



ENERGY FLOW IN THE ECOSYSTEM

Ecosystem Functioning

To understand clearly the nature of the ecosystem, its function must be thoroughly investigated. The function of the ecosystem is to allow flow of energy and cycling of materials which ensures stability of the system and continuity of life. These two ecological processes including interaction between the abiotic environment and the communities may be considered as the 'heart' of the ecosystem functioning. For the sake of convenience, the ecosystem dynamics may be analysed in terms of the following: (i) food chains, (ii) food pyramids, (iii) energy flow, (iv) nutrient cycles, (v) development and evolution of ecosystem, and (vi) homeostasis and stability of ecosystem.

Energy flow in the ecosystem

The behaviour of energy in ecosystem can be conveniently termed as energy flow because of unidirectional energy transformations. Total energy flow that constitutes the energy environment has already been dealt in detail, and now we take up the study of that portion of the total energy flow that passes through the biotic components of the ecosystem. Entrance of energy, its retention within the ecosystem and dissipation into space, are governed by two laws of thermodynamics. According to the first law, the law of conservation of energy, in a closed system, no energy comes in or escapes out and not created or destroyed but may be altered from one form to another. The second law of thermodynamics, the law of entropy, states that there is always a tendency for increase in entropy or degradation from a concentrated (non-random) to a dispersed (random) form leading to dissipation of heat. All the energy entering the earth's surface can be accounted for. Some energy is used in photosynthesis; the rest is used in converting the water into vapours or heating the soil and air. Ultimately the energy reflected back to outer space as heat.

Biogeochemical Cycles

The absorption and utilization of elements by organisms is compensated by their recycling and regeneration back into the environment by the breakdown of these organic compounds again. The more or less cyclic paths of these elements in the biosphere from environment to organisms and into the environment back are called biogeochemical cycles (Bio - living organisms, Geo - rock, soil, air, water).

Many elements enter living organisms in the gaseous state from the atmosphere or as water soluble salts from the soil. As the flux of these elements through an ecosystem gives some measure of its continuity and productivity, the analysis of exchange of various components of the biosphere is essential. Furthermore, society depends upon this life-support system of the earth for sustained and increased production of food, fodder, fibre and fuel.

These biogeochemical cycles may be categorized into three global types:

The hydrological cycle, involving the movement of water.

The gaseous cycle of carbon, oxygen and nitrogen

The sedimentary (non-gaseous) cycle of remaining nutrient elements e.g. phosphorus, calcium and magnesium. Sulphur is to extent intermediate, since H_2S or SO_2 , formed under some circumstances, adds a gaseous component to its normally sedimentary cycle. These elements normally do not cycle through the atmosphere in the absence of a gaseous phase. The elements concerned in the sedimentary cycle are earthbound and follow a basic pattern of flow through erosion, sedimentation, mountain building, volcanic activity and biological transport (e.g. through the excreta of marine birds). Sedimentary cycles are much less perfect than gaseous in that some of the element may get stuck in certain phase of the cycle.

Hydrologic (Water) cycle

The important cycle among all the materials is that of water. Water is by far the most important substance necessary for life. It is very important ecological factor that determines the structure and function of the ecosystem, and regulates the plant environment to a large extent. The cycling of all other elements is also dependent upon water as it provides the solvent medium for their uptake. It provides H^+ for reduction of CO_2 in photosynthesis. It has moderating effect on the temperature of the surrounding area by virtue of its heat absorbing ability. Protoplasm the very basis of life is made up of 85 to 95% of water. The content varies in different tissues of the organism and in different plants and animals. Human blood is 90% water. Water cycle involves an exchange of water between the earth's surface and the atmosphere via precipitation and evapo-transpiration. Water covers about 75% of the earth's surface, occurring in lakes, rivers, seas, oceans, etc. The ocean occupies 70% of the surface and contains 97% of all the water on earth. Much of the remainder is frozen in the ice caps and glaciers. The water in rivers and lake is comparatively small. Less than 1% is in the form of ice-free fresh waters in rivers, lakes and aquifers. Yet this relatively negligible portion of the planet's water is crucially important to all forms of terrestrial and aquatic life. There is also a large underground supply of water. Soils near the surface also serve as reservoirs for enormous quantities of water

