Fundamental of Environmental Engineering

Chapter 2: Fundamental Biological Principles

Biology

Defined as the scientific study of life and living things, often taken to include their origin, diversity, structure, activities, and distribution.

The ways that organisms are affected by and have an effect on the environment including:
- Effects on humans
- Impacts on the environment
- Impacts by humans
- Mediation of chemical transformations in the environment
- Application in the treatment of contaminated air, water, and soil

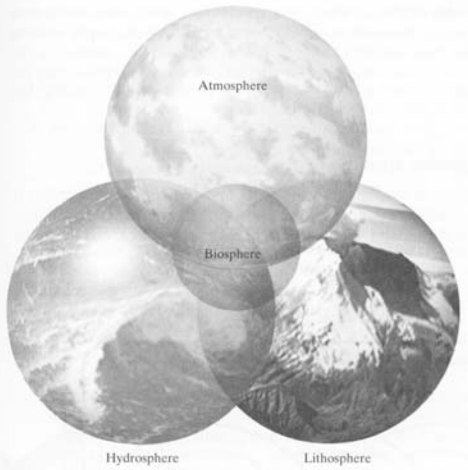


Figure 5-1. The Earth's Great Spheres of living and nonliving material. The atmosphere, hydrosphere, and lithosphere are the nonliving components and the biosphere contains all the living components. The ecosphere is the intersection of the abiotic spheres and the biotic component. (Adapted from *Environmental Science* by Kupchella/Hyland, © 1986, by permission of Prentice-Hall, Inc., Upper Saddle River, NJ.)

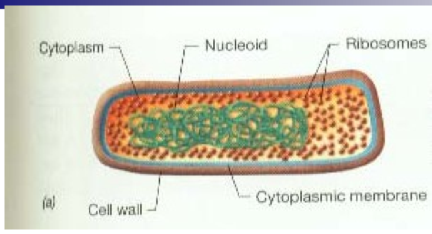
Ecology is the study of structure and function in nature: interactions between living things and their nonliving (abiotic) environment or habitat.

Prokaryotic and Eukaryotic Cells

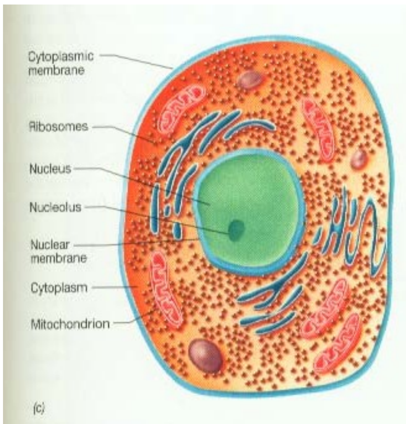
Based on cell structure, living organisms can be divided into prokaryotes and eukaryotes.

Eukaryotic cells have membrane bound organelles; including the membrane-bound nucleus (nuclear membrane), mitochondria, and chloroplasts (in photosynthetic cells only).

Prokaryotic cells usually have a quite simple internal structure, lacking membrane-bound organelles.



Prokaryotes



Eukaryotes

Feeding Strategies:

- Absorption (uptake of dissolved nutrients).

- Photosynthesis (fixation of light energy in simple carbohydrates).

- Ingestion (intake of particulate nutrients).

Five kingdoms:

- Monera (unicellular procaryoyes that obtain nutrients strictly by absorption).

- Protista (mostly unicellular eucaryotes that obtain food by absorption, photosynthesis, or ingestion).

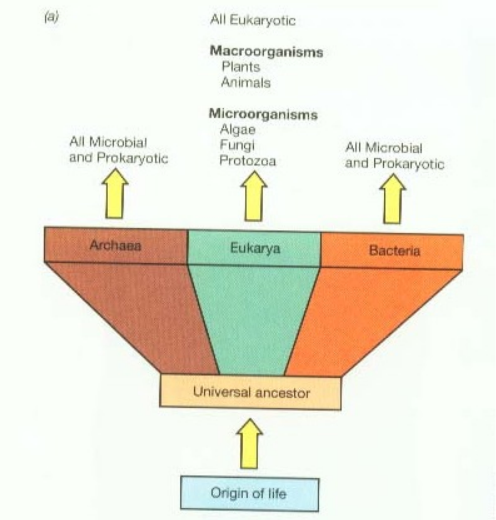
- Fungi (mostly multicellular eucaryotes that obtain food by absorption).

