UNIT 9: FUNCTIONAL ASPECTS OF ECOSYSTEM

PRITAM ROY

Learning Outcomes

After studying this module, you shall be able to

- ❖ Understand the concept of ecological energetics and laws of thermodynamics.
- ❖ Describe the assimilation energy and ecological efficiency in the ecosystem.
- ❖ Understand energy flow in the ecosystem.
- ❖ Describe various models to explain energy flow.
- ❖ Explain ecosystem services and ecosystem homeostasis.
- ❖ Explain mechanism of control of ecosystem function

Introduction

Energy can be defined as the capacity to do work. All biological activities need consumption of energy which ultimately derives from the sun. The solar energy is converted into chemical energy by the process of photosynthesis which is stored in plant tissues and then transformed into mechanical and heat energy during metabolic activities. In the biological world, the energy flows from the sun to plants and then to all heterotrophic organisms, such as microorganisms, animals and human (figure 1)

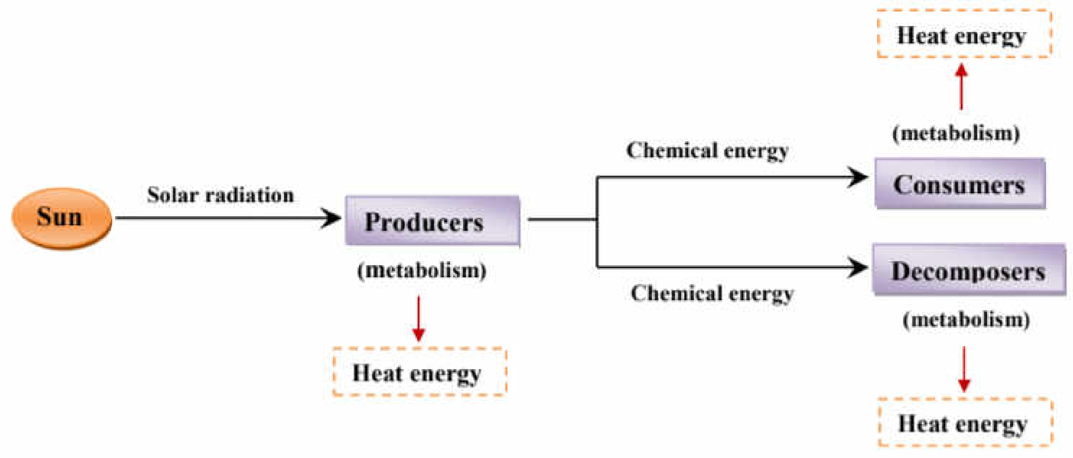

Figure.1: Energy flow from sun to plant and then to all heterotrophic organisms.

Mechanical energy is present in two forms, kinetic energy and potential energy. Kinetic energy can be defined as the energy possess by the body by virtue of its motion. It is measured by the amount of work done in bringing the body at rest. The potential energy is the stored energy which becomes useful after conversion into the kinetic energy. All organisms require a source of potential energy, which is found in the chemical energy of food. The oxidation of food releases energy which is used to do work. Thus, chemical energy is converted into mechanical energy. Food is the means to transfer of both matter and energy in the living world. The unit of measurement of energy is Joule. All forms of energy can be completely converted into heat energy. Heat is measured in calories. One calorie is equal to the heat energy required to raise the temperature of 1 gram of water from 14.5°C to 15.5°C, and one calorie is equal to 4.2 joules.

Ecological energetics

Ecological energetics consists of energy transformation which occurs within the ecosystems. Ecological energetic consists of:

1) The amount of energy reaching to an ecosystem per unit of area/per unit of time.

2) The quantity of energy trapped by green plants which they converted into chemical energy (photosynthesis).

3) The quantity and energy flow from producers to organisms of different trophic levels (consumers) over a period of time in given area.

The energy used by all green plants derived from solar radiations. Only a small fraction of energy reaches to earth's surface (1 to 5%) is used by green plants for photosynthesis and rest is absorbed as heat by ground vegetation or water. In fact, only about 0.02% of the sunlight reaching the atmosphere is used in the process of photosynthesis

Thermodynamics Principle

Energy transformation in ecosystems can also be explained in relation to the laws of thermodynamics, which are usefully applied to closed systems.

