ENERGY IN THE BIOSPHERE

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All living systems need to expend energy not only for growth but also for survival. In living cells there is a constant synthesis of macro molecules from smaller units, and to drive the reactions concerned, a source of energy is required. Where does the energy needed by living organisms come from? The ultimate source of energy for all organisms, save for a few specialist bacteria, is the sun. Solar energy is captured by green plants through the process of photosynthesis, where photon energy is converted into chemical bond energy trapped in organic molecules. A small group of autotrophic bacteria - the chemotrophs - differ from normal green plants in that they do not need solar energy for carbohydrate synthesis, but are able to utilise chemical energy for this purpose. This chemical energy is obtained by oxidation reactions.

Solar energy fixed by green plants drives all the life processes in the biosphere, being transmitted from organism to organism through various food chains, while a part of it is re-radiated in to space as heat and light.

The earliest known forms of life are the prokaryotes which evolved about 3.5 billion years ago in the primordial seas. These early organisms were not autotrophs and lived in an atmostphere devoids of oxygen. They probably obtained their energy by a breaking down of organic molecules by a process similar to that of fermentation. The emergence of the autotrophs was a major step in evolution. The prokaryotes gave way to the eukaryotes, and with a further build up of organic matter by early autotrophic eukaryotes the way was clear for the evolution of multicellular metazoa which depended on these autotrophs for food. They obtained their energy by the breakdown of food (produced by early autotrophs) in the presence of oxygen, by a process termed respiration. The oxygen was obtained from what was gradually built up in the atmosphere by the photosynthesis of eukaryotic autotrophs. The autotrophs themselves developed into more and more complex forms during evolution and were finally able to colonise the land.

With the colonisation of the land, over two billion years ago, new forms of fauna and flora developed, and it was then possible to fix more energy and support more life. The green plants (including the algae) are the main organisms capable of trappping and using solar energy. This occurs during the process of photosynthesis. Photosynthesis is one of the most important biological processes since it is the process by which energy from sunlight is harnessed for the fixation of carbon dioxide into organic compounds.

The green plants are autotrophs which are independent of an external supply of organic compounds for their energy requirements. They manufacture organic compounds using solar energy. Of the total radiant energy that falls on earth only about one per cent is trapped by green plants in photosynthesis. But in tropical evergreen forests and grain fields, sometimes, the figure rises to about 4 to 5 per cent. Though the proportion of energy fixed is very small, worldwide, it is equivalent to the annual production of between 150-200 billion tons of organic matter, and it includes both food for man and the energy which runs the life support systems of the biosphere i.e. the major ecosystems. Of the rest of the radiant energy, i.e. 99 per cent, a small fraction is used in the evaporation of water from the large expanses of oceans and lakes, while the rest is re-radiated into outer space as heat and light.

Solar energy is absorbed by the green pigment chlorophyll which is found in green plants (including algae). Chlorophyll in its forms of chlorophyll a and b absorbs the blue and the red of solar rays and becomes activated. The activated chlorophyll is then utilised by the plant to split up water during the light reaction of photosynthesis. The splitting up of water, called photolysis, results in the release of oxygen to the atmosphere, while the hydrogen combines with an organic compound nicotinamide adenine dinucleotide phosphate (NADP) to form a reducing factor $NADPH_2$. Energy released during the light reaction is used for the formation of the energy rich compound Adenosine triphosphate (ATP). The reducing factor

$NADPH_2$ and the energy rich ATP are necessary for the reduction of the first formed carbon compound in photosynthesis.

During the stage of photosynthesis which does not require light (called the dark reaction) carbon dioxide combines with a 5-carbon compound called ribulose diphosphate (RUDP) to give an unstable 6-carbon compound. This unstable 6-carbon compound breaks down to give the 3-carbon compound phosphoglyceric acid (PGA) which is the first stable carbon compound formed in photosynthesis. The PGA is reduced to phosphoglyceraldehyde (PGAL) by the $NADPH_2$ during the dark reaction and the energy necessary for the reaction is provided by the ATP. The end product is a hexose sugar formed by the combination of two molecules of PGAL. The hexose thus formed has trapped within it part of the energy obtained from the sun.