- Plantae (multicellular eucaryotes that obtain food by photosynthesis).

- Animalia (multicellular eucaryotes that obtain food by ingestion).

"This system of classification is not without exceptions"
For example, cyanobacteria (blue-greeen algae)

More recently, a three-domain system has been proposed in an attempt to resolve this and other difficulties with the five-kingdom approach.



Each kingdom or domain can be further subdivided into phyla, classes, orders, families, genera, and species.

A species is a group of individuals that possess a common gene pool and that can successfully interbreed.

Each species is assigned a scientific name (genus-species), in Latin, to avoid the confusion associated with common names.

The binomial system of nomenclature first developed by Linnaeus for plants and animals. The genus name is applied to a number of related organisms; each different type of organism within the genus has a species epithet. Genus and species names are always used together to describe a specific type of organism, whether it be a single cell or a group of such cells. For example, the bacterium *Escherichia coli*, or *E. coli* for short, has a genus name, *Escherichia*, and a species epithet, *coli*.

Ecosystem

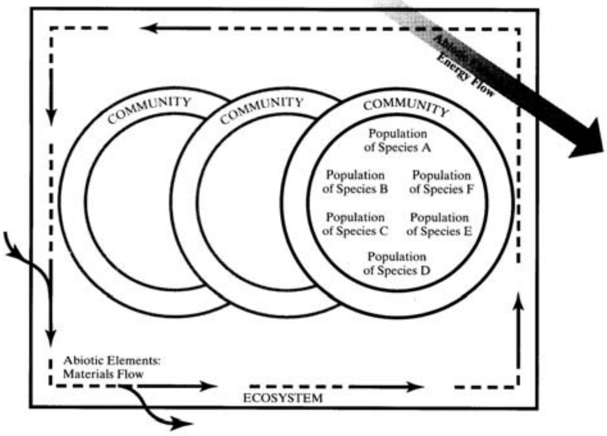


Figure 5-2. The biotic component of an ecosystem can be organized according to species, populations, and communities. Note in this schematic that energy flows through and chemicals cycle largely within the ecosystem. Both natural and engineered environments may be considered as ecosystems. The various biological unit processes employed for wastewater treatment (activated sludge, anaerobic digester, trickling filter, oxidation pond) have communities composed of a variety of microorganism populations. The nature of the ecosystem is determined by the physical design of the unit process and by the chemical and biological character of the wastewater entering the system.

Major Organism Groups

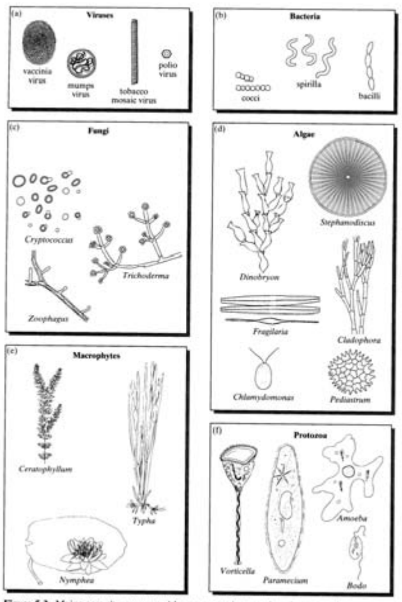


Figure 5-3. Major organism groups with representative members important in environmental science and engineering: (a) viruses, (b) bacteria, (c) fungi, (d) algae, (e) macrophytes, (f) protozoa.

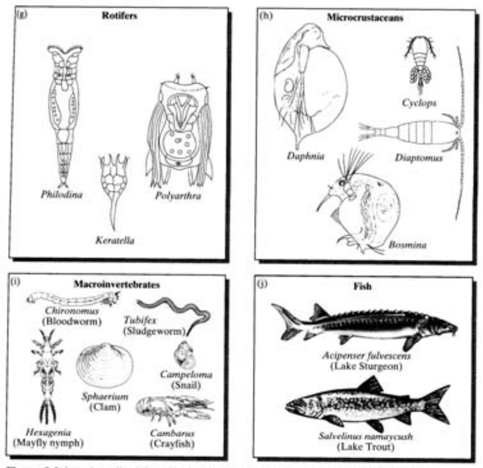


Figure 5-3 (continued). (*g*) rotifers, (*h*) microcrustaceans, (*i*) macroinvertebrates, and (*j*) fish.