Ist Law of thermodynamics (law of conservation of energy)

It state that in a closed system, energy can neither be created nor destroyed but can only be transferred from one form into another. When fuel is burnt to drive a car, the potential energy in chemical bond of fuel is converted into mechanical energy to drive the car. The key point is, the total amount of energy consumed and compare with the total amount of energy produced would always be equal. Such type of energy conservation is also found in biological system. In ecological systems solar energy is converted into chemical energy stored in food materials which is ultimately converted into mechanical and heat energy. Thus, in ecological systems, the energy is neither created nor destroyed but is converted from one form into another. Thus, when wood is burned the potential energy present in the molecules of wood equals the kinetic energy released, and heat is evolved to the surroundings. This is an exothermic reaction. In an endothermic reaction, energy from the surrounding may be paid into a reaction. For example, in photosynthesis, the molecules of the products store more energy than the reactants. The extra energy is acquired from the sunlight, but even then there is no gain or loss in total energy.

2nd Law of thermodynamics

The second law of thermodynamics states that processes involving energy transformation will not occur spontaneously unless there is degradation of energy from a non-random to a random form. In other words, the disorder (entropy) in the universe is constantly increasing and that during energy conservation, an energy transformation will spontaneously occur unless there is degradation of energy from a concentrated form into a dispersed form. For example, in man-made machines (closed systems), heat is the simplest and most recognizable medium of energy transfer. The outcome of this law is very significant in biological system. But in biological systems, energy transfer is not a useful medium, as the living systems are fundamentally isothermal and there is no significant variation in temperature between different cells in the organism or between various cells in a tissue of the organism. At each level of conservation, some of the energy is lost as heat. Therefore, the more conservation taking place between the capture of light energy by plants and the trophic level being considered, the less the energy is available to that level. The efficiency of the transfer ofenergy along food chain from one trophic level to another is generally less than 10 percent as the 90 percent of energy is lost as heat. The study of energy flow is important in determining limits to food supply and the production of all biological resources. The capture of light energy and its conversion into stored chemical energy by autotrophic organisms provide ecosystems with their primary energy source. The total amount of energy converted into organic matter is the gross primary production varies between different systems. The energy stored in the food material is made available through cell respiration. Chemical energy is released by burning the organic compound with oxygen using enzyme mediated reactions within cells. It produces carbon dioxide and water as waste products. Energy flow is the movement of energy through a system from an external source through a series of organisms and back to the environment. At each trophic level within the system, only the small fraction of the available energy is used for the production of new tissue. Most is used for respiration and body maintenance.

Lindeman's trophic-dynamic concept

According to Lindeman (1942), the amount of energy at trophic level is determined by the net primary production (NPP) and the efficiency at which food energy is converted into biomass. The plants use 15 to 70 percent of assimilated energy for the maintenance which is not available to the consumers. The herbivores and carnivores are comparatively more active as compare to plants which uses more assimilated energy for the maintenance. So, the productivity at each trophic level lies between 5 to 20 percent that of the level below it. The percentage of energy which is transferred from one trophic level to the next trophic level is called as ecological efficiency. In general, secondary producers utilize 55% to 75% of assimilated energy in maintenance. Temperature and moisture are two components of the habitat and the type of species determine the maintenance cost. The dry and hot regions require higher maintenance cost, irrespective of the species. For example, the average maintenance cost of few Indian earthworm species was 6.48, 9.96 and 20.54 kJ/g dry tissue/ month in the winter, rainy andsummer seasons respectively in tropical pastures. The maintenance cost varies seasonally and higher was found in summer which was three times more as compare to winter.

Assimilated energy and respiration energy

When the organism eats the food, the digestion and absorption of the food is referred to as assimilated energy, which is used for maintenance, building the tissues or it is removed or excreted in unusable metabolic byproducts. The energy which is lost in the form of heat during metabolic needs is called as respiration energy. A smaller fraction of assimilated energy is excreted in the form of organic or nitrogen containing wastes (ammonia, urea or uric acid) produced when the diet is rich in nitrogen. Assimilated energy of the organism is used for the synthesis of new biomass (production) through growth and reproduction, which may be then consumed by herbivores, carnivores and detritivores. However, organisms are not able to digest and assimilated all food materials like hair, feathers, exoskeleton of insects and cellulose and lignin of plants. These materials are egested by defecation or by regurgitation of pellets of undigested food. Some of these wastes remain relatively unaltered during their passage through an organism, but all these materials are mechanically broken down into fragments by chewing and contractions of the stomach and intestines, which makes them more readily usable by detritus feeders.