Every year 4.46 G of water comes in the form of rainfall of which 3.47 G precipitates over the ocean's surface. About 1 G rainfall occurs over land mass of which 0.2 G runs away and 0.6 G evaporates again, and only a small quantity (0.2 G) is stored as underground water. 0.13 G water moves in the form of water vapour and clouds from ice caps present on South and North poles and on the top of high mountains. Only about 0.004% (~10 G) of the total water is all the time moving in the cycle as much of earth's water is in cold storage. Glaciers and the ice caps cover 11% of the world's land area; permanent frozen ground holds another 10% area in its grip, while 30 to 50% of the land is covered with snow at any given time. Icebergs and pack

ice occupy 25% of the ocean area. Therefore, of all fresh water is locked up as ice, mostly in Antarctica and Greenland.

Carbon cycle

Carbon is present in atmosphere, mainly in the form of carbon dioxide, and thus it cycles in this gaseous phase. Though it is a minor constituent of the atmosphere (0.032% v/v), as compared to oxygen (~21% v/v) and nitrogen (~79% v/v), yet without carbon dioxide no life could exist, for it is vital to the production of carbohydrates through photosynthesis in plants, the basic building blocks for other organic compounds needed in metabolic synthesis and incorporation of the carbon with the protoplasm. Carbon from atmospheric pool moves to green plants (producers), then to animals (consumers), and finally from these to bacteria, fungi and other microorganisms (decomposers) that return it to the atmosphere, through decomposition of dead organic matter. Some of this is also returned to the atmosphere through respiration at various levels in the food chain. It is estimated that half of the carbon fixed is subsequently returned to the soil in the form of decomposing organic matter. The atmospheric pool (711 X 10⁹ tons) is very small as compared to that of carbon in ocean (39,000 X 10⁹ tons) and in fossil fuels (12,000 X 10⁹ tons). Before the onset of industrial revolution flows among atmosphere, continents and oceans were balanced, but with industrialization and urban development this equilibrium appears to be disturbed. Fossil fuel burning, forest fire, deforestation and agriculture are some of the important sources of new input. On the contrary, forests are important carbon “sinks” as forest biomass is estimated to contain 1.5 times and forest humus 4 times the amount of carbon in the atmosphere.

There are two main sources of carbon in the abiotic world:

The rocks containing carbonates such as lime stone in the earth’s crust.

The carbon dioxide of the air and that dissolved in water.

In addition, there is present large amounts of carbon in fossil fuel (coal, petroleum, natural gas, etc.) but this is not available to the plants until and unless it is burned to produce carbon dioxide.

Carbon dioxide is released from carbonate rocks by acids resulting from geological action and also by acids formed during fermentation and by bacteria that produce nitric acid and sulphuric acid. An insignificant amount of carbon dioxide is also produced by activity by bacterium *Carboxydismonas oligocarbophila* which oxidizes carbon monoxide to carbon dioxide. Carbon monoxide (a poisonous gas for aerobic organisms including man) is not of common occurrence in nature but may be produced due to partial combustion of fossil fuel. When carbon dioxide dissolves in water, some of it reacts to form carbonic acid (H₂CO₃) which immediately produces carbonate (CO₃⁻²) and bicarbonate (HCO₃⁻) ions.

The richest source of stored carbon today is in the ocean, and in the form of these ions. The oceans contain about 50 times more carbon dioxide than in the atmosphere. This regulates atmospheric carbon dioxide than in the atmosphere. This regulates atmospheric carbon dioxide content level to 0.03% despite photosynthetic uptake. Thus, there is a continuous exchange of carbon dioxide between the atmosphere and organisms on the one hand and between the atmosphere and sea on the other hand. However, the majority of ocean-dissolved CO₂ (HCO₃⁻) is below the thermocline and inaccessible for rapid exchange with the atmosphere. The immediate source of CO₂ for exchange is thus restricted to relatively small quantity of epilimnic CO₂. The sea water being rich in calcium and being alkaline (NaOH) helps in accelerating the process of carbonate decomposition. About 48 ml l⁻¹ CO₂ occurs as carbonate in sea water. Such deposits in the form of coral reefs and calcium carbonate rocks are common in the tropical regions of the oceans. In warm climates, high temperatures and greater salinity and alkalinity favour the process of carbonate decomposition, and it is also reflected in thicker, shells of moluscs.

