Fundamentals of Ecology and Ecotoxicology

This section of the guidance provides an overview of the basic concepts of ecology and ecotoxicology, the technical areas that provide the basis for ecological risk assessments. The intent is not to train RPMs to become ecological risk assessors, ecologists, or ecotoxicologists, but rather to provide sufficient background on these topics to facilitate an understanding of terms and concepts that technical specialists (both contractors and regulators) may use when providing consultation on an ERA.

1.0 Ecology

Ecology is the study of how organisms interact with the other living organisms and the non-living components (e.g., sunlight, soil, water, air) in their surrounding environment. The term "ecology" is derived from two Greek words, oikos ("house"), and logos ("study of", or "governing rules"), literally, "the rules of the house." The "rules" refer to the relationships and interconnections between organisms and their environment. The term environment refers to all the external conditions and factors, both living and non-living, that affect an organism.

Ecological risk assessments are used to identify the ecological components that are most at risk from contaminants at a site and to quantify the magnitude of risk from those contaminants. In order to make these determinations, the relationships among organisms and between organisms and their physical environment must be understood. It is important to understand not only the physiological characteristics of individual organisms, but also their food habits, behavioral patterns, and habitat requirements. These factors all have important effects on the exposure of individual organisms to contaminants and the associated risk of this exposure. The risk to higher level ecological components such as communities or ecosystems (see below) will be affected by the effects of contaminants on individual organisms within those components as well as attributes specific to the surrounding environment.

In addition to understanding the potential effects of contaminants on individual species, an ecological risk assessor must be cognizant of the important ecological relationships applicable to the site. Because each species at a site is in some way dependent upon other species and upon abiotic components of the environment, indirect effects of contamination are possible as well. Thus, while a contaminant may not be directly toxic to one species, by affecting species upon which it depends for food or that may feed upon it, the ecology of a site (and, perhaps, surrounding areas) may be at risk. Similarly, contaminants that affect processes such as decomposition or nutrient availability can drastically alter ecological relationships as well.

1.1 Ecological Levels of Organization

Ecological risk assessments are usually concerned with effects at four different levels of ecological organization or complexity. These levels of organization, arranged from the simplest to most complex, are individual organisms, populations of organisms, communities and ecosystems. Each of these organizational levels has characteristic measures of extent, function, structure, and change associated with it. Ecological risk assessments are intended to estimate the risk that stressors (e.g., chemical contamination) will affect these ecological characteristics.

1.1.1 Species

Different types of organisms have specific (and often unique) requirements such as temperature, moisture conditions, chemical constituents, and diet. Collectively, a group of individual organisms that are potentially capable of interbreeding under natural conditions are referred to as a species and each species is typically reproductively isolated from other species. Organisms of the same species can have different physical or behavioral characteristics. As an example, consider the species *Homo sapiens* (humans). Humans exhibit considerable variety in skin, hair, and eye color, size, and other characteristics. This same type of variety also occurs in plant and animal species.

Ecologists often have technical backgrounds aligned with particular taxonomic groups under the broad subdivisions of plant ecology or animal ecology. Different types of organisms can differ considerably in their ecological characteristics and in how they are affected by exposure to contaminants. For example, the exposure to PCBs and the potential effects of PCBs in sediments on birds can be strongly influenced by the behavior and food habits of individual species. Other types of organisms, such as burrowing invertebrates, will have different exposure pathways and associated risks.

1.1.2 Populations

A group of individuals of the same species that occupy a particular area over a given interval of time are referred to as a population. Note that a population does not necessarily include all the individual members of a species and there can be multiple populations for each species. For example, a particular fish species may have several populations that occur in different areas of the oceans, with little or no exchange of individuals between the various populations. The size and extent of populations is often described in terms of density (i.e., the number of individuals per unit area). Population structure is the relative number of individuals in a particular age class (i.e., a readily identifiable stage within the life cycle of an organism) such as eggs, juveniles, and adults, or some other descriptive category (e.g., male or female). The size, extent, and structure of populations are affected by birth and death rates, changes in environmental conditions, competition with individuals of other species, and movement of individuals into and out of the area, all of which may be affected by exposure to a contaminant or some other environmental stressor.

Examples of populations include:

- all of the largemouth bass living in a pond
- all of the meadowlarks living in a particular region
- all of the white oaks in a particular forest
- all of the cougars in the Santa Ana Mountains of Southern California

Population size refers to the number of individuals in a given population. A maximum population size can be reached for a limited area and time frame, given specific and limited amounts of food, shelter, living space, and other resources. The maximum population size that can be sustained in a given area is termed the carrying capacity. The carrying capacity can vary seasonally, monthly, or even daily according to changes in environmental conditions (Odum, 1971).

1.1.3 Communities

Populations of various species living in the same area, representing a multitude of interactions and dependencies, are referred to as a community. The interactions between populations and the abiotic elements of the environment determine the geographical distribution and structure (e.g., numbers, types, and mix of species present) of communities. Although the species within a community are, to some extent, replaceable by other species over space and time, their functions within the community are relatively fixed in that they modify the physical aspects of an area, supply food to other organisms, die, and decompose. Communities can change over long periods of time in a process known as ecological succession. During succession, some species are displaced through time by other species as new environmental conditions develop. For example, when a meadow undergoes succession that ultimately results in a forest, annual plants are replaced gradually by perennials, shrubs, and trees. Each plant type modifies the environment in ways that tend to favor the succeeding type.

1.1.4 Ecosystems

The community and the abiotic (i.e., non-living) elements of a particular area function as a unit called the ecosystem. This is typically the highest organizational level of interest to ecologists and is often of interest in ecological risk assessments (ERA), depending on the extent of environmental contamination in a geographic area. Each level of organization is important to consider when scoping the ERA. It is important to keep in mind that evaluations of ecosystems within an ERA will be the most difficult and costly evaluations you are likely to encounter. Typically, effects on ecosystems are inferred on the basis of evaluations of populations and communities.

