Unit: Ecology and Pollution

How ecosystem work, ecosystems and evolution, human population change and the environment, environmental resistance and carrying capacity.

Evolution of life forms

The origin of life is considered a unique event in the history of the universe. In the solar system of the Milky Way galaxy, the earth was supposed to have been formed about 4.5 billion years back. Life appeared 500 million years after the formation of the earth, i.e., almost four billion years back. There are different theories put forward by various scientists for the evolution of life on earth. One of these theories was proposed by **Charles Darwin**.

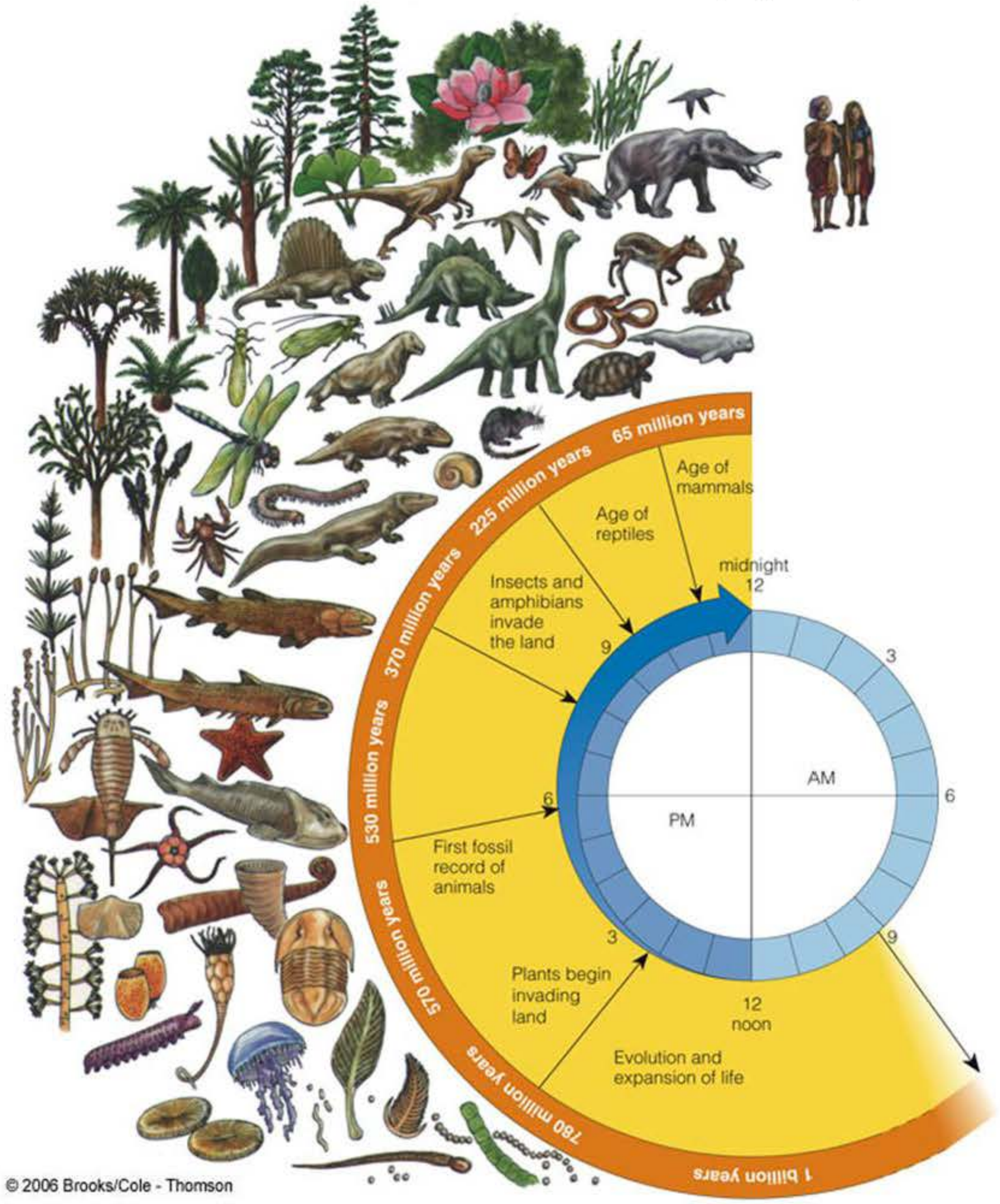


Fig. 1: Evolution of life

Charles Darwin was a British naturalist who proposed the theory of biological evolution by natural selection. He defined **evolution** as "**descent with modification**," the idea that species change over time, give rise to new species, and share a common ancestor. The mechanism for evolution proposed by him was **natural selection**. As per the theory of natural selection, the organisms with heritable traits that favoursurvival and reproduction will tend to leave more offspring than their peers, causing the traits to increase in frequency over generations in the presence of limited resources. In return, this natural selection causes populations to become **adapted**, or increasingly well-suited to their environments over time.

Based on observations made during a sea voyage in a sailing ship called **H.M.S. Beagle** around the world, **Charles Darwin** concluded that existing living forms share similarities to varying degrees not only among themselves but also with life forms that existed millions of years ago. Many such life forms do not exist anymore. There had been extinctions of different life forms in the years gone by just as new forms of life arose at different periods of the history of the earth. There has been a gradual evolution of life forms. Any population has built-in variation in characteristics. Those characteristics which enable some to survive better in natural conditions (climate, food, physical factors, etc.) would outbreed others that are less endowed to survive under such natural conditions. Another word used is the **fitness of the individual or population**. Fitness, according to Darwin, refers ultimately and only to **reproductive fitness**. Hence, **those who are a better fit in an environment, leave more progeny than others**. These, therefore, will survive more and hence are selected by nature. He called it **natural selection** and implied it as a mechanism of evolution.

Darwin's theory of evolution
Darwin had the following idea regarding the theory of natural selection:

- Species keep on evolving or changing with time. As the environment changes, the requirements of an organism also change and they adapt to the new environment. This phenomenon of changing over a period of time as per the natural requirements is called **adaptation**.
- As per Darwin's theory, only the superior changes are naturally selected and the inferior ones are eliminated. Thus, not all adaptations contribute to progressive evolution. For example, people living in tropical countries have more melanin in their bodies to protect them from the sunlight.
- Almost all organisms share common ancestry with some organisms. According to Darwin, all organisms had one common ancestor at some point in time and kept on diverging ever since.
- According to Charles Darwin, evolution is a very slow and gradual process. He concluded that evolution took place over a very long period of time. It is a very steady process as the changes and adaptation take a long time to stabilize and give rise to a new species.