The carbon dioxide has the unique property of absorbing infra-red radiations. While the small quantities of carbon dioxide are helpful in keeping the earth warm, the enhanced atmospheric carbon dioxide results in rise in the temperature of the atmosphere much in the same way as glass houses do (i.e. they permit the radiations to pass through and strike the earth, but once converted into heat and reflected upwards, the heat waves are absorbed by carbon dioxide rich atmosphere and cause rise in temperature) and in turn, causes rise in ocean level.

Oxygen cycle

Oxygen which is in abundance (20.9476% v/v) in the atmosphere is another indispensable material for life. According to Broecker (1970), each square metre of the earth's surface is covered by 60,000 moles (about a ton) of oxygen gas. Terrestrial, aquatic and marine plants, during photosynthesis release about 8 moles of oxygen annually for each square metre of the earth's surface. Nearly all of this gaseous oxygen is utilized in the process of respiration by plants, animals and bacteria with the result that the amount of oxygen consumed is almost equal to that of released in the atmosphere. However, there is a small net addition of oxygen to the atmosphere (about 1 part in 15 million parts of the oxygen present), which probably does not bring about any change in the oxygen content, as much of this is utilized in the oxidation of carbon, iron, sulphur and other minerals during the normal process of weathering.

Oxygen in bound state, occurs as oxides of carbonates in rocks, and in water. Oxygen dissolved in water is the main source of oxygen for aquatic plants, which may act as one of the limiting factors in their growth and development. Another important phase of oxygen is the ozone layer (oxygen acted on by short-wave radiation to produce ozone), of the outer atmosphere, which by shielding out the deadly ionizing short-wave ultraviolet radiations, protects the life. Oxygen is thus present in atmosphere in sufficiently large quantities and there is no possibility of oxygen deficiency on global scale even if all the earth's organic matter including the fossil fuel is burnt.

Nitrogen cycle

Gaseous nitrogen is the most abundant element of the atmosphere (78.084% v/v), and seems to have a highly complex nutrient cycle in the terrestrial and aquatic ecosystems. This substance is very important for plants and animals as an essential, constituent component of chlorophyll and proteins. Despite its immense value and indispensable nature it is never taken directly from the atmosphere by animals or higher plants. Atmospheric nitrogen is rather inert and does not readily participate in any reaction.

The chief sources of nitrogen for plants are nitrates in the soil. The atmospheric nitrogen is fixed symbiotically as well as asymbiotically by a variety of microorganisms. The chief nitrogen fixers are bacteria belonging to the genus *Rhizobium* found in root nodules of legumes. Asymbiotic nitrogen fixers are some blue green algae, like *Anabaena* and *Nostoc*, aerobic bacteria like *Azotobacter*, and anaerobic bacteria like *Clostridium*. Certain photosynthetic bacteria like *Rhodospirillum* are also nitrogen fixers. Some proportion of atmospheric nitrogen is fixed during lightening also. The fixed atmospheric nitrogen reaches the soil as nitrates, which are taken up by plants for manufacture of complex nitrogenous compounds which in turn, are eaten by animals. The dead organic matter formed due to death of plants and animals is decomposed by various types of bacteria, actinomycetes and fungi occurring in soil and water. This releases nitrogen either in free stage or as ammonia gas in the atmosphere. Ammonia gas may reach the soil as nitrates through the activity of nitrifying microbes, *Nitrosomonas* and *Nitrobacter*. Some nitrates of soil due to activity of denitrifying microbes, *Pseudomonas*, may also be converted to free nitrogen gas returning to the atmosphere. This inorganic nitrogen is again recycled into the organic system upon absorption by higher plants. It is presumed that the fixation of nitrogen by microorganisms is generally in equilibrium with denitrification.