Ecosystems are typically classified by ecologists as aquatic or terrestrial ecosystems. Examples of terrestrial ecosystems in North America include arctic tundra, deciduous forests, hot deserts, cold deserts, coniferous forests, sand dunes, short-grass prairie, mountain meadows, and bottomland hardwood forests. Lakes, ponds, bogs, streams, and rivers are examples of freshwater ecosystems. Marine ecosystems include estuaries, intertidal zones, coral reefs, open ocean and deep ocean valleys and trenches. Experienced ecologists can often infer what types of organisms and environmental conditions are likely to be present at a site by knowing what type of ecosystem is being considered and the geographic location. Understanding the abiotic and biotic components of ecosystems and ecosystem processes is the basis for defining the types of exposures that can occur at contaminated sites. Abiotic factors can include amount of sunlight, average temperature, temperature range, average precipitation and seasonal distribution, and type of soil or sediment. Examples of chemical factors that influence the functioning of ecosystems include soil nutrients, toxic substances, salinity, and dissolved oxygen.

Ecosystem type varies with location based on climatic, topographical, geological, chemical, and biotic factors. Ecosystems also vary in size. For example, a small pond and associated marsh vegetation around the pond periphery can be a distinct ecosystem while other types of aquatic environments such as a large lake, stream, or river are each considered functioning ecosystems. Boundaries between ecosystems are often not obvious and adjoining ecosystems include some shared plant and animal species. A lake and a deciduous forest may share such wildlife as frogs, salamanders, and insect-eating birds. The transition areas between land and water ecosystems are typically wetlands classified as freshwater and saltwater marshes, wet meadows, bogs, and swamps.

1.2 Habitat and Niche

An understanding of a species' habitat is essential in determining its spatial distribution within an ecosystem. Habitat refers to the place or type of place where an organism most commonly occurs. The habitat provides factors necessary for survival of individuals and populations. Examples of important habitat features for animals include cover (i.e., protection from weather extremes and predators), nesting and birthing sites, feeding sites, and denning/hibernation sites. Important habitats from an ecological risk perspective may be habitats that are chemically contaminated and have restricted areal extent or represent important seasonal use areas by large game animals such as white-tailed deer, mule deer, and wild turkeys.

Examples of habitats of limited extent within an ecosystem may include: a spring woodland pond used by amphibians for reproduction; a wooded hillside with rock outcrops used as den sites and cover by copperheads or timber rattlesnakes; and shrub-covered areas on south- facing wooded slopes used by deer as winter bed down areas. In some cases, ecologists consider a particular habitat type to be especially important because it is present in limited amounts within a given area or region. Limited habitat types will vary from one site to another and some areas may not have any habitats that are regionally unique or important. Plant habitat is often defined on the basis of topography and soil conditions. For example, a silver maple stand is common in floodplains of rivers where standing water occurs during at least part of the year. Saguaro cactus, on the other hand, is found on dry rocky slopes and sandy soils within the Sonoran Desert of Arizona, Baja California, and Sonora, Mexico.

An understanding of animal distribution within an ecosystem is based, in part, on familiarity with the structural diversity of vegetation required for all aspects of a species survival and how vegetation is distributed across a landscape. Knowing the amount of fragmented and isolated habitat compared to continuous habitat of a given type in an area is important to the wildlife manager attempting to understand the suitability of an area to sustain viable species population levels, and to resource managers attempting to protect rare or unique biotic communities or habitats of special interest to a State or local community. This understanding is equally important to an ecological risk assessment attempting to determine species of concern and the habitats most likely to be affected by contaminants or site remediation actions. Habitat fragmentation can result in reduction in the total amount of a particular habitat type in an area, and in smaller more isolated patches of habitat that cannot sustain viable species populations. The degree of fragmentation can also influence the movement of wildlife between patches.

The concept of ecological niche is useful in explaining how seemingly similar species can coexist in the same biotic community. Ecological niche is the particular combination of biotic and abiotic factors required by a species to live in any one location.Niche is sometimes thought of as the “role” an organisms fills in the ecosystem. Abiotic factors may include temperature, moisture, soil, pH, or salinity. Biotic factors may include an organisms’s food requirements and the type of habitat with which it is typically associated (e.g., forest, grassland, etc.). The term niche has been used by ecologists to refer to habitat, food, reproductive requirements, and physical and chemical factors related to a species survival.

1.3 Energy and Nutrient Flow Through Ecosystems

In order to understand what an ecological risk assessment should evaluate, it is important to understand the way that energy and materials moves through an ecosystem. This is important because it forms the basis for understanding how ecosystems are balanced, how contaminants will move through an ecosystem, and how ecosystems may be affected by human activities or contaminants.

In terms of energy flow through ecosystems, organisms can be either *producers* or *consumers*. Producers convert energy from the environment into the chemical energy stored in carbon bonds, such as those found in the sugar glucose. Plants are the most obvious examples of producers. Plants use energy from sunlight to convert carbon dioxide and water into glucose (or other sugars) through the process known as photosynthesis. Algae and cyanobacteria (known as blue-green algae) are also photosynthetic producers, like plants.

Consumers cannot generate energy-containing sugars as plants can. Instead, they use a metabolic process called respiration to derive energy from carbon-carbon bonds. When respiration occurs, carbon-carbon bonds are broken and the carbon is combined with oxygen to form carbon dioxide. This process releases the energy, which is either used by the organism (to move its muscles, digest food, excrete wastes, think, etc.) or the energy is lost as heat.

Figure 1.1 shows how energy flows through an ecosystem. Energy "flows" through an ecosystem in the form of carbon-carbon chemical bonds and the solid arrows in Figure

1.1 represent the movement of this energy between trophic levels. Note that all the energy is initially derived from the sun, and that the ultimate fate of all the energy in ecosystems is to be lost as heat. Energy does not recycle.

The flow of inorganic nutrients through the components of the ecosystem is also shown in Figure 1.1. These nutrients are referred to as "inorganic" because they do not contain carbon-carbon chemical bonds. Examples of inorganic nutrients include the phosphorous in teeth, bones, and cellular membranes; the nitrogen in amino acids (the building blocks of protein); and the iron in blood. The movement of inorganic nutrients is represented by the dashed arrows in Figure 1.1. Producers obtain inorganic nutrients from the inorganic nutrient pool, which is usually the soil or water surrounding the plants or algae. Inorganic nutrients are passed from organism to organism as one organism is consumed by another. Ultimately, all organisms die and become detritus, which serves as the food source for decomposers. At this stage, the last of the energy is extracted (and lost as heat) and the inorganic nutrients are returned to the soil or water to be taken up again. The inorganic nutrients are recycled, the energy is not.