Darwin's theory of natural selection holds that variation within species occurs randomly and that the survival or extinction of each organism is determined by that **organism's ability to adapt to its environment**. It is the process where organisms with a particular beneficial trait are selected and reproduced in succeeding generations with that trait more than other traits.

Example of natural selection: Before industrialization set in, it was observed that there were more white-winged moths on trees than dark-winged or melanized moths. However, after industrialization, there were more dark-winged moths in the same area, i.e., the proportion was reversed. The explanation put forth for this observation was that 'predators will spot a moth against a contrasting background'. During the post-industrialization period, the tree trunks became dark due to industrial smoke and soot. Under this condition the white-winged moth did not survive due to predators, the dark-winged or melanized moth survived. Before industrialization set in, thick growth of almost white-colored lichen covered the trees - in that background the white-winged moth survived but the dark-colored moth was picked out by predators. Hence, moths that were able to camouflage themselves, i.e., hide in the background, survived.

Ecosystem

The term was coined by **A.G. Tansley**. **Eugene P. Odum** defined ecosystem as "any unit that includes all the organisms that function together in a given area interacting with the physical environment so that a flow of energy leads to clearly defined biotic structures and cycling of materials between living (biotic) and non-living (abiotic) parts". In other words, it is the structural and functional unit of the biosphere consisting of abiotic and biotic components which interact with each other and maintain a balance in nature. For example, the forest ecosystem.

Components of Ecosystem:

Every ecosystem has two components, namely, **biotic components and abiotic components**. **Biotic components** refer to all living organisms in an ecosystem while **abiotic components** refer to non-living things. These biotic and abiotic components interact with each other to maintain equilibrium in the environment.

Biotic components have a direct or indirect influence on other organisms in an environment. For example, plants, animals, and microorganisms. These biotic components are grouped under three main categories:

1. **Producers/Autotrophs:** They are chlorophyll-bearing, self-nourishing organisms, which prepare organic compounds from inorganic raw materials, through the processes of photosynthesis. For example, all green plants.
2. **Consumer/heterotrophs:** They depend on the energy produced by the producers. Different categories of consumers are herbivores, carnivores, and omnivores.
3. **Decomposers:** They attack dead animals, producers, etc. and convert the complex organic compounds into simpler compounds (by the process of decomposition and disintegration) and then recycle all the nutrients back. For example, bacteria and fungi.

Abiotic components of an ecosystem include all chemical and physical elements i.e., non-living components. Abiotic components can vary from region to region, from one ecosystem to another. They mainly take up the role of life supporters. They determine and restrict the population growth, number, and diversity of biotic factors in an ecosystem. Hence, they are called limiting factors. A terrestrial ecosystem consists of abiotic factors like climate, type of soil or rock, light, etc., whereas abiotic components in an aquatic ecosystem include dissolved gases, depth of water, salinity, pH of water, etc.

Functions of Ecosystem:

There are two main functional aspects of any ecosystem, viz, energy flow and nutrient cycling. Energy flow within the ecosystem is maintained through the food chain and food web; while nutrient circulation is maintained mainly through different biogeochemical cycles.

Nutrients Cycling:

The producers use nutrients and prepare food, the consumers consume it and the decomposers recover the nutrients. These nutrients keep flowing between biotic & abiotic components, thus forming a nutrients cycle known as the **biogeochemical cycle**. The biogeochemical cycle involves the movement of elements and compounds among the land (lithosphere), organisms, air (atmosphere), and oceans (hydrosphere). There are mainly two types of biogeochemical cycles, viz., **gaseous type** and **sedimentary type.** In the gaseous type, the reservoir is in the atmosphere and hydrosphere. E.g., the carbon cycle and the nitrogen cycle. In the sedimentary type, the lithosphere acts as the reservoir, e.g., sulphur and phosphorus cycles.

Energy Flow: Food chain

The process of eating and being eaten by successive creatures is known as the **food chain**. In short, it is the flow of energy from producer to tertiary consumer.

Types of Food Chain

i. **Grazing food chain**: It starts from green plants and through carnivores, it reaches the decomposers for the final breakdown of the complex in a simpler one. For example, grassland ecosystems, pond ecosystems, etc.

   The number of trophic levels in the grazing food chain is restricted as the transfer of energy follows the **10 percent law** – only 10 percent of the energy is transferred to each trophic level from the lower trophic level (**Lindemann's law**).

Trophic level: Producers and consumers in the ecosystem can be arranged into several feeding groups, each known as the trophic level (feeding level). Producers represent the first trophic level (primary), herbivore represents the second trophic level (secondary), primary carnivores represent the third trophic level (tertiary), and so on.

Example: ***Grass --- grasshopper – frog – snake – hawk***

ii. **Parasitic food chain:** Parasitic food chain is a type of food chain that starts from herbivores, but the food energy transfers from larger organisms to smaller organisms, without killing in case of a predator.

   Bird (herbivore) – lice – bugs (hyper parasites)

iii. **Saprophytic or detritus food chain**: The detritus food chain (DFC) begins with dead organic matter. The dead organic substances are decomposed by microorganisms. The organisms that feed on dead organic matter or detritus are known as detritivores or decomposers, or saprotrophs. These detritivores are later eaten by predators.