Ecological efficiency

Ecological efficiency can be defined as the product of efficiencies in which organisms exploit their food resources and convert them into biomass for next higher trophic level. As biological production is almost consumed, the overall exploitation efficiency remains 100 percent, whereas, ecological efficiency is dependent on two factors: the proportion of assimilated energy incorporated in growth, storage and reproduction. The first proportion is called as assimilation efficiency and second is net production efficiency. The product of the assimilation efficiency and net production efficiencies is called as gross production efficiency. It is the proportion of food energy that is transformed into consumer biomassenergy. Net production efficiency of plants is the ratio of net production to gross production. This index varies between 30 percent and 85 percent, depending on habitat and growth form. The Rapidly growing plants in temperate zones have high net production efficiencies (75 to 85 per cent). Similar vegetation types in the tropics exhibit lower net production efficiencies, perhaps 40 to 60 per cent respiration increases relative to photosynthesis at low latitudes.

Definition of various energetic efficiencies.

$$\text{Exploitation efficiency} = \frac{\text{Ingestion of food}}{\text{Prey production}}$$

$$\text{Assimilation efficiency} = \frac{\text{Assimilation}}{\text{Ingestion}}$$

$$\text{Net production efficiency} = \frac{\text{Production (growth \& reproduction)}}{\text{Assimilation}}$$

$$\text{Gross Production efficiency} = \text{Assimilation efficiency} \times \text{Net production efficiency} = \frac{\text{Production}}{\text{Ingestion}}$$

$$\text{Ecological efficiency} = \text{Exploitation efficiency} \times \text{Gross production efficiency} = \frac{\text{Consumer production}}{\text{Prey production}}$$

The nutritional value of plant foods is determined by the amount of lignin, cellulose and other indigestible materials present in the plant. The animal food is more easily digested when compare with plant food. Assimilation efficiency can vary in different predatory species from 60 percent to 90 percent. The vertebrate prey species can be digested efficiently as compare to insect prey. This is because the insects have larger proportion of indigestible exoskeletons of body than the hair, feathers and scales of the vertebrates. Moreover, the assimilation efficiencies of insectivores can differ in between 70 percent to 80 percent, and most of the carnivores have about 90 percent efficiency. In warm homeothermic (warm blooded) animals, energy is needed for maintenance, movement and heat production that otherwise could be utilized for growth and reproduction. The homeothermic animals exhibit low net production efficiency. For example birds showless than 1 percent and small mammals with high reproductive rates exhibit up to 6 percent of net production efficiency. However, sedentary poikilothermic animals (cold blooded) of aquatic species can direct up to 75 percent of their assimilated energy into the growth and reproduction. In domesticated animals, the extreme high value approaches the biochemical efficiency of egg production and tissue growth, between 70 to 80 percent (Ricklefs, 1974). The gross production efficiency (i.e., biomass production efficiency within a trophic level) is the product of assimilation efficiency and net production efficiency. Gross production efficiencies of warm-blooded terrestrial animals rarely go beyond 5 percent, and those of some birds and large mammals fall below 1 per cent. Gross production efficiencies of insects occur in between 5 to 15 percent, and those of some aquatic animals go beyond 30 per cent.

Models of Energy Flow in Ecosystem

Single Channel Energy Flow Model

The principle of food chain and the working of the two laws of thermodynamics can be clarified by means of Single channel energy flow model. All biological activities need energy which they derived from the sun. The energy obtained from the sun is transformed into chemical energy by the process of photosynthesis. This energy is stored in plant tissue and transformed into heat energy during metabolic activities. The solar energy captured by autotrophs never revert back to sun, however, it passes to herbivores and that which passes to herbivores does not go back to autotrophs but passes to consumers. Thus, in biological system, the energy flows from the sun to plants and then to all heterotrophic organisms. The flow of energy is unidirectional and non-cyclic. Due to unidirectional flow of energy, the entire system would collapse if primary source of energy were cut off. At each tropic level there is progressive decrease in energy as heat in the metabolic reactions and also some of the energy is utilized at each tropic level.

This one way flow of energy is governed by laws of thermodynamics which states:

(a) Energy can neither be created nor be destroyed but may be transformed from one form to another.

(b) During energy transfer there is degradation of energy from a concentrated form (mechanical, chemical etc.) to dispersed form (heat).

(c) Energy transformation is never 100% efficient, it is always accompanied by some loss of energy in the form of heat.

Therefore, all biological systems including ecosystems must required energy on a continuous Basis.

