts and forms runoff. In certain areas very large or intense feed lots of animals, may result in excessive surface runoff of phosphate and nitrate into streams. Other human sources of phosphate are in the out flows from municipal sewage treatment plants. Without an expensive tertiary treatment, the phosphate in sewage is not removed during various treatment operations. Again, an extra amount of phosphate enters the water (TEE, 2012).

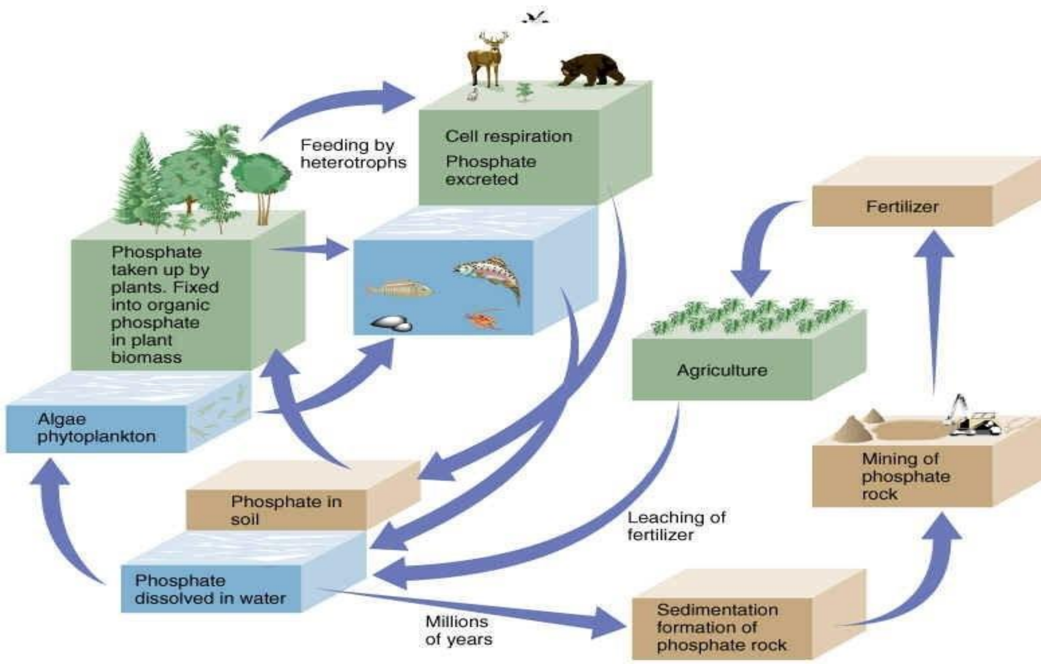



Fig. 2.4 Generalized Phosphorus Cycle in the environment

## 2.8 Environmental System

A system may be considered as interconnected set of components which 'behaves as a whole in response to stimuli to any part'.

In all natural or environmental systems there exists a hierarchy of levels. Each system is, in fact, a component of a super-system and itself comprised of a collection of subsystems.

For example:

- biochemical or physical systems ( a cell, a pond, a unit of a treatment plant)
- plant or animal systems ( aquatic or terrestrial ecosystems)
- urban or rural community
- national or regional ( a country could be an example)

**Summary**

**Carbon Cycle vs Nitrogen cycle: Comparative Chart**

| Carbon Cycle | Nitrogen cycle |
|---|---|
| • Carbon cycle is a series of processes by which compounds of carbon are interconverted in ecosystems.<br>• Involved in recycling carbon in ecosystems.<br>• Photosynthesis, deposition and decomposition are important processes.<br>• Increased release of carbon dioxide to the atmosphere may cause global warming.<br>• Animals and plants are involved in these processes. | • Nitrogen cycle is the series of processes by which nitrogen and its compounds are interconverted in ecosystems.<br>• Involved in recycling nitrogen in ecosystems.<br>• Fixation, mineralization, nutrition and De-nitrification are important processes.<br>• Human should interfere in the addition of nitrogen sources into plants.<br>• Microorganisms are involved in the processes. |
| **Sources of carbon** | **Sources of Nitrogen** |
| • Fossil fuel combustion/use<br>• Transportation sector<br>• Industrial sector<br>• Ocean-atmosphere exchange<br>• Plant and animal respiration<br>• Soil respiration and decomposition | • Uptake of nitrogen by plants from the atmosphere<br>• Uptake of ammonium and nitrate by plants from soil and water<br>• Ammonification<br>• Nitrification<br>• Denitrification<br>• Release of ammonia |
| **Role of carbon** | **Role of nitrogen** |
| • Carbon is an essential element for all life, so understanding how it moves helps us to understand biological processes and factors that influence them.<br>• Photosynthesis<br>• Global warming<br>• Climate change<br>• decomposition | • The nitrogen cycle helps bring in the inert nitrogen from the air into the biochemical process in plants and then to animals.<br>• Plant needs nitrogen to synthesis chlorophyll and so the nitrogen cycle is absolutely essential for them.<br>• Due to the nitrogen cycle nitrates and nitrites are released into the soil with nutrients needed for cultivation.<br>• Plant use nitrogen for their biochemical processes, animals obtain the nitrogen and nitrogen compounds from plants. Nitrogen is needed as is an integral part of the cell composition. It is due to the nitrogen cycle that animals are also able to utilize the nitrogen present in the air |
| **Deficiency symptoms of carbon** | **Deficiency symptoms of nitrogen** |
| • No deficiency symptoms of carbon have been determined. Root exposure during six days 10,000 ppm CO2 or near zero CO2 had no visible effect, and plants develop normally. | • Chlorosis(yellowing of leaves)<br>• Suppressed or late flowering<br>• Increase in starch but decrease in protein content.<br>• Older leaves turn completely yellow |

**Brainstorming Exercises:**

1. The following table indicates the energy flow in ecosystem. Fill the table with appropriate carbon source, energy source with suitable examples. (Few blanks are filled as examples).

| Nutritional Group | Carbon sources | Energy sources | Examples |
|---|---|---|---|
| Chemo autotrophs | | | |
| Chemo heterotrophs | Organic Carbon | | |
| Photo autotrophs | | Light | |
| Photo heterotrophs | | | Non-Sulphur bacteria |

2. The following table indicates the process in Nitrogen cycle. Fill the table with appropriate source, sink, mechanism and agent in each process.

| Process | source | Sink | Mechanism | Agent |
|---|---|---|---|---|
| N-Fixation | | | | |
| Ammonification | | | | |
| Assimilation | | | | |
| Nitrification | | | | |
| De nitrification | | | | |