Viruses: Submicroscopic particles (there is some argument as to whether they are very complex biochemicals or very simple organisms, i.e., are they truly alive?) ranging in size from 0.02 μm to 0.3 μm, composed of a nucleic acid core and a protein coat and containing all of the hereditary material required for reproduction; all are parasitic, depending on a host for protein and the energy needed to reproduce; all are pathogenic, causing a variety of diseases: notably AIDS and, in water, hepatitis, polio, and gastroenteritis; because of public health concerns, viruses are of particular importance to engineers involved in water and wastewater treatment. Other noncellular agents of disease include the viroids, consisting only of small RNA molecules (lacking a protein coat) that infect plants and the prions, protein units that infect animals, causing scrapie in sheep and goats and mad cow disease.

Bacteria: Monerans; 0.1–10 μm in size; typically reproduce by fission (splitting); acquire nutrients by absorption; many are pathogenic, causing tuberculosis, diphtheria, strep throat, whooping cough, Lyme disease, tetanus and, in water, cholera and typhoid, thus also of importance in water and wastewater disinfection. Although some bacteria depend on sunlight as a source of energy, most use chemicals for this purpose, and thus play an important role in mediating various biochemical transformations, for example, decomposition of organic matter, oxidation of ammonia to nitrate, and reduction of sulfate to sulfide. Bacteria are of major importance in cycling material and energy in natural and engineered systems, for example, hydrocarbon-degrading bacteria have received significant attention for their ability to break down toxic chemicals (e.g., gasoline, solvents), thus aiding in the remediation of contaminated soil and water environments. In soils, the unsaturated zone typically contains 10^5 to 10^8 viable bacterial cells per gram of soil, and the saturated zone (i.e., groundwater) typically contains 10^2 to 10^7 viable bacterial cells per gram of soil–water mixture. Bacteria are important in the production of foods, especially fermented milks (cheese, yogurt, buttermilk) and vegetables (pickles, olives, sauerkraut), antibiotics, enzymes, and industrial solvents.

Algae: Protistans (unicellular; 1–100 μm) and nonvascular plants (multicellular; ranging to several meters); obtain nutrition through photosynthesis; reproduce asexually (simple division with no exchange of genetic material) and/or sexually (with exchange of genetic material). Algae play an important role in the cycling of materials and energy in aquatic ecosystems, and together with macrophytes, are the major sources of organic matter in lakes and reservoirs. Excessive algal growth can lead to taste and odor problems in water supplies, a reduction in water clarity in lakes, and depletion of oxygen reserves as algae settle to the bottom of lakes and decompose. The free-floating algae of lakes are termed *phytoplankton* (i.e., plants dependent on currents and eddies for transport).

Fungi: Unicellular (yeasts) or multicellular (molds) Fungi; range in size from a few μm to several cm (some filamentous soil fungi may cover hectares of land area); reproduce asexually (budding, spores) or sexually (spores); lack chlorophyll and feed by absorption. In tribute to their role in cycling organic matter in soil, water, and wastewater, fungi are sometimes called "the great decomposers." Fungi are important in the pharmaceutical (antibiotics) and food (alcoholic beverages, cheese, soy sauce) industries, during composting, and are responsible for a variety of diseases: ringworm, athlete's foot, and toxic shock syndrome.

Protozoa: Protistans; 10–300 μm in size; reproduce asexually by fission (splitting) and budding or sexually; some form "resting" cysts to weather hostile environmental conditions. Protozoa are considered to be "animal-like" because they lack chlorophyll, are motile, and ingest dead particulate matter or living cells, for example, bacteria, algae, or other protozoa; however, some feed by absorption. They are important in the decomposition process in wastewater treatment and in lakes, as they solubilize particulate organic matter, producing the dissolved substrates required by bacteria and fungi. This group includes the well-known genera *Amoeba* and *Paramecium*, and the pathogenic genera *Giardia* and *Cryptosporidium* are of concern to drinking water supply engineers because they produce cysts which are resistant to disinfection.