The energy flow diagram (figure 2)) depicting three trophic levels (box 1, 2 and 3) in a linear food chain. Here the boxes represent the trophic level (producers, herbivores and carnivores) and the pipe depicts the energy flow in and out of each trophic level. There is loss of energy (represented as pipes) at every successive trophic level, there is also a corresponding decline in biomass (represented as box). However, it does not specify any correlation between the biomass and energy. The connection between biomass and energy content may vary according to different conditions. For example, one gram of algae may be equivalent to several grams of forest leaves, due to the fact that the production rate of algae is higher than the forest leaves. The higher biomass of the organism does not necessary indicate the higher productivity. Energy flow in the system balance the energy out flows as required by the First law of thermodynamics and each energy transfer is accompanied by loss of energy in the form of unavailable heat energy (respiration) as stated by second law of thermodynamics. The energy flow is significantly reduced at each successive trophic level. Thus, at each transfer of energy from one trophic level to another trophic level, major part of energy is lost in the form of heat or any other form. There is successive reduction in the energy flow whether we consider it in term of total flow (I+A) or secondary productivity and respiration component. Total of 3000 KCal of light falling upon green plants. 50% is absorbed (1500KCal), 1% is converted at first trophic level (15 KCal) Secondary productivity tend to about 10% at successive consumer level although efficiency may be up to 20% at the carnivores level.

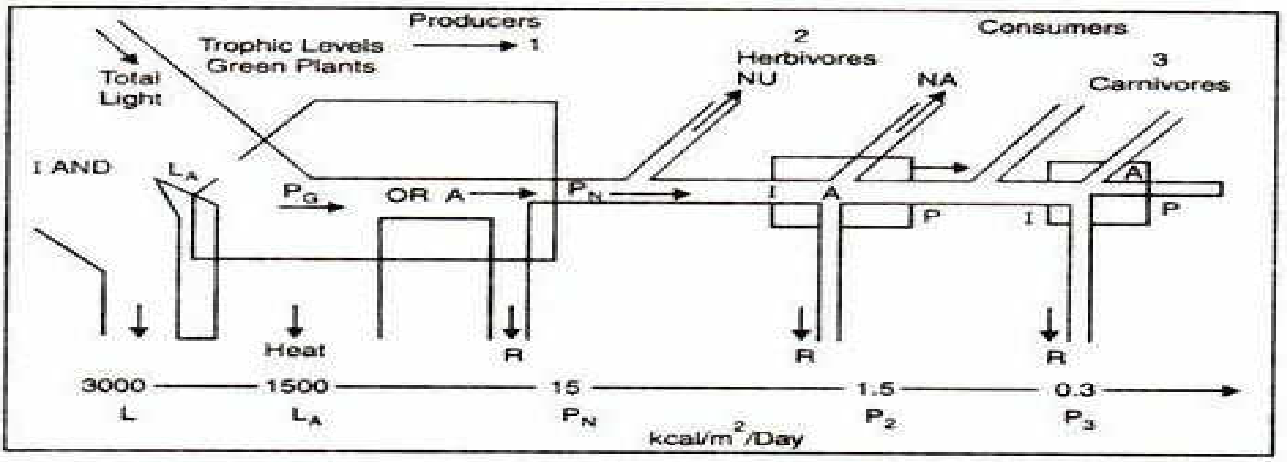

Fig. 4.4. Simplified energy flow diagram depicting three trophic levels (boxes numbered 1, 2, 3) in a linear food chain (after Odum).

Figure 2. Linear energy flow model in an Ecosystem. (I-Total energy input, A- total assimilation, LA- Light absorbrd by plants, PG- Gross primary Productivity, PN- Net primary productivity, P-Secondary productivity, NU- Energy not used, NA- Energy not assimilated by consumer, R- respiration).

Y-shaped or double channel energy flow model

Y- shaped model shows a common boundary, light and heat flow as well as import, export and storage of organic matter. Decomposers are placed in separate box to partially separate the grazing and detritus food chains. In terms of energy levels decomposers are in fact a mixed group. Micro consumers (bacteria & fungi and the macro consumers (animals) differ greatly in size- metabolism relations in two models. In Y-shaped energy flow, grazing and detritus food chain are sharply separated. It is more practical than simple linear chain energy model as:

i) It confirms the basic stratified structure of ecosystem

ii) It separates the grazing food chain from detritus food chain (Direct consumption of living plants and utilization of dead organic matter respectively) in both time and space.

iii) Macroconsumer (animals) and microconsumers (bacteria & fungi) differ greatly in size-metabolism relations.

In Y-Shaped model (figure 3)) one arm represents the grazing food chain and the other arm represents detritus food chain. The two arms differ fundamentally in such a way that they can influence primary producers. For Example, in marine bay, the energy flow through grazing food chain is larger than the energy flow via detritus food chain. Whereas reverse is true for forest food chain where 90% or more of net primary production is normally utilized in detritus food chain. Thus, in marine ecosystem the grazing food chain is the major pathway of energy flow whereas in the forest ecosystem, the detritus food chain is more important. Ingrazing chain, herbivore feed on living plant, therefore they directly affect the plant population. What they not eat is available, after death, to the decomposer. As a result, decomposers are not able to directly influence the rate of supply of their food.