1.4 Trophic Levels and Food Webs

The life histories of the biotic components and the patterns of energy and matter flow through ecosystems provide background information that is necessary to analyze the possible exposure and extent of contaminant effects within an ecosystem. Typically, risk assessors will base the evaluation of the potential for contaminants to move through an ecosystem on knowledge about trophic levels and food webs for that ecosystem and will evaluate effects at several different trophic levels.

The term *trophic level* refers to an organism's position in a food chain. Plants are at the base of the food chain and are known as producers. Organisms that eat other organisms are referred to as consumers. Ecologists typically distinguish between four types of consumers, based upon what is being eaten by the consumer (Table 1.1). Organisms that eat plants are called *herbivores* or *primary consumers*. Organisms that eat other animals are referred to as carnivores. The trophic level designation for a carnivore is determined by the trophic level of the animal it eats. An animal that eats a primary consumer is a *secondary consumer*, an animal that eats a secondary consumer is a *tertiary consumer*, and so on. It is important to note that many animals do not specialize in their diets. *Omnivores* (such as humans) eat both animals and plants. In addition, except for some specialists, most carnivores don't limit their diet to organisms of only one trophic level. Frogs, for instance, don't discriminate between herbivorous and carnivorous insects in their diet. If it's the right size, and moving at the right distance, chances are the frog will eat it.

In order to visualize and track the feeding relationships between various organisms, ecologists use food chains and food webs. A food chain describes the transfer of matter and energy from one organism to another organism as one individual eats another or dies and decomposes. Food chains are normally arranged according to trophic levels. An example of a food chain that might be typical for a field ecosystem is shown in Figure 1.2.

In reality, feeding relationships in an ecosystem are more complicated than can be depicted by a simple food chain. While some organisms do specialize in their diets (e.g., anteaters feed exclusively on termites or ants), many organisms do not. For example, hawks don't limit their diets to snakes, snakes eat things other than mice, mice eat grass as well as grasshoppers, and so on. A more realistic representation of feeding relationships in an ecosystem is a food web. An example of a food web for an aquatic ecosystem is shown in Figure 1.3. This figure also identifies trophic levels for the types of organisms indicated, although many of the organisms could be identified as belonging to more than one trophic level. Although decomposers, such as fungi or bacteria, are not shown in Figure 1.3, they could be included in the food web as well.

Note that, Figure 1.3 identifies only general types of organisms for many of the feeding steps (e.g., fish-eating fish). In reality, there are many species that could fall into a particular feeding group. For example, largemouth bass, walleye, or striped bass, are all fish-eating fish. Groups of species with similar feeding modes (or other environmental requirements) are referred to as guilds. Identification of food webs and guilds is important to when designing an ecological risk assessment, because there may actually be a number of potential species that can be used to evaluate the movement and effects of contaminants through particular trophic levels. The selection of the species to be evaluated by a particular ecological risk assessment will depend upon a number of considerations, including availability of information, how representative the species is of the guild or trophic level being evaluated, sensitivity to contaminants, and field sampling difficulties.

An important aspect of the transfer of organic matter and energy from one trophic level to the next is the loss of energy during each transfer. This loss is due to the inability of consumers to fully assimilate the food they eat, and to the dissipation of energy as heat during the chemical breakdown of food that occurs following ingestion. Consequently, only about 10% of the energy at one trophic level is assimilated into the next higher trophic level. This results in a smaller biomass (total amount of biological material) at each successive trophic level (Figure 1.4) and explains why there are fewer predators than prey in ecological systems. This also means that a consumer must ingest a large biomass of food from lower trophic levels in order to acquire sufficient energy to maintain itself. From an ecological risk assessment perspective, this means that consumers will often be exposed to higher doses of contaminants that can accumulate in biological tissues than organisms in lower trophic levels.

1.5 Biogeochemical Cycling

While energy does not cycle through an ecosystem, inorganic nutrients do. The inorganic nutrients cycle through more than the organisms, however. They also enter into the atmosphere, the oceans, the soil, and even rocks. Since these chemicals cycle through both the biological and the geological world, the overall cycles are called biogeochemical cycles. Biogeochemical cycles are essential to continued ecosystem functioning. Nutrients required for normal plant and animal growth are used over and over as they move through the various trophic levels and the physical environment. When environmental contaminants interfere with plant uptake of nutrients and overall plant health, cycling of nutrients through the ecosystem is also affected. Examples of biogeochemical cycles include the hydrologic (water), carbon, and nitrogen cycles.

Figure 1.5 is a simplistic diagram of the water cycle, and illustrates precipitation, storage of water in surface water and groundwater, the evaporation of water into the atmosphere, and the transpiration of water from biota. The hydrologic cycle involves the cycling of water through the environment. The hydrologic cycle begins with solar radiation causing evaporation from the oceans, freshwater bodies, and soils followed by cloud formation. Precipitation over the oceans represents a very short hydrologic cycle. Atmospheric circulation also moves clouds over land, resulting in a more complex pathway for water in the cycle.

Figure 1.6 provides a simple diagram of the carbon cycle. The recycling of carbon between the abiotic and biotic elements of an ecosystem is linked to the flow of energy through photosynthesis and respiration. Carbon is the basic building block of carbohydrates, fats, proteins, DNA, RNA, and other organic compounds needed for life. Most land plants get their carbon by absorbing carbon dioxide gas, which makes up about 0.04% of the atmosphere, through pores in leaves. Phytoplankton (microscopic plants that live in aquatic ecosystems) get their carbon from carbon dioxide that is dissolved in water.

Plants carry out photosynthesis, incorporating the carbon in carbon dioxide into complex organic compounds such as glucose. Cellular respiration in animals, fungi, bacteria, and other organisms, converts the carbon of complex organic compounds back into carbon dioxide for reuse by plants. Other aspects of the carbon cycle involve carbon that is tied up for long periods of time in fossil fuels, as calcium carbonate in sediments, and as carbon dioxide dissolved in the waters of the earth. Burning of carbon-containing fossil fuels and wood and volcanic eruptions are major contributors of carbon dioxide to the atmosphere.