Rotifers: Microscopic animals; 100–1000 μm in size, with one or more rings of cilia or hairs at the head of the body that aid in locomotion and in the drawing in of food. The feeding strategy that rotifers utilize is similar to that of protozoa, ingesting living and dead particles and excreting soluble organic matter useful to bacteria and fungi. Rotifers are thus important in recycling energy and material in wastewater-treatment plants and in natural systems.

Microcrustaceans: Microscopic animals; 1–10 mm in size; commonly represented by the copepods and cladocerans (*Daphnia*, the water flea); relatives of crabs, lobster, and shrimp; feed on bacteria, algae, and other particles in lakes. A primary food source for many species of fish, microcrustaceans are important in energy and material transfer in aquatic systems, but rarely exist in biological wastewater treatment. Taken together, the free-floating animals of lakes (protozoa, rotifers, and microcrustaceans) are termed the *zooplankton* (i.e., animals dependent on currents and eddies for transport).

Macrophytes: Large, vascular plants; grow submerged, floating, or emergent in lakes and rivers. Macrophytes provide important habitat, for example, nursery areas, but can reach nuisance proportions in rivers and lakes enriched with nutrients, creating problems with recreational use and negatively impacting dissolved oxygen budgets.

Macroinvertebrates: Higher animals lacking a spine or backbone, usually inhabiting the bottom muds of lakes and rivers. Macroinvertebrates include worms, clams, snails, and the early life stages of insects. They are important in processing dead organic matter in aquatic ecosystems and are a major food source for fish. Because of their relative lack of mobility, macroinvertebrates are often exposed to and accumulate toxic chemicals, and thus serve as indicators ("canary in the coal mine") of ecosystem health.

Fish: Much could be said about this group of animals that both influence and are influenced by the environment. As a result of their tendency to bioconcentrate hydrophobic organic chemicals and mercury in their tissues, fish can impact the health of humans and other animals that feed on them. The public perception of water quality is clearly linked to the presence of an abundant, diverse, and healthy fish community.

Classification of Bacteria

Classification by physiology

Basic bacterial equation:
Energy source + electron acceptor + carbon source + bacteria → oxidized and reduced products + more bacteria.

Classification by metabolism :

Carbon source :	Inorganic (CO_2)	Autotroph
	Organic	Heterotroph
Energy source :	Chemical	Chemotroph
	Light	Phototroph
Electron donor :	Inorganic	Lithotroph
	Organic	Organotroph
Electron acceptor :	Oxygen	Aerobic
	Nitrate	Denitrifyer
	Sulfate	Sulfate reducer
	CO_2	Methanogen, Acetogen
	Organic Cl	Dehalogenator

Mixotroph – organisms that use either light or chemical energy sources

Facultative – organisms that can switch energy sources or electron acceptors

Classification by adaptation to various environments

Oxygen presence	Obligate aerobes
	Microaerophiles
	Facultative anaerobes
	Obligate anaerobes
Temperature	Psychrophiles
	Mesophiles
	Thermophiles
	Extreme thermophiles

Classification by adaptation to various environments

pH	Acidophiles
Salinity	Halophiles
Pressure	Barophiles

Nutrition and Metabolism

1. Microbial Nutrition

Carbon and Nitrogen

Many prokaryotes require an organic compound of some sort as their source of carbon. Bacteria use carbon compounds to make new cell material. On a dry weight basis, a typical cell is about 50% carbon and carbon is the major element in all classes of macromolecules.

After carbon, the next most abundant element in the cell is nitrogen. A typical bacterial cell is about 12% nitrogen (by dry weight). Nitrogen can be found in nature in both inorganic and organic forms. However, the bulk of available nitrogen in nature is in inorganic form, either as ammonia, nitrate, or N_2.