But in recent years there has been high quantity of atmospheric nitrogen fixation by Industrial process (Haber's process). Nitrogen so fixed is not readily and fully denitrified so as to cause accumulation of nitrates or ammonia in water and soil. The accumulation of nitrates in water causes eutrophication. NO_2 from the incomplete combustion of fossil fuel in automobiles further pollute the environment. It appears that through photochemical and electrical fixation $2.5 \times 10^7 \text{ ty}^{-1}$ and through biological fixation $5\text{--}(6) \times 10^9 \text{ ty}^{-1}$ of nitrate is formed. Industrial nitrogen fixation including oxides of nitrogen formed during fossil fuel combustion is $8 \times 10^7 \text{ ty}^{-1}$. Nitrogen fixed by microorganisms is $1\text{--}(2) \times 10^8 \text{ ty}^{-1}$, which is presumed almost equal to that of denitrification. A tiny fraction of annual N-fixation is lost to fossilization in sediments because the anaerobic sedimentary environment is favourable to denitrifying bacteria.

Sulphur cycle

Sulphur is a component of sedimentary cycle. It is found in the gaseous forms (H_2S , SO_2 , etc.) in the atmosphere, and as sulphates, sulphides and organic-sulphur in the soil. SO_2 gas present in the atmosphere is produced volcanically, by burning of vegetation, and now in copious quantities by oxidation of sulphides and organo-S in fossil fuels. H_2S and dimethyl sulphide are commonly formed by the activity of anaerobic bacteria. The elemental and organic sulphur, and SO_4^{2-} are formed through oxidation of H_2S . SO_2 and H_2S from the atmosphere are returned to the soil through precipitation. Sulphur in the form of sulphates (SO_4^{2-}) is the principal available form that is reduced and incorporated into proteins by autotrophs. Sulphur is an essential constituent of certain amino acids (cysteine, cystine, and methionine), the peptide glutathione and certain vitamins or enzyme cofactors (thiamine, biotine, and thiotic acid). It is the mercaptan, containing the thiol ($-\text{SH}$, or sulphhydryl) group, and as the corresponding oxidized disulfide form that sulphur is most reactive in the plant.

The sulphur cycle links air, water and soil, where microbes play a key role. The sulphur is incorporated in the tissues of autotrophs as $-\text{SH}$ in the proteins. It passes through the grazing food chain and excess of it is released through the faeces of animals. Within the detritus food chain the decomposition of proteins releases sulphur. Under aerobic conditions *Aspergillus* and *Neurospora* and under anaerobic conditions the bacteria like *Escherichia* and *Proteus* are largely responsible for the decomposition. In anaerobic soils and sediments H_2S is formed by sulphate reducing bacteria like *Desulphonovibrio desulfuricans* which utilize the oxygen in the sulphate molecule to obtain energy and in turn reduce the sulphate in deep sediments to H_2S gas:

In iron-rich materials, much of this H_2S is scavenged by ferrous iron to produce the very insoluble, black FeS . Many photosynthetic and chemosynthetic bacteria play an important role in sulphur metabolism. Chemoautotrophic colourless bacteria like *Beggiatoa*, *Thiothrix* and *Thiobacillus* occurring in H_2S containing water oxidizes H_2S to S or S to SO_4^{2-} when the H_2S supply is exhausted.

Thiobacillus thiooxidans under highly acidic conditions (up to pH 0.6) may convert sulphur to sulphuric acid of 10% concentration and thus strongly acidify the soil. There are also green sulphur (e.g. *Chlorobium*) and purple-sulphur (e.g. *Chromatium*) photosynthetic bacteria that use the H_2S as the source of hydrogen in reducing CO_2 .

Green bacteria are able to oxidize H_2S only to elemental sulphur, whereas the purple one can carry oxidation to sulphate stage.

Sulphur cycle plays a key role in the metabolism of other nutrients like iron, copper, cadmium, zinc, cobalt etc. For example, when iron is precipitated as sulphide, phosphorus is converted from insoluble to soluble form and thus becomes available to organisms.