A diagram showing both natural and human activities that influence the nitrogen cycle is shown in Figure 1.7. The nitrogen cycle involves the conversion of gaseous nitrogen in the atmosphere through a process known as nitrification and the conversion of useable nitrogen compounds in the soil back to gaseous nitrogen that is released to the atmosphere through a process called denitrification. Nitrogen is necessary for plant growth and is a key element in the formation of amino acids, the building blocks of proteins. Soil microorganisms and some blue-green algae are the only groups of organisms able to fix or change atmospheric nitrogen into a form that is available for plant use. Bacteria of the genus *Rhizobium* are able to infect plant roots, and act symbiotically with plants to fix nitrogen. Agricultural crops known to support nitrogen-fixing bacteria include legumes such as clover, alfalfa, and soybeans.

As an ecological risk manager it is important to understand how various pathways in biogeochemical cycles may be affected by human activities at your site. The following questions illustrate the types of ecological issues that might be considered in addition to biotic resources when conducting an ecological risk assessment and considering possible remediation options:

- Do contaminant levels at the site affect bacteria responsible for nitrification and denitrification?

- Would pump-and-treat remediation measures for cleaning up groundwater contamination interfere with water levels of ponds, lakes, and marshes that are typically recharged by local groundwater?

1.6 Indicator and Keystone Species

Ecosystem health is often measured by the presence, absence, or abundance of an indicator species in a particular habitat type. An indicator species is a species that has such a narrow range of ecological tolerance that their presence or absence is a good indication of environmental conditions. Their presence does not provide an indication of ecosystem health but a rough indication that the basic ecosystem components necessary to support the species in question are present. Examples of indicator species include the northern spotted owl in old-growth forests of the Pacific Northwest and certain types of insect larvae in aquatic sediments.

Some species are known to have a disproportionately large role in determining the overall community structure within an ecosystem. These species are called keystone species. Removal, addition, or changes in local populations of keystone species can have significant impacts on the functioning of ecosystem processes, predatory relationships, and overall long-term stability. In many ecosystems keystone species cannot be easily defined because the basic knowledge of species requirements is so poorly understood. The role of keystone species is not clearly understood until removal of the species, either artificially or by natural means, has occurred. Consequently, the use of keystone species as monitors of environmental health has limited use in most ecosystems. A classic example of a keystone species is the sea otter (*Enhydra lutris*). The sea otter, preys on sea urchins in large numbers. When sea otter populations were removed by trappers and fishermen sea urchin populations increased dramatically, which led, in turn, to overgrazing of algae and kelp. Entire kelp beds were consumed, which caused declines in important commercial fish species that were dependent on the kelp beds. When sea otters were reintroduced, the kelp beds recovered. Obviously an adverse effect from contaminant exposure on a sea otter population could have significant consequences on an entire ecosystem. Another example of a keystone species is the starfish (*Pisaster ochraceus*), which preys on intertidal invertebrates of rocky habitats along the North American Pacific coast. Experiments where starfish were removed demonstrated their controlling influence on mussels, barnacles, snails and other invertebrates.

Other types of keystone species are important as habitat modifiers. The beaver is an example of a species that can affect the dominant vegetation to such an extent that the entire ecosystem is changed. Beavers remove trees in stream and pond habitats, which can change the surface water and light conditions present in aquatic environments. Flooding can occur in relatively dry areas adjacent to water bodies that changes the mix and abundance of plant species in an area.

1.7 Ecological Stressors

An ecological stressor is any action or material that imposes changes on an ecological system. In order to understand the causes of observed effects at a contaminated site, the types of factors present as stressors need to be defined. Stressors become ecologically significant when they alter population, community, or ecosystem characteristics and function. For example, stressors might affect population size by reducing mating success, reducing egg production, reducing survival of offspring, or reducing survival of reproductive adults. Stressors can also affect population size by changing resistance to disease or parasites or by altering movement of organisms into or out of an area.

At contaminated sites the concern is primarily with chemical factors, although stress from physical and biological forces may also come into play, especially when evaluating remedial alternatives. Stressors can be broadly classified as physical, biological, or chemical.

1.7.1 Physical Stressors

Physical stressors are actions that directly remove or alter habitat. Examples include tilling soil, filling wetlands, or dredging a channel or harbor. Ecosystems are dynamic and possess a certain degree of resilience to recover from disturbances. In fact, natural disturbance is a normal part of ecosystem functioning. Generally, larger and more frequent physical stressors result in more excessive and longer-lasting effects. However, the addition of excessive physical stressors from human activities can sometimes exceed the ability of the ecosystem to rebound. The time required for an area to recover from a physical stressor once it is discontinued will often depend upon the type of ecosystem involved

Aquatic ecosystems are often affected by physical stressors. Erosion from road construction or agricultural activities can create siltation (i.e., sediment buildup) in streams or lakes receiving runoff. Siltation can cause changes to habitat features such as water depth, rooted emergent and submergent rooted plant distribution in a freshwater or saltwater marsh, and loss of refuge or foraging areas for fish fry. Siltation can also result in filling of the interstitial spaces in gravel or cobble materials on the bottoms of water bodies. This can make these areas unsuitable for egg-laying by fishes, can suffocate eggs already present, and reduce or eliminate benthic invertebrates. Water bodies exposed to runoff from soils that are high in clay content can experience increased turbidity for days or weeks after a major rainfall event that, in turn, changes light intensity through the water column. Reduced light penetration can affect a fish's ability to find food and can lower the rate of photosynthesis by aquatic plants.

In addition to disturbing or destroying the immediate habitat(s), activities such as road construction, logging, dredging wetlands, and agriculture can whittle away piecemeal at larger, relatively intact areas. This results in habitat fragmentation. Some species cannot survive if the patch of habitat available to them falls below a certain size, while other species prefer the edges where habitat types change. Thus, habitat fragmentation can result in dramatic changes in community structure by altering the types of species that use fragmented areas. Habitat patches can become so fragmented that they act as islands that isolate populations of species that are unable to traverse inhospitable areas of habitat to interbreed with individuals in other fragments.

Risk assessors should be aware of physical impacts that have occurred at sites, as this may alter the types of evaluations that are conducted. For example, previous activities that removed topsoil from a site will lead to changes in the plant composition and the associated wildlife. It would be inappropriate to conclude that differences between a reference site and the contaminated area are due to contamination alone, unless the effect of the physical alteration of the environment is taken into account. The ecological effects of physical stressors should also be considered when evaluating the effects of remedial alternatives for a site. Removal of soil or trees, filling or dredging of wetlands, and the erosion or siltation impacts of cleanup operations can all have substantial ecological effects that, in some cases, may pose a greater ecological risk than the continued presence of contaminants.