As described earlier, in most plants, the first formed carbon compound in photosyntheis is the C_3 compound phosphoglyceric acid. However, in certain tropical plants like *Zea mays* and *Saccharum*, in addition to the C_3 pathway described, CO_2 is trapped through another pathway. In this process carbon dioxide is trapped by phospho enol pyruvate (PEP) to form a C_4 compound oxalo acetate. This compound is then converted to another C_4 compound, malate. In the bundle sheaths of the leaves, the malate is broken down to form PEP and CO_2 is released. This CO_2 now moves along the normal pathway of ribulose diphosphate (RuDP) with the end formation of a hexose sugar. In this way, in these C_4 plants, CO_2 is trapped along two pathways: 1. along the normal C_3 pathway with RuDP, and 2. along the PEP pathway. These so called C_4 plants fix a greater quantity of CO_2, resulting in the production of a greater amount of sugar, than do normal plants. For example, it has been found in the United States that the conversion of the incident solar energy into plant products in Soya bean, (*Glycine max*) which is a C_3 species, is only half that of a C_4 species like *Zea mays*. Though energy conversion in Zea mays is also below the theoretical maximum of 1.25 per cent, which might be sought in practical agriculture, even this increase, in doubling of production, would be of considerable significance in terms of food production.

The radiant energy trapped in the carbohydrates during photosynthesis by the green plants or primary producer is referred to as gross primary production (Gp). The gross primary production of a green plant increases according to its size. If we consider a succession on land, or a Xerosere, the first formed seral community has plants which have a small biomass. For example, if we take a forest land which has been cleared, cultivated and then abandoned, the very first seral plant community will consist of small herbaceous plants, mainly annuals. After a few months the dominant vegetation will change to slightly bigger herbs and later to shrubs, which are perennials. Ultimately, after many decades, the last or climax community will come up, comprising trees as the main life form. This type of succession may take a couple of hundred years. As a succssion progresses it is seen that there is an increase in size of the plants comprising the seral community. This increase occurs until the climax, which has the largest plants is established. Therefore the gross primary production in a succession too increases till the climax is reached, at which point it remains more or less at a steady level. In green plants some of the energy fixed is stored as organic matter in new tissues. The amount of new tissues measured as dry weight is net primary production (NP). A part of the energy fixed is required to support the living plant. This is more than half the amount of energy fixed and is released during respiration to provide energy for the life processes of the plant. Parts of the plant like leaves, bark, fruit, etc. are lost to the environment. Therefore, in a plant, the total energy fixed, or gross primary production may be represented by the equation:

$$GP - Rs_A = NP$$

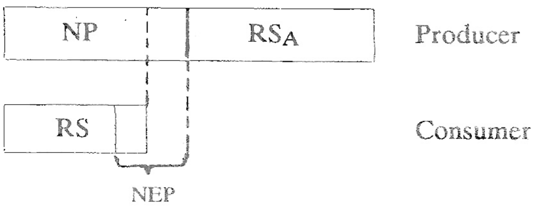
GP is the gross primary production, RS_A is the energy used by the green plant (autotroph) during respiration. The amount left over is net production NP. The growth of the plant is measured in dry weight or energy stored which is net production.

This can be further clarified by the following diagrams:

(1) In a green plant, of the total energy fixed or gross production, a part is expended by the plant as Respiration (RS_A) and the rest goes into net production (NP).

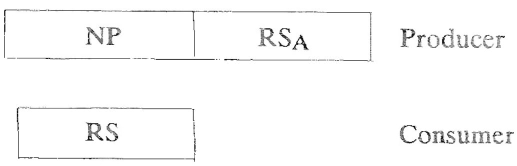
Gross Primary Production

(2) In a successional plant community some of the net production is stored as growth and the rest (fallen leaf litter etc.) is used by consumers, which in turn expend most of it in respiration while storing some part as growth, adding to net ecosystem production (NEP).



Gross Production

(3) In a climax community the total energy fixed by primary producers is used in the respiration of the autotrophs and heterotrophs. Although plants, animals and reducers in the ecosystem go through the normal process of growth, the total energy fixed by the primary producers over a period of time is balanced by the respiration of the primary producers themselves together with the respiration of the animals and the saprophytes. Hence there is no net ecosystem production or NEP.



Thus we see a sharp distinction between a successional or developmental ecosystem and a climax or mature one. In a seral community the total respiration of the green plants is less than the gross production leaving energy (NEP) built into the structure of the ecosystem and added to the resources of the environment in which the plants occur. In a climax system all energy fixed is used in the combined respiration of the primary producers and heterotrophs as well as that of the organisms that live on the decaying organic matter.