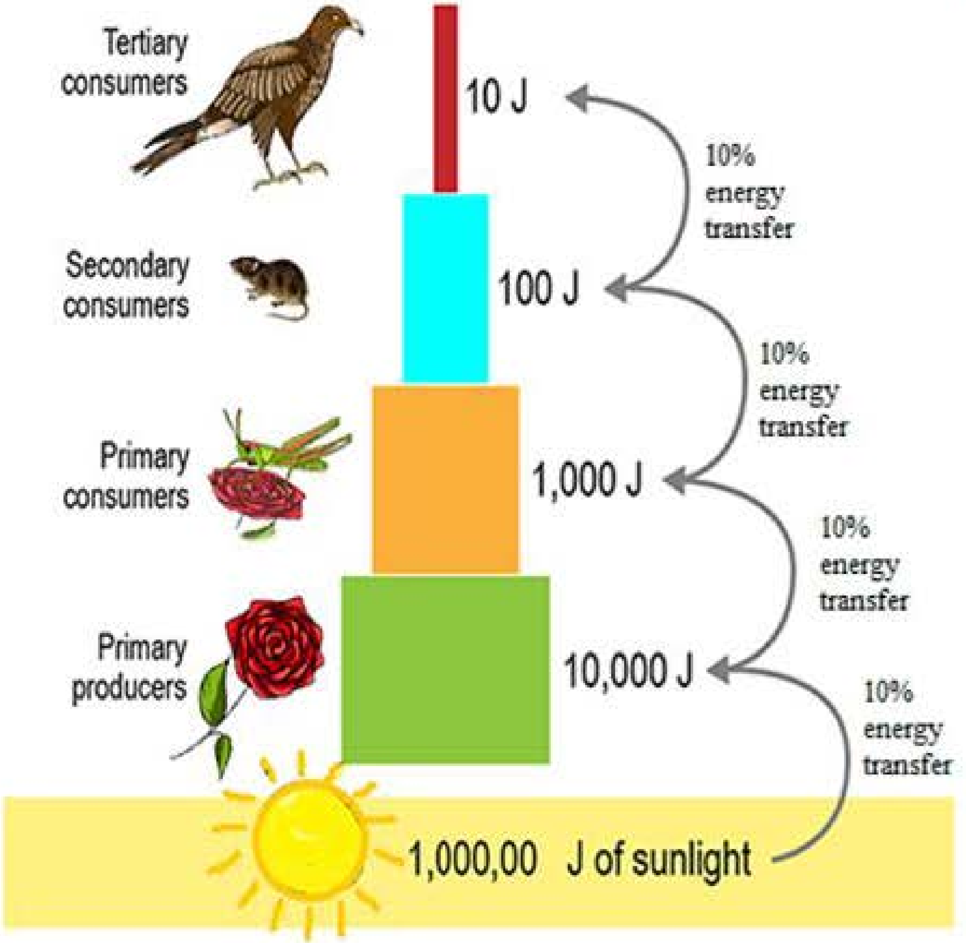


Fig. 2: Energy flow through different trophic levels (90% of the energy is lost as heat at each trophic level)

Food Web:
There is a long-interlinked chain of processes in an ecosystem (Fig. 3). Different food chains are interconnected with each other in a specific pattern. A food web presents all possible feeding relationships among various organisms of the ecosystem. If the chain gets disturbed a little, then it leads to the loss of species and the web breaks down.

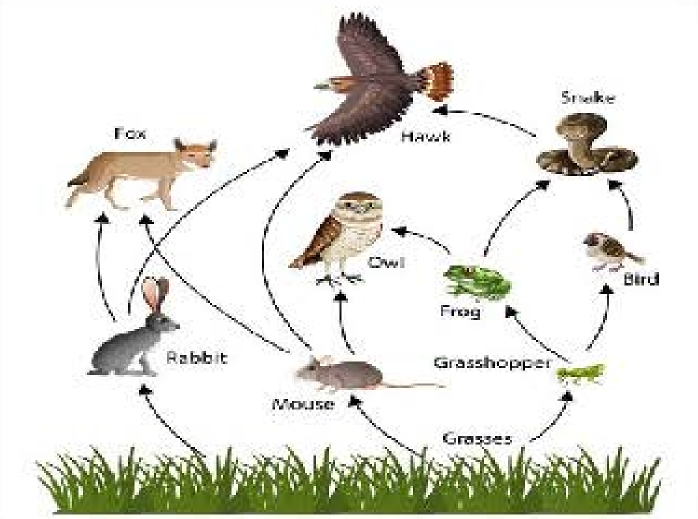


Fig. 3: Food web

Biomagnification:
It refers to the increase in the concentration of the toxicant at successive trophic levels. This happens because of **bioaccumulation** where a toxic substance accumulated by an organism cannot be metabolized or excreted and is thus passed on to the next higher trophic level. It is well known for mercury and DDT.

Ecological Succession:
It is not only the environment that influences the organisms, but organisms too modify their environment as a result of their growth, dispersal, reproduction, death, decay, etc. Thus, the environment is changed due to organisms' activities. Hence vegetation is hardly stable, rather dynamic, changing over time and space.

Succession is a natural process by which different groups or communities colonize the same area over a period of time in a definite sequence. The process continues till the development of a stable community which is more or less in equilibrium with the environment. This final stable community is called a *climax*. Different stages of succession are called **seral stages** and all these seral stages constitute a **sere**. The first community that invades any bare area is known as the **Pioneer community;** while the final and stable community formed is termed as **Climax Community**

Types of Succession

i. **Primary succession:** The area which is unexposed to any life form that gets occupied by a living community for the first time is known as primary succession.
ii. **Secondary succession:** When a new biotic community replaces an already existing biotic community then this type of replacement is known as secondary succession. For example, farm garden.
iii. **Climax Community:** The community that is formed at the end of succession.

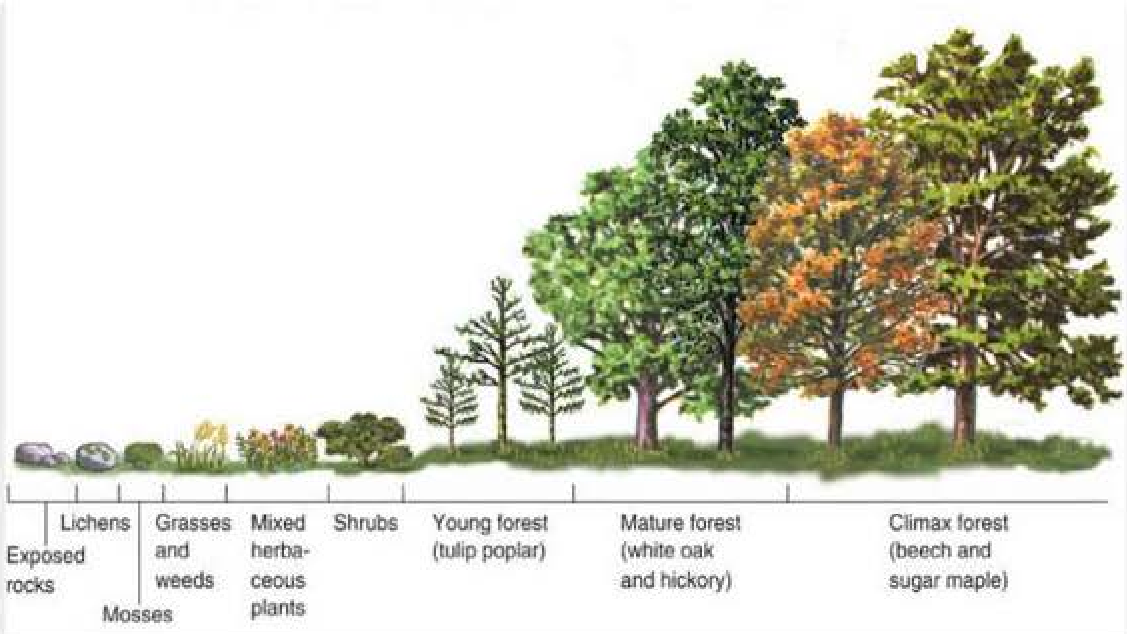


Fig. 4: Stages of Ecological Succession

Ecological Pyramid:

It is the graphical representation of trophic relations in an ecosystem for different parameters such as food, energy, and biomass. The concept of ecological pyramids was given by **Charles Elton,** thus also known as **Eltonian pyramid.** In most ecosystems, all the pyramids of number, energy, and biomass are upright, i.e., producers are more in number and biomass than the herbivores, and herbivores are more in number and biomass than the carnivores; however, there are exceptions to this generalization. There are three types of pyramids:

i. **Pyramid of numbers:** A pyramid of numbers shows the total number of individual organisms at each level in the food chain of an ecosystem. The pyramid of numbers is usually upright; however, it can be inverted or rhombohedral. E.g., upright (general food chain); Rhombohedral/inverted (forest ecosystem: number of insects feeding on a big tree).

ii. **Pyramid of biomass:** In this particular type of ecological pyramid, each level takes into account the amount of biomass produced by each trophic level. The pyramid of biomass is also upright except for that observed in oceans where large numbers of zooplanktons depend on a relatively smaller number of phytoplanktons.

iii. **Pyramid of energy:** When each trophic level is described in terms of the productivity or the amount of energy that passes through trophic levels. It is the only type of ecological pyramid, which is always upright as the energy flow in a food chain is always unidirectional. Also, with every increasing trophic level, some energy is lost into the environment.