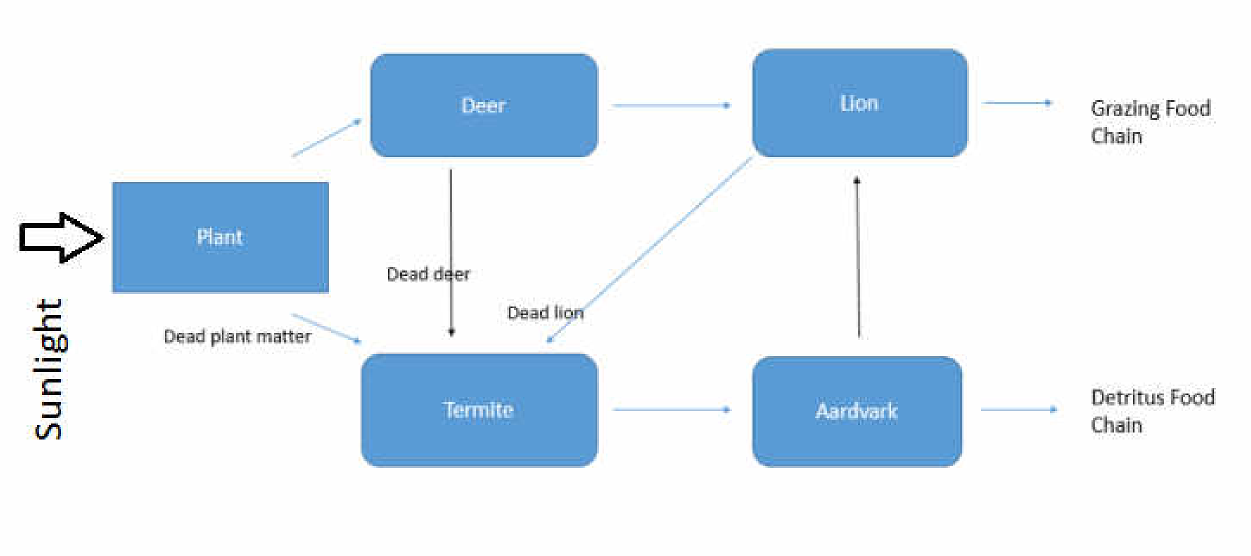

Figure 3: Y-Shaped energy flow model showing linkage between grazing and detritus food chain.

In heavily grazed grassland, 50% or more of the net production may pass down the grazing pathway but many aquatic systems like shallow water operated as detritus system. Since all the food is not assimilated by the grazers, some is diverted to the detritus route. So the impact of grazers on the community depends on the rate of removal of living plant and the amount of energy in the food that is assimilated. Marine zooplanktons commonly graze more phytoplanktons than they can assimilate, the excess being egested to the detritus food chain. Thus energy flow along different path is dependent on the rate of removal of living plant material by herbivores as well as on the rate of assimilation in their bodies. The Y-shaped model further indicates that the two food chains are in fact, under natural conditions, not completely isolated from one another. For example, dead bodies of small animals that were once part of grazing food chain become incorporated in the detritus food chain as do the feces of grazing food animals. The importance of two food chains may differ in different ecosystem, in some cases, grazing is more important and in others, detritus is more important.

Universal energy flow model

Universal model is applicable to any living component, whether a plant, animal microorganism, or individual or population or a trophic group (Odum, E.P., 1968). It can depict the food chain as already shown in single and y-shaped energy flow diagram or bioenergetics of an entire ecosystem. It represents the energy partitioning in the individual or species population showing the living structure or biomass as a box (B) (Figure 4A) I- represents energy input which is light in case of autotrophs and food in case of heterotrophs. The usable part of the input is assimilated (A) and unusable part is not utilized (NU). A large portion of assimilated energy must always be respired (R) to provide maintenance or existence energy to keep the body functioning and repaired. A part of energy can be used for growth and reproduction (P). S is the stored energy, which is used to accept further input of energy. The partitioning of energy between P and R is of vital importance to the individual and species. Large organisms require more maintenance energy than small one as they have more biomass to maintain. The warm blooded animals require more energy than the cold blooded animals. Predators generally must expend a large percentage of assimilated energy in respiration than herbivore, to find and overcoming the prey. The species adapted to unstable, recently derived or under populated area, generally allocate a large portion of their energy to reproduction. The species adapted to stable and more favourable habitats, allocate little energy to reproduction