There is no extra energy left and no net annual storage. Hence NEP = O

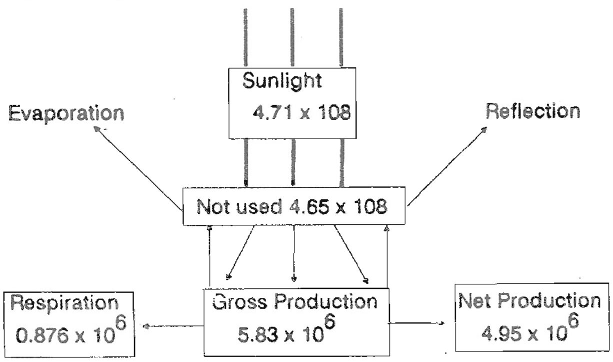
The flow of energy through living organisms in a community is depicted by a food chain. Let us take the case of herbivores or primary consumers that feed on green plants (primary producers). These animals do not receive the entire energy fixed by the primary producers. As we have seen above, a good part of the fixed energy in primary producers goes to support the life processes of the producers themselves with only a small fraction going to build up the biomass. This small fraction is what is available for use at the next trophic level. The first level of consumers comprises herbivores like grasshoppers, caterpillars, deer etc. which feed directly on the green plants, and saprophytes which feed on the decaying leaves and other plant parts. This is illustrated in the following diagram.

Primary producers ——→ Herbivores or primary consumers
↓
Saprophytes

Thus the herbivores may obtain only the energy left after the energy expended for respiration of the green plants and the loss to decaying organisms. The energy available to the second trophic level of a food chain is the net primary production and is only about 10-20 per cent of the gross primary production. When herbivores become prey to carnivores at the next nutrient level of consumers, the energy received by the carnivores is only about 10-20 percent of that received by the herbivores. This is because about 80-90 per cent of the energy in the primary consumers is lost partly as respiration and partly as excretory material deposited in the environment. So, along a food chain there is depletion of energy. Let us take a typical predatory food chain where the energy flows from the primary consumer level, where the organisms are small, to larger organisms at the higher trophic levels. This is the most common type of food chain occurring in nature. An example is given below.

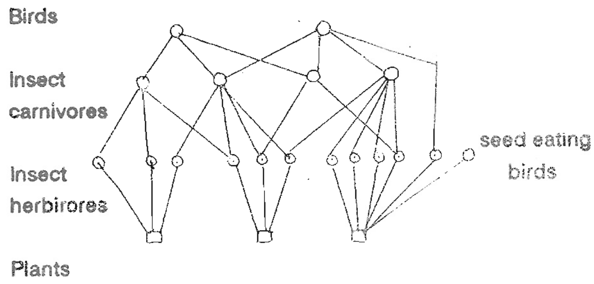
grass ——→ grass hopper ——→ toad ——→ snake
(pr. producer) — pr. consumer/herbivore — sec. consumer/tertiary consumer

The grass (green plant) is the primary producer. Let us assume that gross primary production or energy trapped during photosynthesis in the grass over a period of time is 1000 k cal. A large part of this energy is used up for the respiration of the plant and a small amount lost as decay of plant parts to the soil. The aggregate loss is nearly 80-90 per cent of the gross production. Therefore only about 10-20 per cent is available for the second nutrient level. Of the energy received by the grass hoppers (herbivores), that is, around 150 k cal, once the energy expended in respiration and the energy lost as excretary material to the environment by the grass hopper is excluded, the balance 10-20 per cent only i.e. around 15-30 k cal will be available at the third nutrient level of the toad or secondary consumer. In the toad, too, energy will be utilised in respiration and lost as excretory products to the environment so that only 10-20 per cent of what is received is available for the fourth trophic level of the tertiary consumer or snake. Thus, of the energy that was trapped by the primary producer i.e. 1000 k cal, there will only be approximately 3-4 k cal available for the tertiary consumer. From this we can deduce that if the energy flows along a single pathway then food chain could maintain only about 2 or 3 trophic levels of consumers, since there will be inadequate energy for higher trophic levels.