1.7.2 Biological Stressors

Biological stressors are living organisms (including microorganisms), accidentally or purposely introduced into an area or ecosystem that they would not normally inhabit, that cause adverse impacts to existing species. For example, there has been much attention and concern in the Great Lakes and in San Francisco Bay to the introduction of non-native organisms via ballast water of ships. Humans have a long history of introducing species to new locations. Unlike physical or chemical stressors, biological stressors can reproduce, adapt to the new area over time, and spread, often over a large geographic area.

In some situations, introduced species spread through a geographic area rapidly after their introduction, competing with native species for space, food, nesting sites, etc, and sometimes altering the physical elements of existing habitat. Rapid population growth of introduced animals, in the absence of natural predators, can lead to habitat destruction for native species. Accidental releases of the gypsy moth in Massachusetts and the European spruce sawfly in Canada have led to destruction or damage to large areas of forests in the Northeastern United States and Canada. Species of nearly all taxonomic groups have been introduced into new locations around the world. A few notable examples in North America include bacteria used for biological control, Japanese beetles, house sparrow, European starling, Norway rat, Japanese honeysuckle, common ragweed, saltcedar, and purple loosestrife. The purple loosestrife, introduced from Europe, is quickly spreading throughout the U.S. and impacting wetlands. It poses a threat to waterfowl habitat by forming dense stands of plants and crowding out native marsh plants and by impeding normal surface water flow in wetlands.

Knowing the existing biological stressors at a contaminated site and in the vicinity of the site will help risk assessors distinguish the types of impacts related to the chemicals in question compared to effects from introduced species. Information on biological stressors in the area also may provide insight to the stability of species populations or the entire ecosystem that would help to direct potential options or methods for the ecological risk assessment process, including mitigative measures (e.g., planting vegetation to control erosion) for remedial actions.

1.7.3 Chemical Stressors

Chemical stressors include hazardous waste, industrial chemical, pesticides, and fertilizers. Ecological risk assessments are most commonly used for examining chemical stressors under programs such as CERCLA, RCRA, and the CWA. The effects of chemical stressors can be categorized as occurring at the organism, population, community, or ecosystem levels. Examples of the types of effects at each of these organizational levels includes:

- *Organism level* - mortality, behavioral changes, physiological impairment,
- *Population level* – changes in birth rates and mortality rates, increased dispersal, local extinction, and
- *Community* or *ecosystem level* - changes in community structure and functional components, habitat destruction.

The effects of contaminants on ecological systems can be influenced by a variety of environmental factors. These factors can alter the outcome of contamination by chemically changing the contaminant to make it more or less toxic, affecting the bioavailability (see Section 2.1) of the contaminant, and by affecting the tolerance that organisms have for a contaminant. Examples of factors that can affect toxicity include temperature, pH, salinity, water hardness, and soil characteristics. Temperature affects the chemical activity of contaminants and the physiological processes of organisms, thus affecting toxicity. The pH within the soil, surface water, or groundwater can affect the form, reactivity, solubility, and toxicity of some contaminants. The tolerance of organisms to salinity can also be affected by the presence of certain contaminants. Hardness refers to the amount of calcium, magnesium and ferric carbonate in water. Hardness can affect the toxicity of some contaminants, especially many heavy metals. This is why state and Federal water quality criteria and standards are sometimes dependent on hardness, pH, or salinity.

In terrestrial ecosystems, soil characteristics such as clay content and amount of organic matter commonly affects toxicity and bioavailability. In addition, the nature of the soil can affect the mobility of the contaminant to other areas or media.

Effects on individual organisms from exposure to chemical contaminants can range from rapid death through sublethal effects to no observable. In the case of threatened and endangered species, the loss of a few individuals is more likely to be significant because the species is already at critically low levels. Effects become ecologically significant when they affect the survival, productivity, or function of enough individuals so that the population size reaches critically low levels, population structure is altered, or the function of a population is impaired. Contaminant effects may also be ecologically significant if the rates of specific ecological processes, such as decomposition, photosynthesis, or nutrient uptake, are significantly altered.

Population structure can be altered if stressors differentially affect different subgroups in the population (e.g., females affected more than males, young affected more than adults, larval survival reduced)

Community and ecosystem effects occur as a result of changes in the ability of populations to interact. Effects can be reflected as changes in species diversity, the number of trophic levels, or reductions in functions such as production of biomass by plants, or disruption of biogeochemical cycles.

2.0 Ecotoxicology and Ecological Risk Assessment

Ecotoxicology is the study of toxic effects of chemicals on non-human organisms within an ecosystem at the individual, population, or community level (Suter 1993). In order to qualitatively and/or quantitatively evaluate risks posed by contaminants to ecological resources, ecological risk assessments rely heavily upon the field of ecotoxicology. Ecological evaluations of risks from contaminants can also be beneficial in identifying exposure pathways for human populations. Thus, it is important for risk managers to be familiar with basic terminology and concepts from the field of ecotoxicology.

2.1 Bioavailability and Exposure

Ecological exposure to chemical stressors occurs when a chemical reaches an organism and is in a form that is bioavailable. In order to be bioavailable, a chemical must reach a location on or in an organism where it can cause an effect. The degree of bioavailability can be measured through various studies, depending upon the type of contaminant under consideration. The lower the bioavailability, the lower the risk that will be posed by the contaminant. In the absence of bioavailability, there is no exposure and the contaminant will essentially pose no risk to an organism. Keep in mind however, that the degree of bioavailability differs among species and can change under different environmental conditions.

2.2 Bioconcentration, Bioaccumulation and Biomagnification

In order to understand how contaminants travel through the various trophic levels of the ecosystem, the risk assessment team must be knowledgeable of the potential for the chemicals of concern to bioaccumulate. Bioaccumulation refers to the degree to which an organism takes up and retains a contaminant from all applicable exposure routes. Bioaccumulation takes into account that organisms may accumulate contaminants through multiple exposure routes and that the total accumulation will depend upon the rate of intake versus the rate at which the organism is capable of eliminating (through urine or feces) or breaking down the chemical through metabolic processes

Bioconcentration refers to the absorption or uptake of a chemical from the media to concentrations in the organism's tissues that are greater than in surrounding environment. The degree to which a contaminant will concentrate in an organisms is expressed as a bioconcentration factor (BCF), which is defined as the concentration of a chemical in an organism's tissues divided by the exposure concentration. Thus, a BCF of 100 means that the organism concentrates that chemical to a concentration 100 times greater than in the surrounding media. Bioconcentration factors are most commonly applied to aquatic organisms such as fish or aquatic invertebrates. Within a species, bioconcentration factors differ for different chemical compounds. For example, the BCF for the water flea (*Daphnia magna*) for three chemicals is shown in Table 2.1. BCFs also vary among species for the same contaminant and site-specific environmental conditions can affect BCFs. Consequently, the data needed to calculate site-specific BCFs for particular species is collected for some ecological risk assessments. This usually involves analyzing the concentrations of contaminants in an organism's tissues and comparing this to the concentrations of those contaminants in the surrounding media.