Other Macronutrients: P, S, K, Mg, Ca, Na, Fe

TABLE 4.1 Macronutrients in nature and in culture media

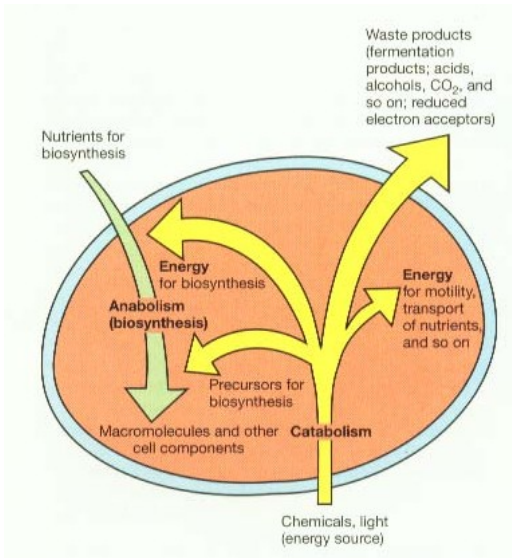
Element	Usual form of nutrient found in the environment	Chemical form supplied in culture media
Carbon (C)	CO_2, organic compounds	Glucose, malate, acetate, pyruvate, hundreds of other compounds, or complex mixtures (yeast extract, peptone, and so on)
Hydrogen (H)	H_2O, organic compounds	H_2O, organic compounds
Oxygen (O)	H_2O, O_2, organic compounds	H_2O, O_2, organic compounds
Nitrogen (N)	NH_3, NO_3^-, N_2, organic nitrogen compounds	*Inorganic:* NH_4Cl, $(NH_4)_2SO_4$, KNO_3, N_2 *Organic:* Amino acids, nitrogen bases of nucleotides, many other N-containing organic compounds
Phosphorus (P)	PO_4^{3-}	KH_2PO_4, Na_2HPO_4
Sulfur (S)	H_2S, SO_4^{2-}, organic S compounds, metal sulfides (FeS, CuS, ZnS, NiS, and so on)	Na_2SO_4, $Na_2S_2O_3$, Na_2S, cysteine, or other organic sulfur compounds
Potassium (K)	K^+ in solution or as various K salts	KCl, KH_2PO_4
Magnesium (Mg)	Mg^{2+} in solution or as various Mg salts	$MgCl_2$, $MgSO_4$
Sodium (Na)	Na^+ in solution or as NaCl or other Na salts	NaCl
Calcium (Ca)	Ca^{2+} in solution or as $CaSO_4$ or other Ca salts	$CaCl_2$
Iron (Fe)	Fe^{2+} or Fe^{3+} in solution or as FeS, $Fe(OH)_3$, or many other Fe salts	$FeCl_3$, $FeSO_4$, various chelated iron solutions (Fe^{3+} EDTA, Fe^{3+} citrate, and so on)

Micronutrients (Trace elements)

TABLE 4.2 Micronutrients (trace elements) needed by living organisms[a]

Element	Cellular function
Chromium (Cr)	Required by mammals for glucose metabolism; no known microbial requirement
Cobalt (Co)	Vitamin B_{12}; transcarboxylase (propionic acid bacteria)
Copper (Cu)	Certain proteins, notably those involved in respiration, for example, cytochrome *c* oxidase; or in photosynthesis, for example, plastocyanin; some superoxide dismutases
Manganese (Mn)	Activator of many enzymes; present in certain superoxide dismutases and in the water-splitting enzyme of photosystem II in oxygenic phototrophs
Molybdenum (Mo)	Present in various flavin-containing enzymes; also in molybdenum nitrogenase, nitrate reductase, sulfite oxidase, DMSO-TMAO reductases, some formate dehydrogenases, oxotransferases
Nickel (Ni)	Most hydrogenases; coenzyme F_{430} of methanogens; carbon monoxide dehydrogenase; urease
Selenium (Se)	Formate dehydrogenase; some hydrogenases; the amino acid selenocysteine
Tungsten (W)	Some formate dehydrogenases; oxotransferases of hyperthermophiles (for example, aldehyde:ferredoxin oxidoreductase of *Pyrococcus furiosus*)
Vanadium (V)	Vanadium nitrogenase; bromoperoxidase
Zinc (Zn)	Present in the enzymes carbonic anhydrase, alcohol dehydrogenase, RNA and DNA polymerases, and many DNA-binding proteins
Iron (Fe)[b]	Cytochromes, catalases, peroxidases, iron–sulfur proteins (for example, ferredoxin), oxygenases, all nitrogenases

a Not every micronutrient listed is required by all cells; some metals listed are found in enzymes present in only specific microorganisms.
b Needed in greater amounts than other metals—not generally considered a trace element.