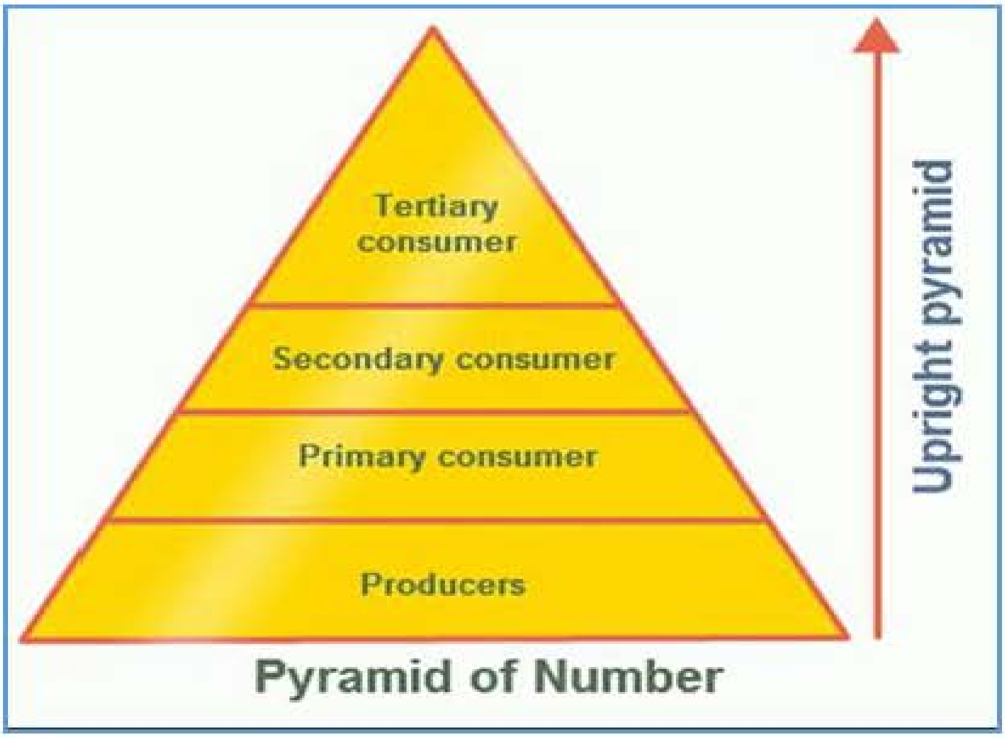


Fig. 5: Pyramid of Number

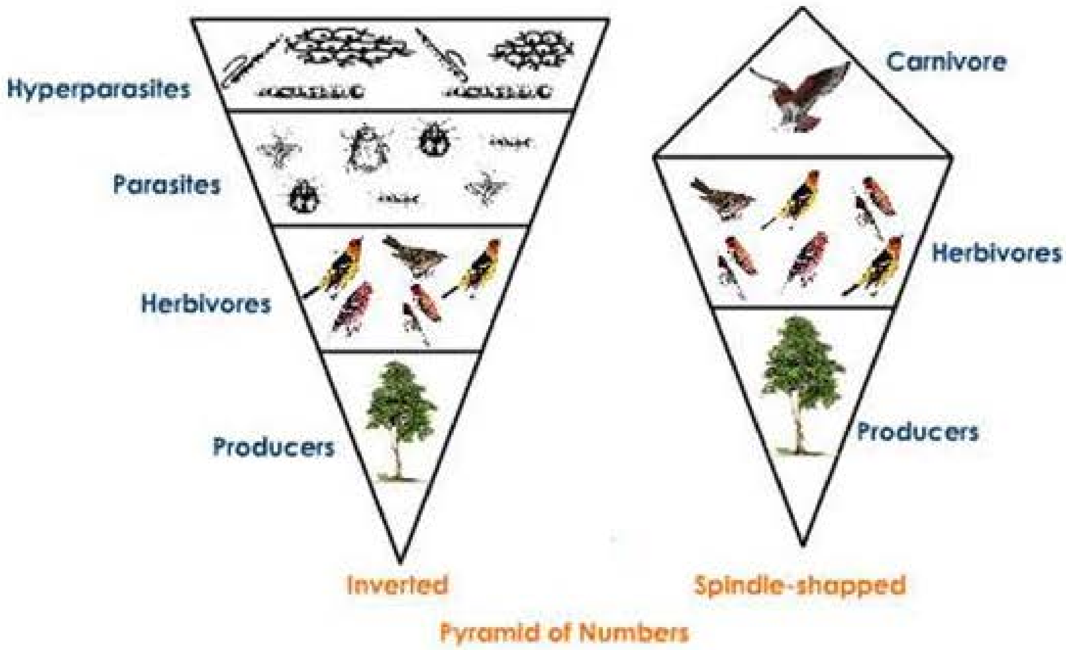


Fig. 6: Pyramid of Number in various shapes

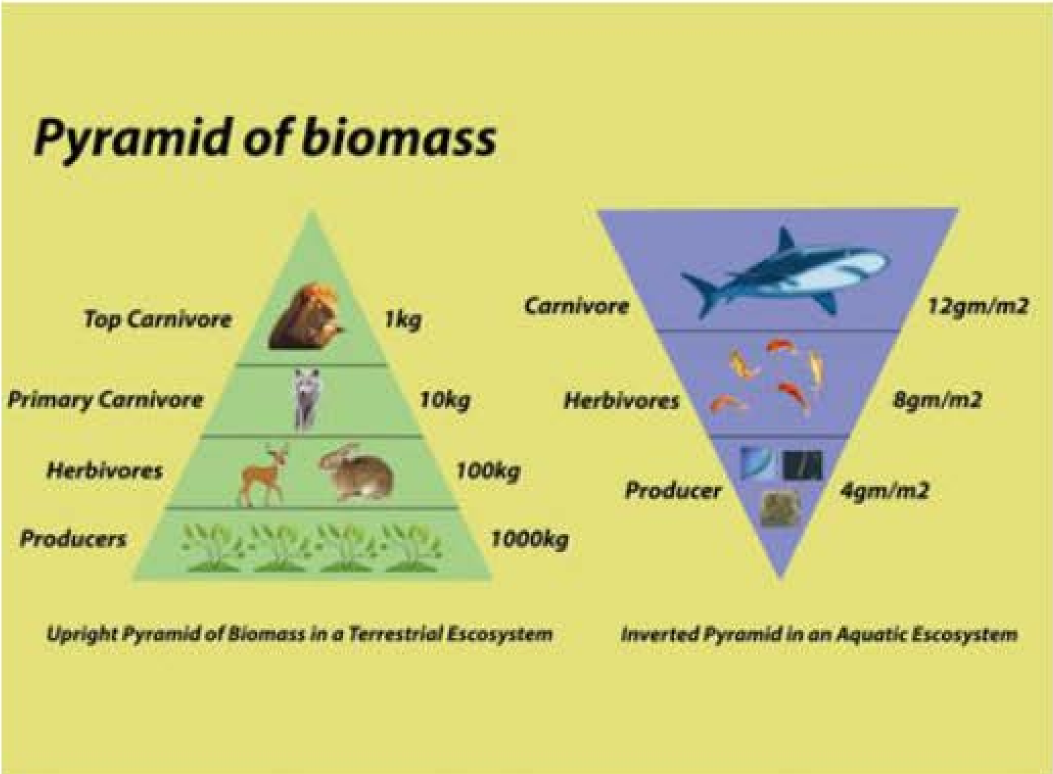


Fig. 7: Pyramid of biomass

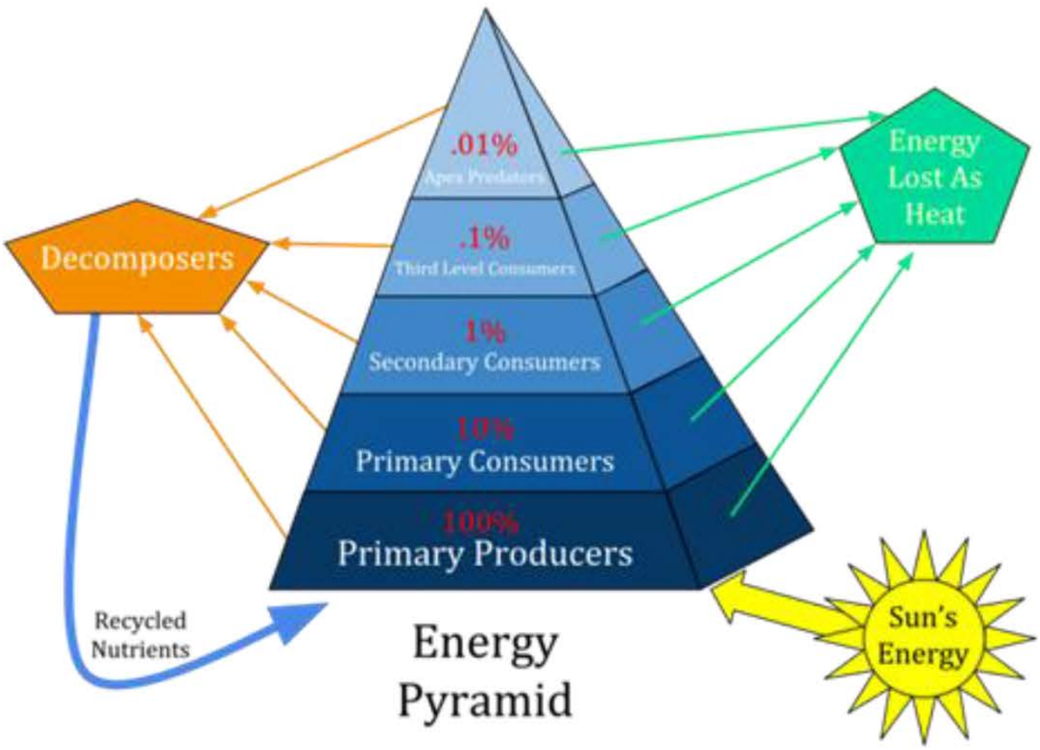
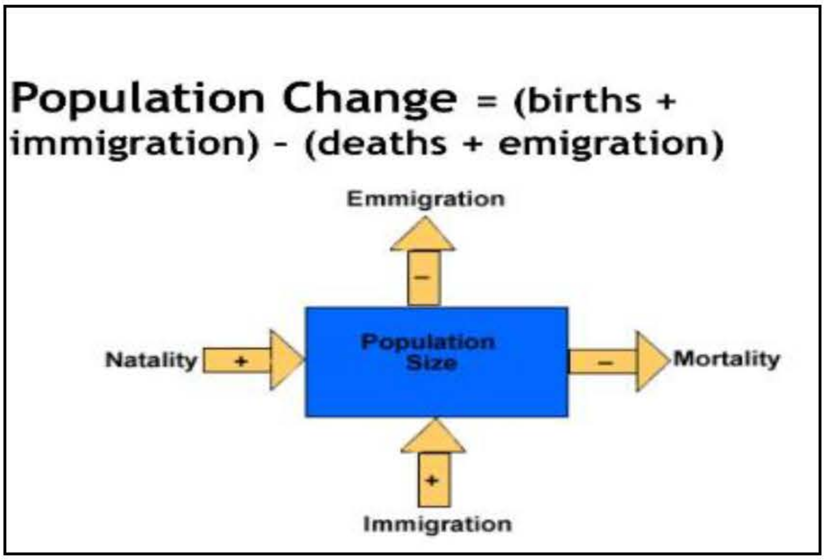


Fig. 8: Pyramid of Energy

Population density

The density of a population is the number of individuals per unit area or volume. There are four population parameters that affect the density, viz., natality (birth rate), mortality (death rate), immigration and emigration.