Phosphorus cycle

Like sulphur, phosphorus is also a component of sedimentary cycle. It is an essential component as in the form of ATP it acts as an energy carrier. It is comparatively less abundant in natural ecosystems, particularly in terrestrial ecosystems and occurs in meager amounts in aquatic ecosystems too. The phosphorus is made available to the plants from the phosphatic rocks by slow weathering process. The phosphatic (inorganic phosphates typically orthophosphate ions) are metabolised in the plant body and pass through the food chain to animals, and then to decomposers (as food as well as through death and decay) in the form of organic phosphate, which is subsequently made available in the soil for reutilization through mineralisation and decomposition. However, a major proportion of phosphorus becomes lost to this central cycle through run off to the deep sediments of the oceans and in biological processes, such as formation of teeth and bones. On the contrary some quantities of phosphates are returned back to the earth in the form of bird guano (excreta) and fishes. In recent years the excessive use of phosphate fertilizers and the detergents is a problem of global concern as it has been considered responsible for accelerated eutrophication of water bodies.

Calcium cycle

It is important element needed by plants for building their cell walls and by animals for bone formation. It is being regularly added to the soil pool through the weathering of rocks and through atmosphere. A large proportion of this is kept in a state of cycling by uptake from soil into the biotic pool of plants and animals and their return through litter fall, death and decay via detritus food chain. Only a small portion is lost out of the ecosystem through stream flow and this is replenished by weathering and precipitation.

Cycle of toxic elements

Several non-essential elements like mercury, lead, cadmium, arsenic and fluorine, despite their substantial toxicity are freely cycled through biological systems in well-regulated and balanced manner. Growing industrial use, mining operations and other man's activities tended to perturb this equilibrium and upset the balance towards greater accumulation and lesser dispersion of toxic elements. A very significant role in the mobility and dispersion of these elements in the biosphere is played by microorganisms.

1 Mercury

It is one of the most important toxic elements which is now increasingly (about four-fold) discharged in soils and water as an unwanted by-product of certain industrial and agricultural activities. Mercury cycle is better known and the potential rate determining the role of biomethylation of mercury in an ecosystem involving lakes, rivers, coastal environment, soil, etc., is now well established. The natural level of mercury in soils is as high as 0.04 ppm, and in water 0.06 ppm. The amount of mercury found in the air depends on conditions of the environment. The element is poisonous in the metallic state, as inorganic salts of mercury or in the form of organic mercury compounds. It does not have to be ingested being poisonous. Metallic mercury gives off vapours at room temperature; some of the metal even vaporizes at the freezing point of water and this being highly volatile gets dispersed into biosphere. Elemental mercury can exist in three alternative states, viz., Hg^{2+} , Hg_2^{2+} and HgO and certain microorganisms are capable of interconverting the three forms. Naturally occurring methyl-vitamin B12 compounds can aid the synthesis of methyl mercury as well as dimethyl mercury in natural habitats. The bioaccumulation of mercury is greatly facilitated by the natural synthesis of stable alkylmercury compounds (Wood, 1974). About 25% of the world mercury production form chlorine plant, where mercury is used as in electrolyte electrode, escapes in fuel gases. Methyl mercury compounds formed probably in sulphide-rich sediments by the activity of *Methanobacterium amalgamophilum* are also highly toxic and move in the ecosystem either in solution or as atmospheric volatiles. Methyl mercury chloride is particularly toxic to animals as it is easily passed across cell membranes. Dimethyl mercury, which is highly volatile, passes into the air and decomposes into CH_4 , C_2H_6 and Hg_2O , thus causing air pollution.

The mercury cycle shows that the mercury in ecosystem passes through food chain or by inhalation of dust or ingestion of surface-contaminated food. Mercury pollution can be best assessed by measuring the concentration of total mercury in sediments and also the rate of uptake of methyl mercury by fish.