Biomagnification refers to the tendency of some chemicals to become increasingly concentrated at successively higher trophic levels of a food chain or food web. As discussed in Section 1.3, producers take up nutrients from the surrounding environment in order to synthesize the complex molecules required for various biological processes. Because the available supply of many nutrients tend to be limited in the environment, plants often utilize considerable energy to actively pump these nutrients into their cells. They may even take up more than immediately needed and store them for future use. Thus, plants often have tissue concentrations of important nutrients that are higher than concentrations in the surrounding media. In some cases, pollutants that are chemically similar to some of these inorganic nutrients are present in the surrounding environment and are taken up and stored in plant tissues as well.

The first step in biomagnification occurs when contaminants are stored in producer tissues at concentration higher than in the surrounding environment. The second stage of biomagnification occurs when the producer is eaten by a consumer. Recall from Section 1.4, that relatively little energy is available from one trophic level to the next. This means that a consumer (of any level) has to consume a lot of biomass from lower trophic levels. If that biomass contains a contaminant, the contaminant will be taken up in large quantities by the consumer. Contaminants that biomagnify have another characteristic. Not only are they taken up by the producers, but they are absorbed and stored in the bodies of the consumers. This often occurs with contaminants that are soluble in fat, such as DDT or PCB's. These materials are digested from the producer and move into the fat of the consumer. If the consumer is eaten by another consumer, its fat is digested and the contaminant is then stored in the tissues of the new consumer. In this way, the contaminant builds up in the fatty tissues of the consumers and the concentration of the contaminant in the tissues of consumers becomes higher with each trophic level. Water-soluble pollutants usually cannot biomagnify in this way because they would dissolve in the bodily fluids of the consumer. Since every organism loses water to the environment, as the water is lost the pollutant would leave as well.

A classic case of biomagnification is that of DDT. During the years that it was used in the U.S., the pesticide DDT caused thinning of eggshells in many birds-of-prey, including hawks and eagles. DDT was present at low concentrations in water due to runoff from agricultural fields. However, DDT is very persistent (long-lived) and accumulates in fats. This resulted in biomagnification in the food chain, beginning with aquatic plants and invertebrates, then moving through fish, and finally to fish-eating birds. The lower doses in lower trophic levels resulted in no observable adverse effects. However, the high doses accumulated by fish-eating birds caused thinning of eggshells and reduced reproductive success, resulting in drastic declines in populations of these species nationwide.

2.3 Toxicity Testing/Endpoints

Toxicity testing is normally carried out under laboratory conditions to measure effects on target organisms exposed to a chemical in various concentrations during a specified time. It is not always possible or appropriate to conduct toxicity tests on species that actually occur at the site. A representative species is typically used as a surrogate for laboratory testing, especially in cases where an endangered species is the species of concern, where no data are available, or proven testing techniques are not known for the species of concern.

On the basis of the types of exposures to chemicals expected to occur at the contaminated site, field laboratory tests may be necessary to determine acute or chronic effects. In cases of acute toxicity exposures may lead to death or extensive impairment of physiological functions and behavior of individual organisms relatively soon (i.e., hours or days) after exposure to contaminants. Chronic toxicity occurs when organisms are exposed to low levels of contaminants over an extended time period (i.e., weeks, months, years).

In addition to considering whether the exposure is chronic or acute, the effects of contaminants can be broadly segregated into lethal and sublethal effects. Lethal effects, as the term implies, refers to direct mortality of exposed individuals. Sublethal refers to adverse effects other than death for exposed individuals. Examples of sublethal effects that may result from chemical exposure include reproductive impairment, reduced rates of growth or photosynthesis, behavioral changes, and increased susceptibility to disease or other environmental stresses (e.g., temperature changes). From an ecological standpoint, many sublethal effects may be as relevant as direct lethality from a contaminant. For example, if a contaminant significantly reduces photosynthesis, the change in plant production may lead to a reduction in organisms in all other trophic levels. Similarly, a contaminant exposure that results in reproductive failure for a given species will likely have drastic population-level effects within a single generation. Thus, an ERA will ultimately need to consider the ecological significance of any toxic effects.

2.4 Dose-Response Relationships

When evaluating possible effects from exposure to chemical contaminants one must carefully evaluate doses likely to be received by individuals throughout their lifetime or at critical periods within their life cycle. Based on toxicity test results one can estimate dose-response relationships for the species being evaluated. It is important to remember that concentration and dose are not synonymous. Concentration refers to the amount of contaminant in a given amount of media (e.g., a surface water concentration for lead could be 10µg/l). Dose refers to the amount of contaminant that an organism is exposed to, usually in amount of contaminant per unit body weight of the organism (e.g., a dose of lead to a bird might be expressed as 5 mg lead/kg body weight). Sometimes, dose is expressed as a dose per unit time (e.g., 5 mg lead/kg body weight/day).

Depending upon whether a particular toxicity test is designed to evaluate the effects of media concentration or the dose received by an organism, two statistics are commonly used to describe the degree of lethality: the median lethal concentration (LC_{50}) or median lethal dose (LD_{50}). These statistics refer to the concentration or dose that kills 50 percent of the exposed test organisms. Similarly, sublethal effects can be statistically described as the median effect concentration (EC_{50}) or median effect dose (ED_{50}). These metrics identify the concentration or dose at which 50% of an exposed population is affected. When comparing the toxicity of contaminants using these statistics, lower values indicate greater toxicity. Figure 2.1 and Figure 2.2 show hypothetical dose responses for sheepshead minnows exposed to contaminants at different concentrations under different exposure durations.