Natality: It is defined as the rate of birth of people per unit area per unit of time. The population grows when birth rate is more than death rate in any period of time.

Mortality: Mortality is the number of deaths of organisms in a population of a particular location over time. The population shrinks when the death rate is higher than the growth rate.
Immigration: Populations grow when individuals move into a region from elsewhere.
Emigration: Populations decrease in size when individuals move out of the location.

Types of Population Growth

i. **Exponential growth:** Resource (food and space) availability is obviously essential for the unimpeded growth of a population. Ideally, when resources in the habitat are unlimited, each species has the ability to realize fully its innate potential to grow in number, as Darwin observed while developing his theory of natural selection. Then the population grows in an exponential or geometric fashion. In simple words, it is the unrestricted growth of a population of organisms, occurring when resources in its habitat are unlimited.

If in a population of size N, the birth rates (not the total number but per capita births) are represented as b and death rates (again, per capita death rates) as d, then the increase or decrease in N during a unit time period "t" will be represented as,

$$\frac{dN}{dt} = (b - d) \times N \qquad \text{(Eq. 1)}$$

Here, the difference between birth rate and death rate is also termed as "**intrinsic rate of natural increase**" and can be symbolised as "**r**". This is a very important parameter chosen for assessing impacts of any biotic or abiotic factor on population growth.

Let (b–d) = r, then $\frac{dN}{dt}$ becomes,

$$\frac{dN}{dt} = rN \qquad \text{(Eq.2)}$$

The above equation describes the exponential or geometric growth pattern of a population (Fig.7a) and results in a J-shaped curve when we plot N in relation to time.

Above equation can be written as,

$$N = N_0 e^{rt} \qquad \text{(Eq. 3)}$$

Where:

N is the population size at time t
N_0 is the initial population size at time t=0
r is the growth rate of the population
t is time
e is the base of the natural logarithm, approximately equal to 2.718

Example

Find out the population size at time t=5 years, given an initial population size of 1000 individuals, a growth rate of 0.1 per year.

Solution:

Using Eq. 3, the population can be estimated as,

$N(5) = 1000 \times e^{(0.1*5)} = 1000 \times e^{0.5} = 1000 \times 1.648 = 1648$ individuals

This means that the population size at t=5 years is approximately 1648 individuals.

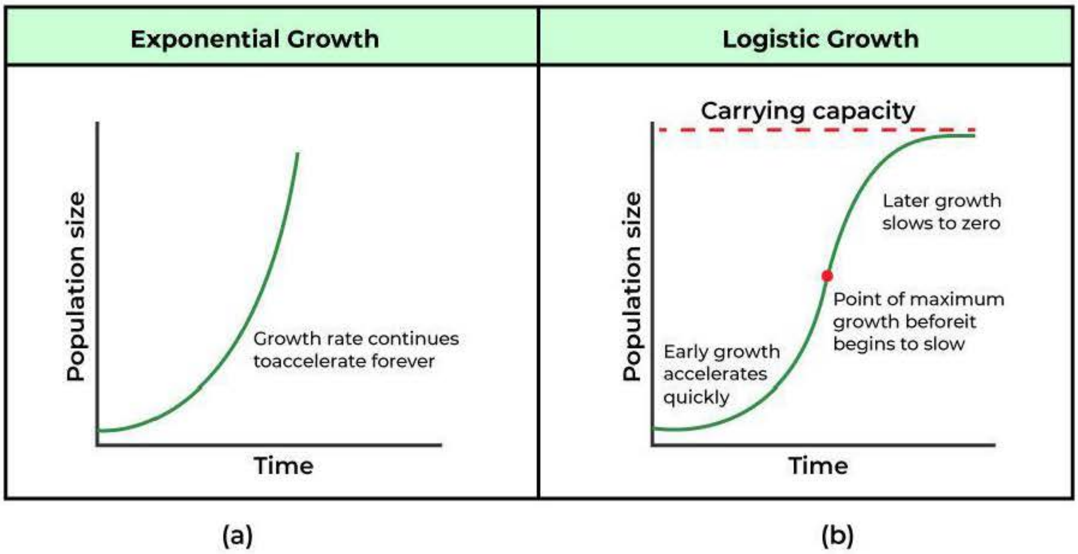


Fig. 9: Population growth models

Logistic growth: No population of any species in nature has at its disposal unlimited resources to permit exponential growth. This leads to competition between individuals for limited resources. Eventually, the 'fittest' individual will survive and reproduce. The governments of many countries have also realized this fact and introduced various restraints with a view to limit human population growth. A population growing in a habitat with limited resources show initially a lag phase, followed by phases of acceleration and deceleration and finally an asymptote, when the population density reaches the carrying capacity. A plot of N in relation to time (t) results in a sigmoid curve. This type of population growth is called **Verhulst-Pearl Logistic Growth** (Fig.7b) and is described by the following equation:

$$\frac{dN}{dt} = rN(1 - \frac{N}{K}) \qquad \text{(Eq. 4)}$$

Where N is the population size, K is called the carrying capacity of the environment, and r is the exponential growth rate constant that would apply if the population size is far below the carrying capacity. Strictly speaking, r is the growth rate constant when N=0; the population is zero. As N increases, the rate of growth slows down, and eventually, as N approaches K, the growth stops altogether, and the population stabilizes at a level equal to the carrying capacity. At the K/2 position, Maximum growth occurs i.e., (N= **K/2**). The factor (1-N/K) is often called environmental resistance.

The logistic growth equation is a useful tool for understanding how populations grow and how they respond to changes in the environment. It is often used in ecology, biology, and economics to predict the future size of a population and to evaluate the impact of various factors on population growth. Since resources for growth for most animal populations are finite and become limiting sooner or later, the logistic growth model is considered as a more realistic one.