2 Arsenic

It also has a biological cycle in nature. It is an element that is intermediate between the metals and non-metals. It is more abundant in nature as compared to mercury. In drinking water it may occur at levels of upto 50 ppm, whereas mercury levels commonly do not exceed 1 ppm. Arsenic compounds are known as to accumulate through food chains (Summers and Silver, 1978), with the result that even small doses can be lethal. Severe poisoning of human can be caused by as little as 100 mg, and 130 mg found to be fatal. It occurs in rocks, soils and water at much higher levels than does in mercury. It is found in many vegetables and fruits. Some marine organisms, especially shellfish tend to concentrate arsenic within their bodies, which may contain more than 100 ppm. For example, 174 ppm in prawn, 42 ppm in shrimp, and 40 ppm in bass. In moist soils, it is present upto 500 ppm. It has also been detected at concentration

of 10 to 70 ppm in several commonly marketed house hold detergents. It may often stimulate plant growth in very low concentrations, but is injurious in excessive quantities. Destruction of chlorophyll appears to be the main effect. As little as 1 ppm of arsenic trioxides in the water has caused injury into plants. U.S. Public Health Service in 1942 set a safe limit of 0.05 ppm, and in 1962 it recommended a maximum of 0.01 ppm in drinking water. There is also evidence that arsenic accumulates in the livers of mammals. Skin cancer has been found to be associated in several regions with arsenic intake in drinking water.

Arsenate is reduced to arsenite and then microbially methylated to form dimethylarsine and trimethylarsine. The conversion of arsenate through arsenite and methylarsenic acid occurs in lake sediments; di- and tri-methylarsines are released in water. These become oxidized in air to less toxic dimethylarsenic acid. The dimethylarsenic acid is thus cycled between air and sediment (Wood, 1974). Dimethylarsine is highly toxic to fish and other organisms.

3 Lead

The lead is prevalent in the natural environment. The earth's crust contains an average of about 10 to 15 ppm lead, though the content in rock, soil and water is extremely variable. Lead enters the environment in enormous quantities and particularly efficiently dispersed to the atmosphere by the use of tetraethyl and tetramethyl lead as antiknock additives to petrol (gasoline), which may contain about 2 g Pb gal⁻¹. About 2.5×10^8 kg y⁻¹ Pb enters the oceans from this source and the mean sea-water concentration has increased almost seven fold during the past 50 years and is now about 0.07 μ g kg⁻¹ (Goldberg, 1971).

Normally lead is not strongly absorbed from soil, by plants. The main toxicity hazard is therefore, from inhalation of dust or ingestion of surface-contaminated food. However, plants grown on heavily contaminated soil absorb several thousand μ g g⁻¹ compared as the normal plant content of between 1 and 15 μ g g⁻¹ (Johnston and Proctor, 1977).

4 Cadmium

Cadmium belongs to same family of elements as zinc and mercury. A major source of cadmium is zinc mining and smelting in addition to its release by other industries such as metal plating, and in making pigments, ceramics, photographic equipments, and nuclear reactors as well as those engaged in textile printing, lead mines and various chemical industries.

There is no evidence that cadmium has any role in nutrition of plants and animals. It is toxic in relatively small amounts. Being highly mobile in soil and water it is taken up freely by plants and passed on to grazing food chain (Coughtrey and Martin, 1976). In animals and humans,

cadmium tends to accumulate in kidneys, pancreas and bones. In Japan the disease itai itai was caused by people's consumption of heavy metals, primarily cadmium either by drinking water or by eating rice which had accumulated the metal from the irrigation water. The affliction is characterized by kidney malfunction, a drop in phosphate level of blood serum, loss of minerals from the bones, and a condition called osteomalacia, which is a rickets-like condition characterized by pathogenic bone fracture and intense pains.

5 Fluorine

Fluorine makes up about 0.1 per cent of the earth's crust. In its elemental state it is a gas. However, in nature it is always found in various combinations. The greater proportion is in the form of the mineral fluorspar (Calcium fluoride, CaF_2) and in large deposits of mineral cryolite (sodium aluminium fluoride, Na_3AlF_6). Sources of atmospheric fluorine are aluminium smelting using cryolite as a flux, coal burning and the firing of clays in brick manufacture.

Fluorine is freely mobile in the atmosphere and ultimately appears in rainfall as fluoride. Plants take it from soil and water. In gaseous form, it enters open stomata, causes collapse of mesophyll cells, loss of photosynthetic activity and necrosis. Animals derive it from food, water, and minerals. The effect on tooth decay from drinking the water deficient in fluorine was noted. On the other hand, teeth impairment, called dentineri or black teeth, was observed among people.