A simplified view of cell metabolism.

2. Metabolism

This term is used to refer to all the chemical processes taking place within a cell.

Anabolism is the process by which a cell is built up from the simple nutrients obtained from its environment. Because anabolism results in the biochemical synthesis of new cell material, it is also called biosynthesis.

Biosynthesis is an energy-requiring process, and each cell must thus have a means of obtaining energy. Cells also need energy for other functions, such as transport and motility.

Catabolism is the process by which chemicals are broken down and energy released. Catabolism, biochemical reactions leading to the production of usable energy (usually ATP) by the cell.

3. Energetics

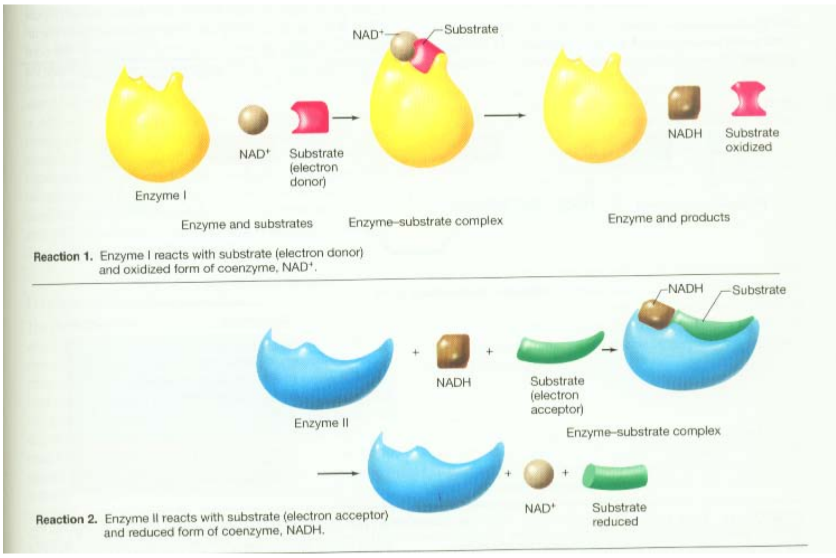
Energy is defined as the ability to do work. Chemical energy is the energy released when organic or inorganic compounds are oxidized.

A kilocalorie is defined as the quantity of heat energy necessary to raise the temperature of 1 kg of water 1 ^{o}C.

In microbiology, free energy (G) is defined as the energy released that is available to do useful work.

ΔGº is the free energy value obtained under standard conditions: pH 7, 25 ºC, all reactants and products initially at 1 M concentration.

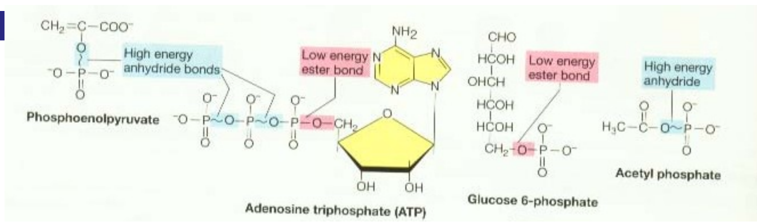
If the ΔGº is negative, the reaction will proceed with the release of free energy, energy that the cell can conserve in the form of ATP. Such energy-yielding reactions are called **exergonic**. However, if ΔGº is positive, the reaction requires energy in order to proceed, such reactions are called **endergonic**.



High Energy Compounds and Energy Conservation

Energy released as a result of oxidation-reduction reactions must be conserved for cell functions. In living organisms, chemical energy released in redox reaction is usually conserved in the form of high energy phosphate bonds. These compounds then function as the energy source to drive energy-requiring reactions in the cell.

In phosphorylated compounds, phosphate groups are attached via oxygen atoms by ester or anhydride bonds.