Carrying Capacity

At the time when b=d, there would be no net growth in the population.

$$\frac{dN}{dt} = 0$$

This situation is called **Carrying capacity of the environment (K).** Thus, it can be defined as the maximum population that a natural ecosystem or environment can sustain under a given set of environmental conditions.

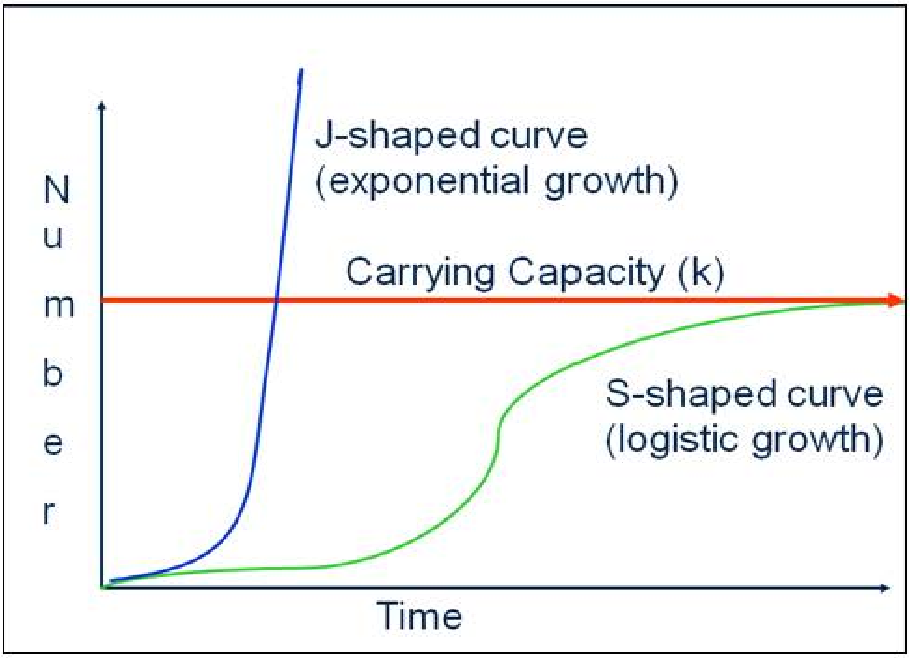


Fig. 10: Carrying Capacity of Population

Environmental Resistance

It is the sum of the environmental factors (such as drought, mineral deficiencies, and competition) that tend to restrict the biotic potential of an organism and impose a limit on their numerical increase. It is a density-dependent population control as the magnitude of the above factors is dependent on the size of the population. The term '(1-N)/K' in the equation for logistic population growth represents the environmental resistance, where K is the carrying capacity and N is the number of individuals in a population over time.

Question

Suppose a population of butterflies is growing according to the logistic equation. If the carrying capacity is 500 butterflies and r = 0.1 individuals/(individual*month), what is the maximum possible growth rate for the population?

Solution:

From the plot of dN/dt vs. N, we know that the maximum possible growth rate for a population growing according to the logistic model occurs when N = K/2, thus N = 250 butterflies.

Now,

$dN/dt = rN\,[1- (N/K)]$

$= 0.1(250)[1-(250/500)] = 12.5$ individuals / month

Limits to population growth

There are two types of limiting factors that determine the carrying capacity of an environment for any species.

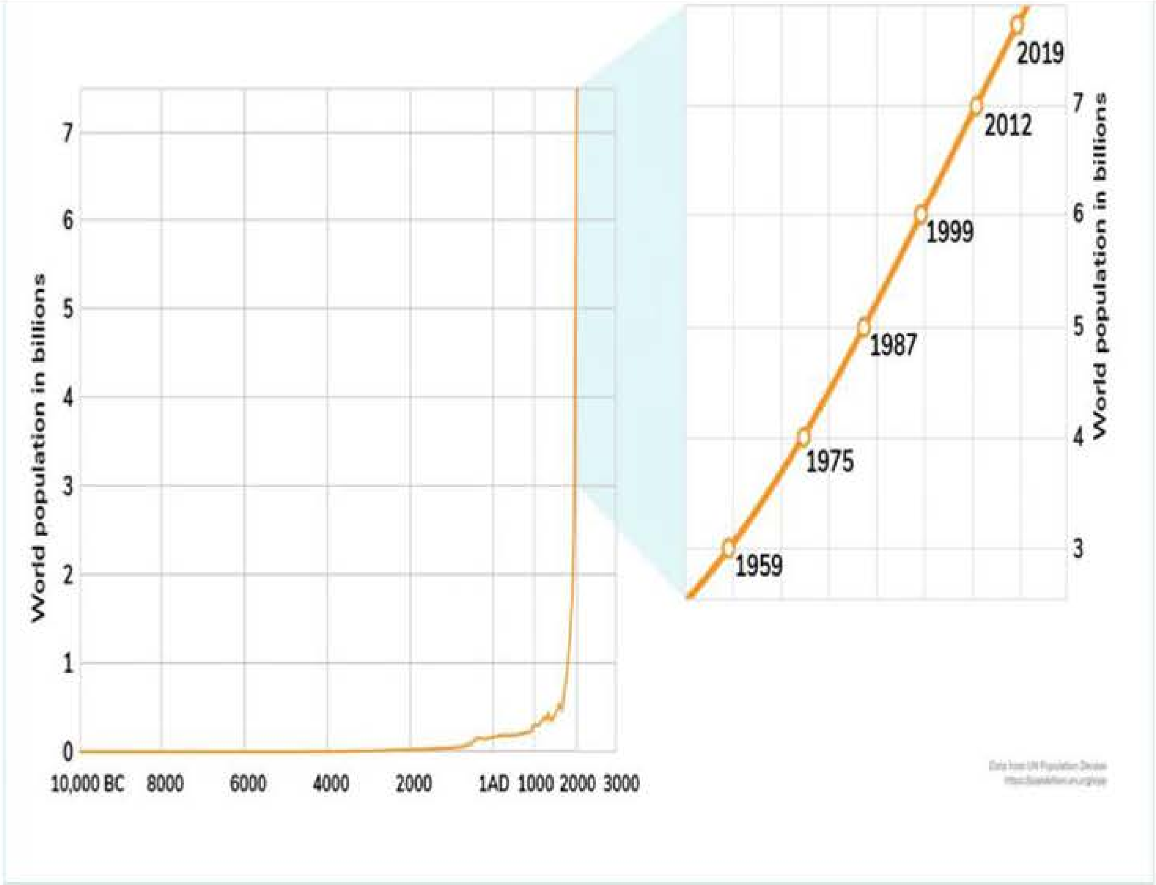
i. **Density-dependent limiting factors**: These factors operate only when population density reaches a certain level. For example, competition, predation, etc.

ii. **Density-independent limiting factors**: These factors affect all populations in similar ways, regardless of population size or density. For example, natural disasters.