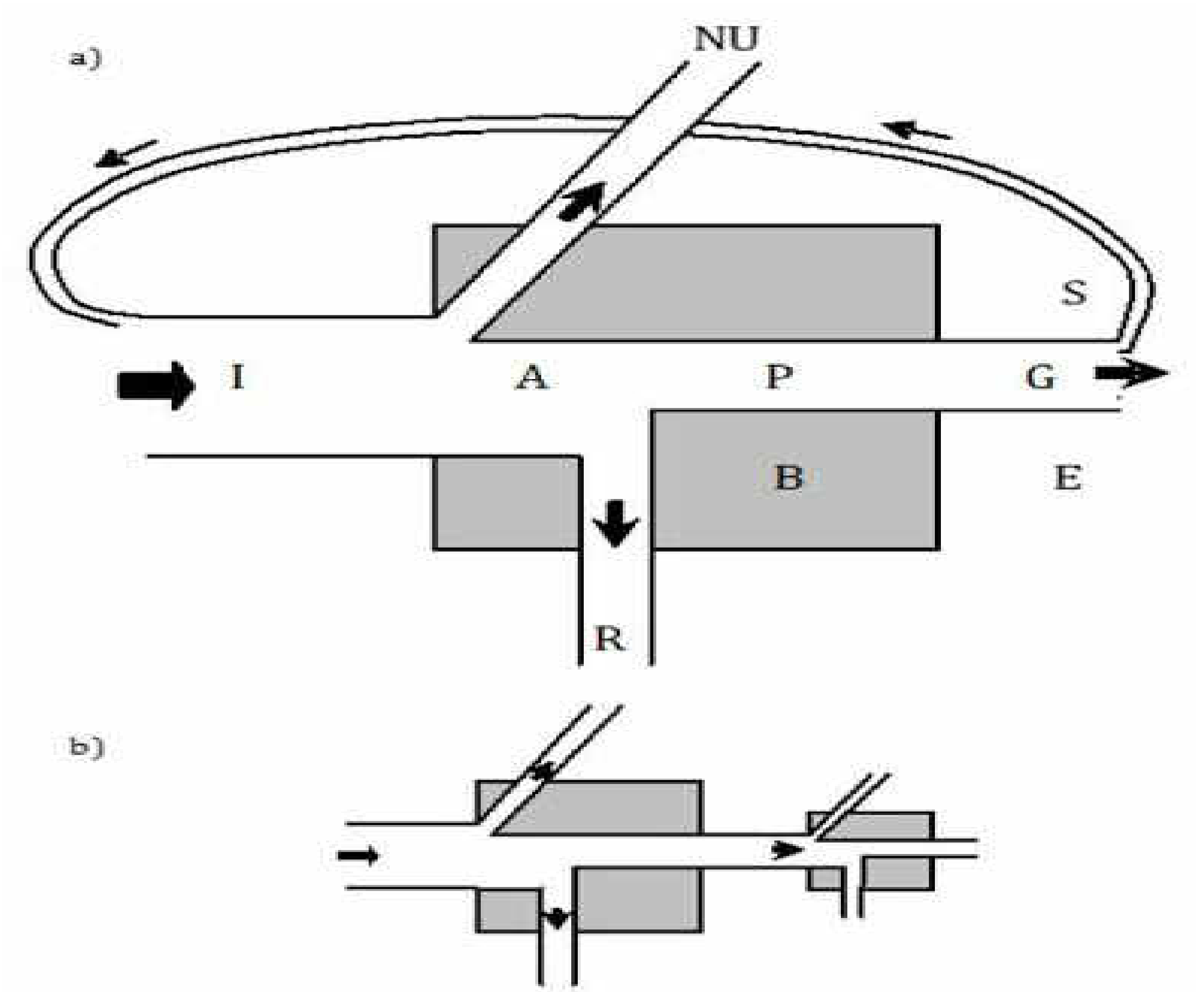

Figure 4: Universal Energy Flow Model. I- input or ingested energy; NU- not utilized energy; A- assimilated energy; P-production; R-respiration; B-biomass; G-growth; S-stored energy; E-excreted energy (Odum, 1963).

The universal model of energy flow can be used in two ways:

i) it can represent a species population in which case the appropriate energy inputs and the links with other species would be shown as conventional species oriented food-web diagram

or

ii) the model can represent a discrete energy level in which case the biomass and energy channels represent all or parts of many population supported by the same energy source. Foxes, for example, usually obtain part of their food by eating plants (fruits etc) and part by eating herbivores (rabbit, field mice etc). A single box diagram could be used to represent the whole population of foxes if our objective is to stress intrapopulation energetic. On the other hand, two or more boxes (figure 4B) would be employed if we wish to separate the metabolism of a population into two or more trophic levels in accordance with the proportion of plant and animals consumed. These models depict the basic pattern of energy flow in the ecosystem. In practice, under natural condition, the organisms are interrelated in a way that several food chains become interlocked and this result into a complex food web.