Researchers conducting toxicity tests may also identify chemical concentration (NOAEC) or dose (NOAEL) levels below which there are no adverse effects on the test organisms. The lowest level at which an adverse effect is observed is referred to as the lowest observed adverse effect concentration (LOAEC) or level (LOAEL for doses). Together, a NOAEL and a LOAEL (or NOAEC and LOAEC) describe a range for which effects are unknown. The assumption is that effects begin to occur somewhere within this range. Figure 2.3 depicts a hypothetical NOAEC and LOAEC observed during toxicity testing of sheepshead minnows exposed to different concentrations of a contaminant. Depending on how large the range between the NOAEC and LOAEC is, it may be desireable to conduct additional toxicity tests for an ERA. For example, the uncertainty range for a contaminant with a NOAEC of 10 ppm and a LOAEC of 200 ppm may be unacceptable to the risk assessment team and thus require additional exposure tests to more narrowly identify where effects begin to occur.

Susceptibility to chemical contaminants may differ among various life stages of an organism. Table 2.2 shows the variation in LOAECs for different life stages of fathead minnows exposed to a hypothetical contaminant.

3.0 References

Odum, E. P., 1971. *Fundamentals of Ecology*, W. B. Saunders Company, Philadelphia, PA, 574 p.

Suter, G.W., 1993. *Ecological Risk Assessment*, Lewis Publishers, Boca Raton, 538 p.

Wagner, R. H., 1971. *Environment and Man*, W. W. Norton and Company, Inc., New York, 491p.

Figure 1.1 Energy and Nutrient Transfer Through an Ecosystem

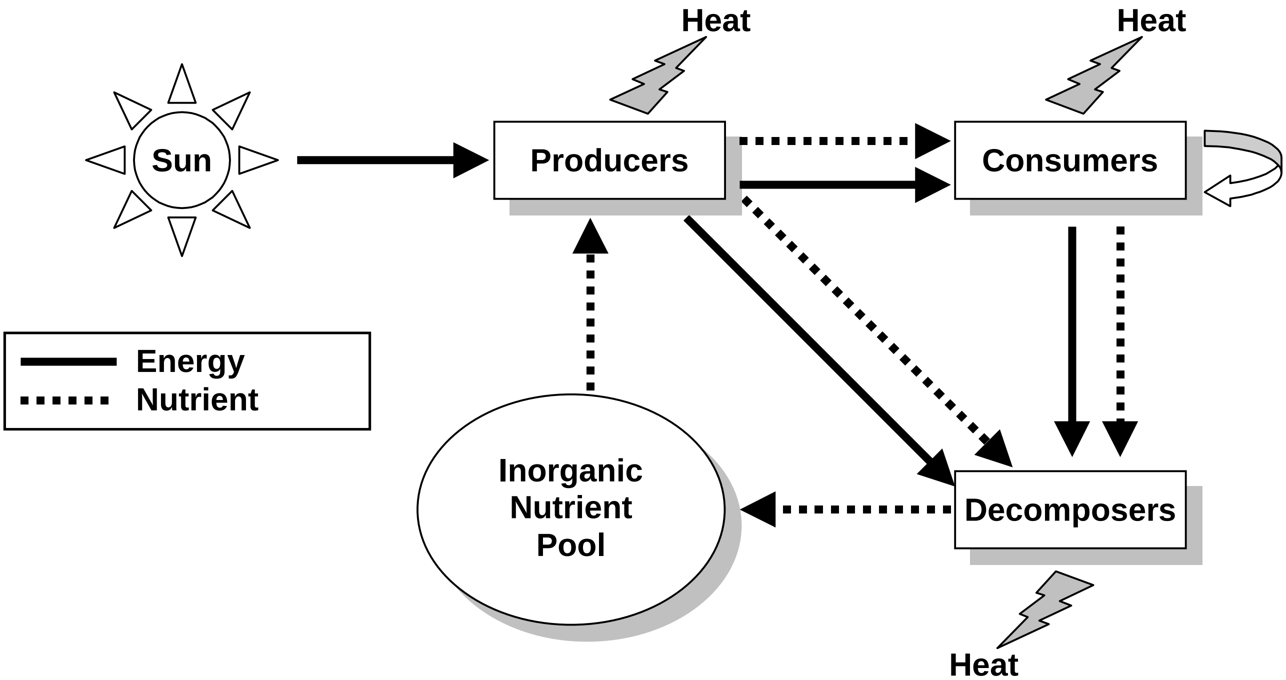
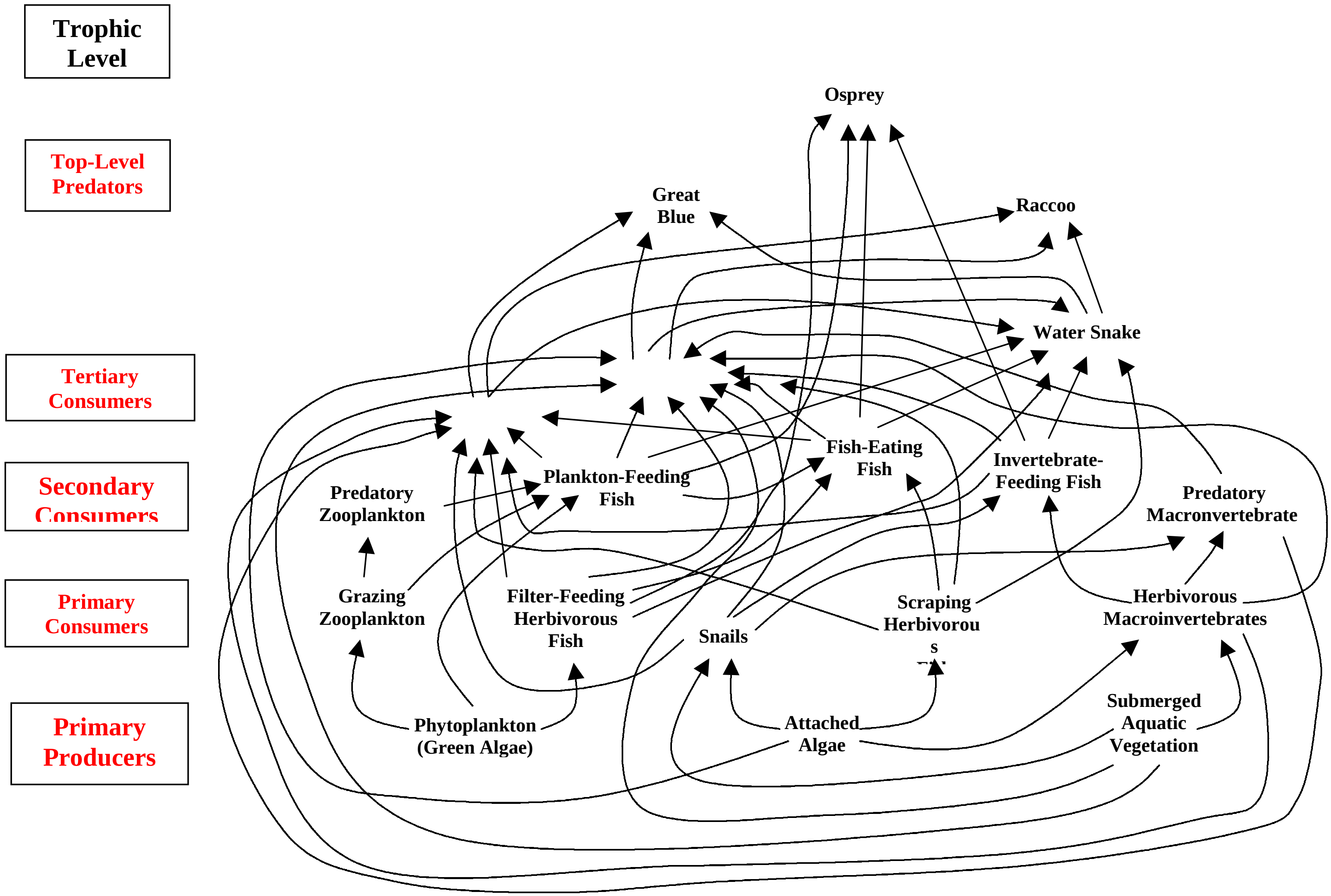