High Energy Phosphate Groups

Compound	$G^{o'}$ kJ/mol
High energy	
Phosphoenolpyruvate	-51.6
1,3-Bisphosphoglycerate	-52.0
Acetyl phosphate	-44.8
ATP	-31.8
ADP	-31.8
Low energy	
AMP	-14.2
Glucose-6-phosphate	-13.8

Adenosine Triphosphate (ATP)

The most important high energy phosphate compound in living organisms is ATP. ATP consists of the ribonucleoside adenosine, to which three phosphate molecules are bonded in series. ATP serve as the prime energy carrier in living organisms, being generated during exergonic reactions and being used to drive endergonic reactions.

$$ATP + H_2O \rightarrow ADP + P_i \qquad \Delta G^o = -7.3 \text{ kcal/mol}$$

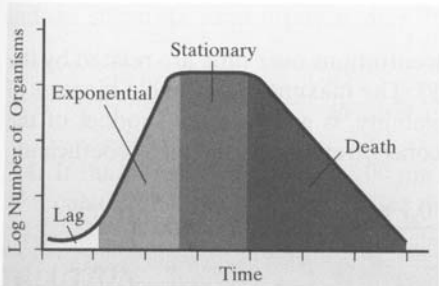


Figure 5-10. Population dynamics in batch culture illustrating four commonly observed regions: a lag phase, an exponential growth phase, a stationary phase, and a death phase. During the lag phase, growth is slow as cells take up nutrients, activate enzyme systems, and equilibrate with their physical and chemical environment. During the exponential or log growth phase, growth is rapid and well approximated by the exponential model, $dX/dt > 0$. During the stationary phase, growth is balanced by death and steady-state conditions are reached, $dX/dt = 0$. The death phase is characterized by resource limitation and/or buildup of toxic materials which inhibit growth; therefore, losses control, $dX/dt < 0$.

1. The *lag* or *acclimation phase* where growth is slow as cells take up nutrients, activate enzyme systems, and equilibrate with their physical and chemical environment;
2. The *exponential* or *log growth phase*, where growth is rapid and well approximated by the exponential model, $dX/dt > 0$;

3. The *stationary phase*, where growth slows due to resource depletion or crowding and is balanced by losses to respiration (as defined in Section 5.3.1) and predation; therefore, steady state is reached, $dX/dt = 0$;
4. The death phase, where resource limitation and/or the buildup of toxic byproducts inhibits growth and losses to respiration and predation control biomass dynamics, $dX/dt < 0$.

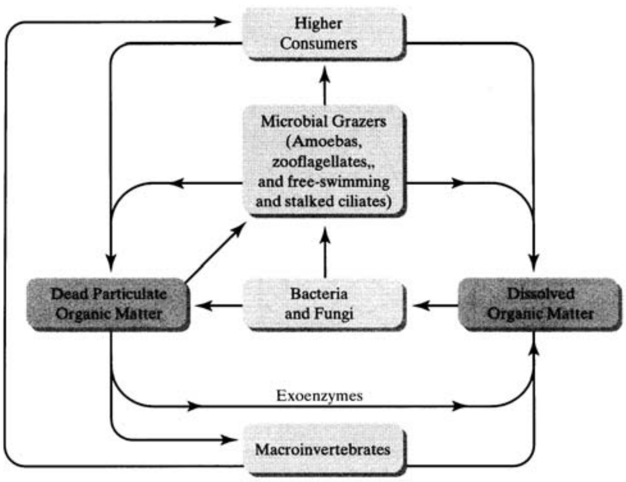
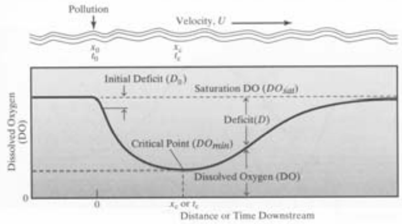
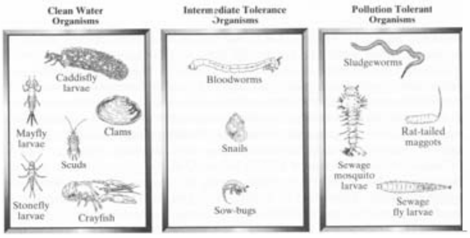


Figure 5-16. The food chain and web illustrated in Figure 5-15 implies that all movement of energy is "upward." Detritus (dead organic matter) generated during material transfer moves "down" and is processed by detritivores that recycle chemicals and energy, making them available once again for upper trophic levels. This microbial loop recovers a significant amount of energy that would be otherwise lost to the ecosystem. However, the decomposer–consumer loop is not self-perpetuating (as is the producer–consumer loop) due to inefficiencies described in the text.