Human Population Changes and the Environment

Human population growth impacts the Earth system in a variety of ways. Human activities can change the balance of Earth's processes. Careless human activity can also alter or destroy habitats and damage ecosystems. With the increase in human population, the demand for resources increases simultaneously. The increased extraction of resources from the environment such as fossil fuels (oil, gas, and coal), minerals, trees, water, etc. often releases pollutants and waste that degrade air and water quality, and harm the health of humans and other species.

Population dynamics have important environmental implications but the sheer size of population represents only one important variable in this complex relationship. Other demographic dynamics, including changes in population flows and densities, can also pose challenging environmental problems. Fulfilling the resource requirements of a growing population, ultimately requires some form of land-use change to provide the expansion of food production through forest clearing, to intensify production on already cultivated land, or to develop the infrastructure necessary to support increasing human numbers. These types of land-use changes have several ecological impacts. Converting land into agricultural use can lead to soil erosion, and the chemicals often used in fertilizers can also degrade soil. Deforestation is also associated with soil erosion and can reduce the ability of soil to hold water, thereby increasing the frequency and severity of floods. Human-induced changes in land use often result in habitat fragmentation and loss, the primary cause of species decline. Other major impact of population growth on environment is the climate change.



World human population growth from 10,000 BC to 2019 AD. Data from: The United Nations

Fig 11: Human population growth over the years

Global Climate Change

Recent years have been the warmest on record. Research suggests that temperature has been influenced by growing concentrations of greenhouse gases, which absorb solar radiation and warm the atmosphere. Research also suggests that many changes in atmospheric gases are human-induced. The demographic influence appears primarily in three areas. First, contributions related to industrial production and energy consumption lead to carbon dioxide emissions from fossil fuel use. Second, land-use changes such as deforestation, affect the exchange of carbon dioxide between the Earth and the atmosphere; and third, some agricultural processes, such as paddy-rice cultivation and livestock production, are responsible for greenhouse gas releases into the atmosphere, especially methane.

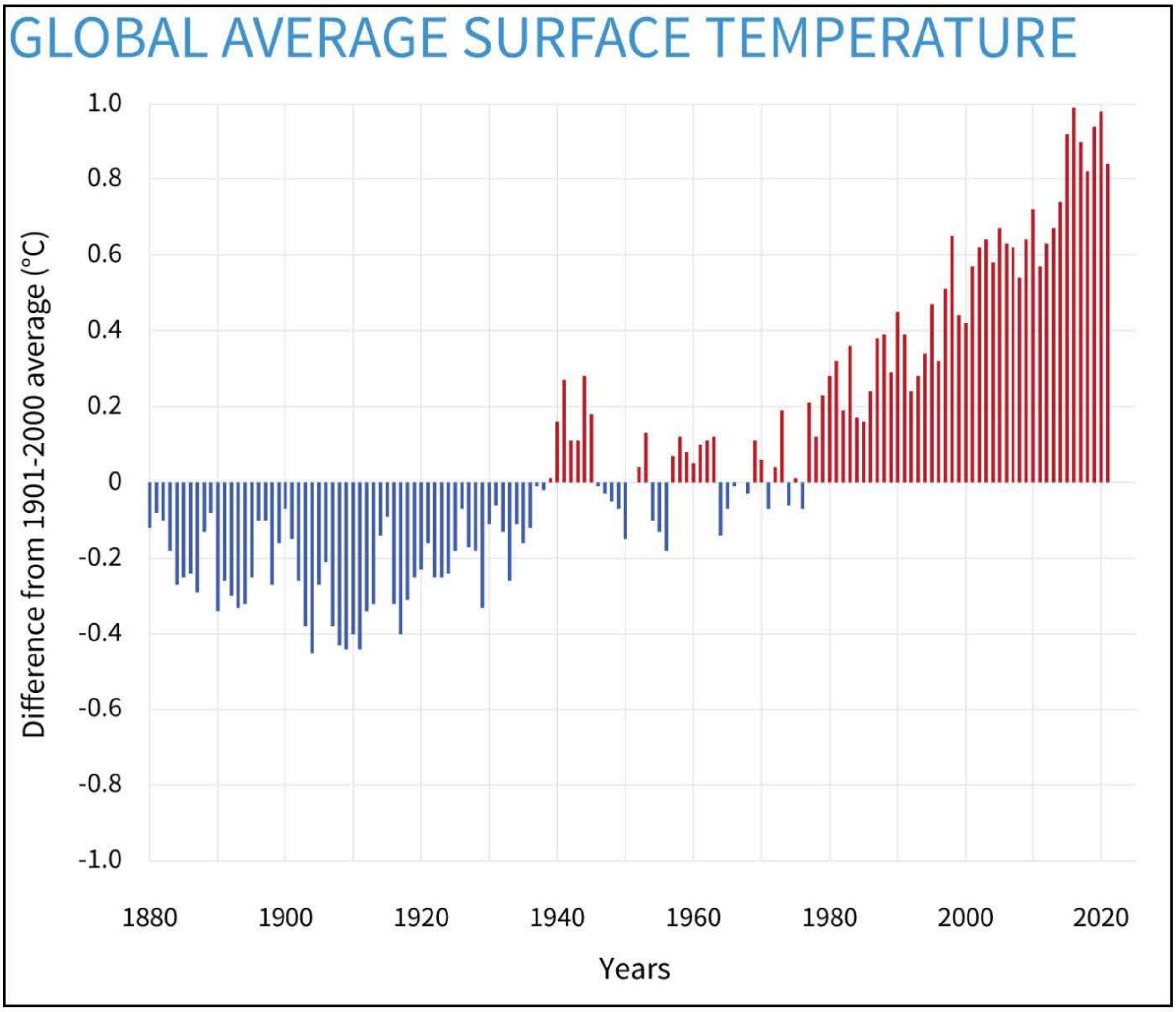


Fig. 12: Variation in surface temperate in different time scales (Source: Climate.gov)