Homeostasis in ecosystem

Ecosystem has characteristics of self maintenance, and self regulation. It has important application in ecology as humans are continuously disturbing the natural control or attempts to substitute artificial mechanism for natural one. Homeostasis refers to the tendency for a biological system to resist change and to remain in the state of equilibrium. However, the control depends on "feedback" either in positive or negative way. The positive feedback is deviation accelerating, while negative feedback is deviation counteracting. Both natural and manmade activities induced the changes in the ecosystem, but regulated feedback mechanism tends to resist the same, thus, homeostasis is maintained. In every ecosystem, there are three basic components: input, internal cycling and output, those are influenced by soil & climate. The input of nutrient into the ecosystem depends on the type of biogeochemical cycle. Nutrients with a gaseous cycle, such as carbon and nitrogen, enter the ecosystem via the atmosphere. In contrast, nutrients such as calcium and phosphorous, have sedimentary cycles with inputs dependent on the weathering of rocks and minerals. Primary productivity in ecosystems depends on the uptake of essential minerals (inorganic) nutrients by plants and their incorporation into living tissues. Nutrients in organic forms, stored in living tissues represent a significant proportion of the total nutrient pool in most ecosystems. As these living tissues senescence, the nutrients are returned to the soil or sediments in the form of dead organic matter. Various microbial decomposers transform the organic nutrients into a mineral form, a process called mineralization and the nutrients are once again available to the plants for uptake and incorporation into new tissues. This process is called internal cycling and is an essential feature of all ecosystems. It represents a recycling of nutrients within the ecosystem. The export of nutrients i.e., output from the ecosystem represent a loss that must be offset by inputs if a net decline is not to occur. Export can occur in a variety of ways, depending on the nature of the specific biogeochemical cycling. Carbon is exported to the atmosphere in the form of CO_2 via the process of respiration by all living organisms. Likewise, a variety of microbes and plant processes result in the transformation of organic and inorganic nutrients to a gaseous phase that can subsequently be transported from the ecosystem in the atmosphere. The generalized model is shown in the figure. The feedback system as available in internal cycling balances the homeostasis of ecosystem

Control on Ecosystem Function

There are two theories of the control of ecosystems. The first, called bottom-up control, it states that nutrient supply to the primary producers controls ecosystems function. If the nutrient supply is increased, it results in the increase in production of producers is propagated through the food web and all of the other trophic levels will respond to the increased availability of food (energy and materials will cycle faster)

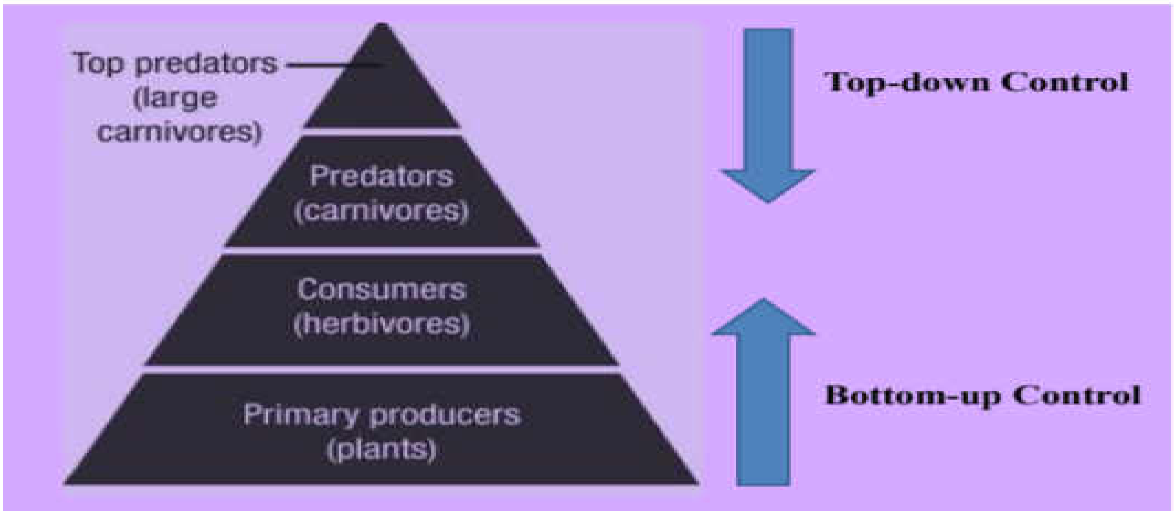

Figure 7: Top-down and Bottom-up control on ecosystem.