Stream Zones					
	Clean Water	Degradation	Damage	Recovery	Clean Water
Physical conditions	Clear water; no bottom sludge	Floating solids; bottom sludge	Turbid water; malodorous gases; bottom sludge	Turbid water; bottom sludge	Clear water; no bottom sludge
Fish species	Cold or warm water game and forage fish; trout, bass,	Pollution-tolerant fish; carp, gar, buffalo	None	Pollution-tolerant fish; carp, gar, buffalo	Cold or warm water game and forage fish; trout, bass,
Benthic invertebrate	clean water	intermediate tolerance	pollution tolerant	intermediate tolerance	clean water



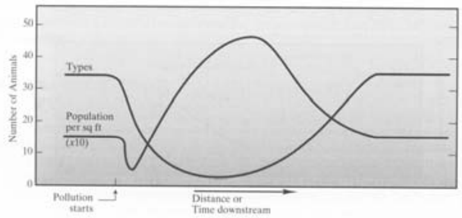


Figure 5-24. The dissolved oxygen sag curve and associated water quality zones reflecting impacts on physical conditions and the diversity and abundance of organisms.

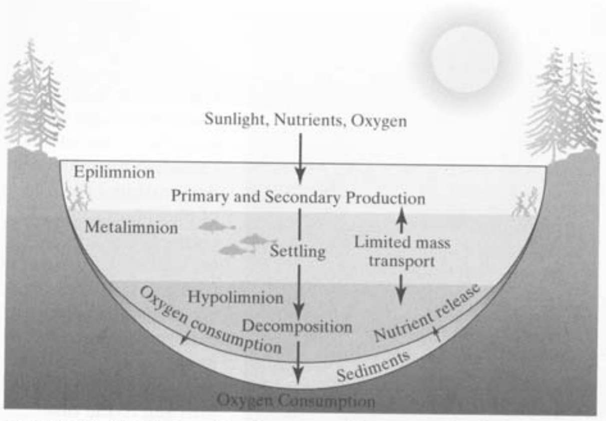


Figure 5-35. The interaction between primary production, thermal stratification, and degradation of water quality in lakes. The oxygen resources of the hypolimnion are largely fixed at stratification. Subsequent production, deposition, and mineralization of organic matter may deplete these reserves leading to poor water quality.

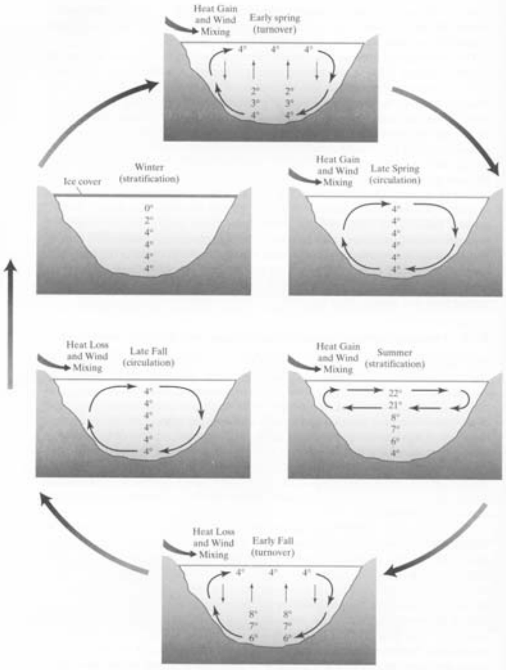


Figure 5-34. The annual cycle of stratification, overturn, and circulation in temperate lakes. Variation in meteorological conditions (temperature, wind speed) may impart significant variation to the timing and extent of these events.