The fate of solar energy incident on perennial grass-herb vegetation in Michigan USA. All measurements in cal/m^2/year

However, in nature, long food chains with a number of trophic levels have been recognised. This is possible because at higher trophic levels consumers, (snakes/toads) derive their inputs of energy from several food chains and not along a single food chain. For example, toads feed on a number of insects and not only on grass hoppers. Therefore predatory food chains are inter linked and joined by others to form what are known as food webs.

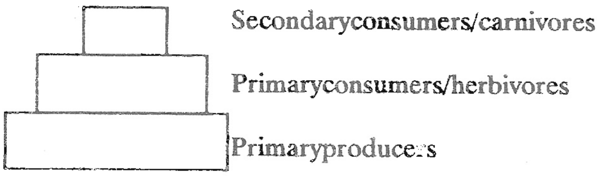


Hypothetical Food Web

Animals of different trophic levels are of different sizes. Any one large sized animal usually eats a variety of food, so that it is a part of several food chains. But food chains commencing from a plant source must always radiate outwards as the plant is used as food by different herbivores and these herbivores are in turn eaten by different carnivores. Thus a complex web is formed.

A food chain therefore can be defined as the path along which energy travels in nature. The energy which originally came from the sun does not go back to the sun. The energy flows along an open ended chain and is not cyclic. Thus energy flow in nature is an open system.

Other points to note in a food chain are the biomass and the numbers at each trophic level. In our previous example the largest animale were found at the nutrient level of the snakes, unless another predator ate the snake. The snake feeds on toads which live close to water and, though smaller in size, are present in greater numbers. The toads are insect eaters, their food being the grass hoppers and other small insects. These in turn feed on organisms smaller that themselves. As one works upwards along a food chain it seems that the animals become progressively larger but less abundant. A community can be separated into groups of animals of similar size. The animals in each of these groups would be feeding at about the same trophic level of a food chain. The smallest size class would have the largest number. If the number of individuals in each size class are represented in the form of a diagram with the first trophic level at the base one would get roughly a pyramidal figure. Each box represents a size class and would consist of animals feeding at the same level of a food chain. This is termed the pyramid of numbers.



Although we have heard of food chains from primary producer to primary and secondary consumer and so on, there is another important part of the food web which has not been considered. All organisms, whether primary producer or consumer, eventually die and the dead organic matter is decomposed by saprophytic organisms like bacteria and fungi. In addition, nitrogenous compounds are excreted to the environment and are broken down by saprophytic organisms. In some cases, where animals die, a greater part of their bodies are eaten by scavenger animals. Ultimately the scavenger chain ends also with the saprophytic organisms which break down all the complex compounds into simple molecules and releases them into the environment. In this type of food chain energy flows along the dead substrates to the living scavengers and can be termed as a decomposer or saprophytic food chain.

In other instances organisms live parasitically on the host, and energy is diverted along a parasitic chain. When a parasite is in turn parasitised by another organism e.g. a protozoan living on a tick which is living parasitically on a cow, the energy passes into the protozoan. If there are a nimber of *Cuscuta* plants on a single tree, and they are in turn parasitised by worms, this could be a parasitic food chain. In these food chains, as in the scavenger food chains, the organisms at a particular higher trophic level are smaller than their host, or the previous level, and the niches they occupy require that they be smaller than the organisms from which they derive their food.

In nature, the direct rays of the sun heat up the earth. As stated earlier a good part of this energy goes back into space as infra red energy. But due to man's activities in industry, and in the clearing of forests, this delicate balance is being upset and there is a build up in the concentration of gases like carbon dioxide, oxides of nitrogen and sulphur in the atmosphere. These gases trap the heat in the atmosphere preventing a part of the energy being re-radiated into space, thus causing global warming. This is called the "green house effect". Carbon dioxide levels are 25 per cent higher now than a century ago and the amount of carbon dioxide in the atmosphere seems to be increasing. By the middle of the next century global mean temperatures could rise from between 1.5^0 to 4.5^0 Celsius. The result of this would mean the melting of glaciers and the ice at the poles, and the warming of the sea causing expansion of the water, and these in turn will cause a rise in the sea level which may be as much as two or three metres. The result would be an inundation of low lying coastal areas and islands all over the globe. Unless remedial measures are taken eg. forest restoration programs and cutting down in the use of fossil fuels, the effect will be harmful to mankind.

In conclusion, we could recognise that the radiant energy of the sun is trapped by green plants. This energy is passed along food chains in nature. A greater part is reflected back into space as heat and light. This energy flow in nature is not a closed system.