The second theory, called top-down control, states that predation and grazing by higher trophic levels on lower trophic levels ultimately controls ecosystem function. For example, increase in number of predators, results in low population of herbivores, and that decrease in herbivores will result in turn in more primary producers because fewer of them are being eaten by the grazers. Thus the control of population numbers and overall productivity "cascades" from the top levels of the food chain down to the bottom trophic levels.

Productivity in Ecosystem

Introduction to Productivity in Ecosystem:

The rate of biomass production is called productivity. The portion of fixed energy, a trophic level passes on to the next trophic level is called production.

Productivity in ecosystems is of two kinds, i.e., primary and secondary. Green plants fix solar energy and accumulate it in organic forms as chemical energy. As this is the first and basic form of energy storage, the rate at which the energy accumulates in the green plants or producers is known as primary productivity.

Productivity is a rate function, and is expressed in terms of dry matter produced or energy captured per unit area of land, per unit time. It is more often expressed as energy in calories/cm^2/yr or dry organic matter in g/m^2/yr (g/m^2 x 8.92 = lb/acre). Hence, the productivity of different ecosystems can be easily compared.

Primary productivity has two aspects:

(i) Gross and

(ii) Net.

The total solar energy trapped in the food material by photosynthesis is referred to as gross primary productivity (GPP).

However, a good fraction of gross primary productivity is utilised in respiration of green plants. The amount of energy-bound organic matter created per unit area and time that is left after respiration is net primary productivity (NPP).

Net productivity of energy = Gross productivity — Energy lost in respiration.

The rates at which the heterotrophic organisms resynthesise the energy-yielding substances are called secondary productivity. Here, the net primary productivity (NPP) results in the accumulation of plant biomass, which serves the food of herbivores and decomposers.

It is notable that the food of consumers has been produced by the primary producers, and secondary productivity depicts only the utilisation of this food for the production of consumer biomass. Secondary productivity is the productivity of animals and saprobes in ecosystem.

Concepts of Productivity:

a. Standing crop,

b. Materials removed, and

c. Production rate.

a. Standing Crop:

This is abundance of organisms existing in the area at any one time. It may be expressed in terms of number of individuals, as biomass of organisms, as energy content or in some other suitable terms. Measurement of standing crop reveals the concentration of individuals in various populations of the ecosystem.

b. Materials Removed:

The second concept of productivity is the materials removed from the area per unit time. It includes the yield to man, organisms removed from the ecosystem by migration, and the material withdrawn as organic deposit.

c. Production Rate:

The third concept of productivity is the production rate, at which the growth processes are going forward within the area. The amount of material formed by each link in the food chain per unit of time per unit area or volume is the production rate.

Environmental Factors Affecting the Productivity in Ecosystem:

1. Solar radiation and temperature.

2. Moisture, i.e., leaf water potential, soil moisture, fluctuation of precipitation, and transpiration.

3. Mineral nutrition, i.e., uptake of minerals from the soil, rhizosphere effects, fire effects, salinity, heavy metals and nitrogen metabolism.

4. Biotic activities, i.e., grazing, above ground herbivores, below ground herbivores, predators and parasites and diseases of primary producers.

5. Impact of human populations, i.e., populations of different sorts, ionising radiations, such as atomic explosions, etc.

6. In aquatic systems, productivity is generally limited by light, which decreases with increasing water depth. In deep oceans nutrients often become limiting for productivity. Nitrogen is most

important nutrient limiting productivity in marine ecosystems.

The largeness of primary productivity depends on the photosynthetic capacity of producers and the existing environmental conditions, such as solar radiation, temperature and soil moisture.

In tropical conditions, primary productivity may remain continuous throughout the year, provided adequate soil moisture remain available.

While in temperate regions, primary productivity is limited by cold climate and a short snow-free growing period during the year.

Primary productivity of the major ecosystems of the world is as follows:

Table 12.1. Geographical area, mean plant biomass and net productivity in major world ecosystems

Major world ecosystems	*Geographical area* 10^6 km^2	*Mean plant biomass* ($t\ ha^{-1}$)	*Mean net primary productivity* ($t\ ha^{-1}\ year^{-1}$)
1. Tropical rain forest	17	440	20
2. Tropical deciduous forest	8	360	15
3. Temperate deciduous forest	7	300	12
4. Temperate coniferous forest	12	200	8
5. Savanna	15	40	9
6. Temperate grassland	9	20	5
7. Desert shrub	18	10	0.7
t = ton = 1000 kg ; ha = 10,000 m^2			