Figure 1.2 Diagrammatic Representation of a Food Chain, Showing Trophic Levels

Vegetation	→	Grasshopper	→	Mouse	→	Snake	→	Hawk
(Primary Producer)		**(Primary Consumer)**		**(Secondary Consumer)**		**(Tertiary Consumer)**		**(Quaternary Consumer)**

Figure 1.3 Example of an Aquatic Food Web



Note that organisms above the primary consumer trophic level often occupy a number of trophic levels. For example, turtles act as primary consumers when they feed on vegetation, secondary consumers when they feed on herbivorous invertebrates and fish, and tertiary consumers when they feed on predatory fish.

Figure 1.4 Pyramid of Biomass, Showing Less Biomass in Successively Higher Trophic Levels

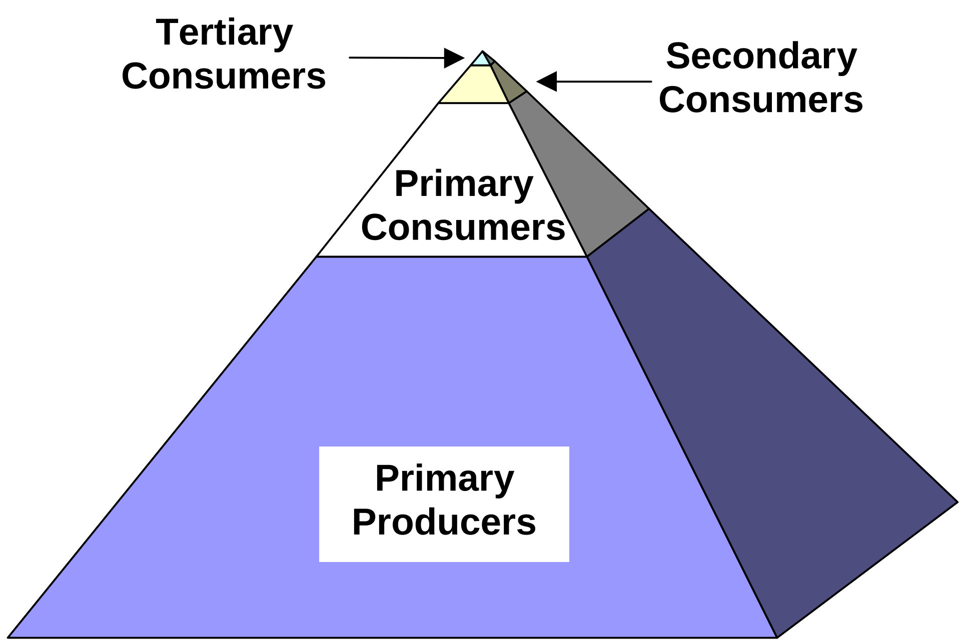


Figure 1.5 The Hydrologic Cycle

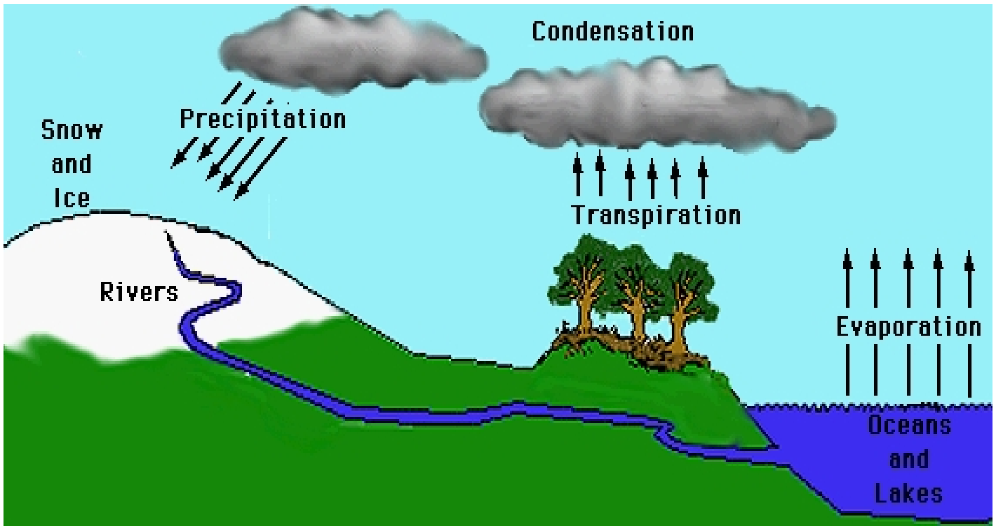


Figure 1.6 The Carbon Cycle

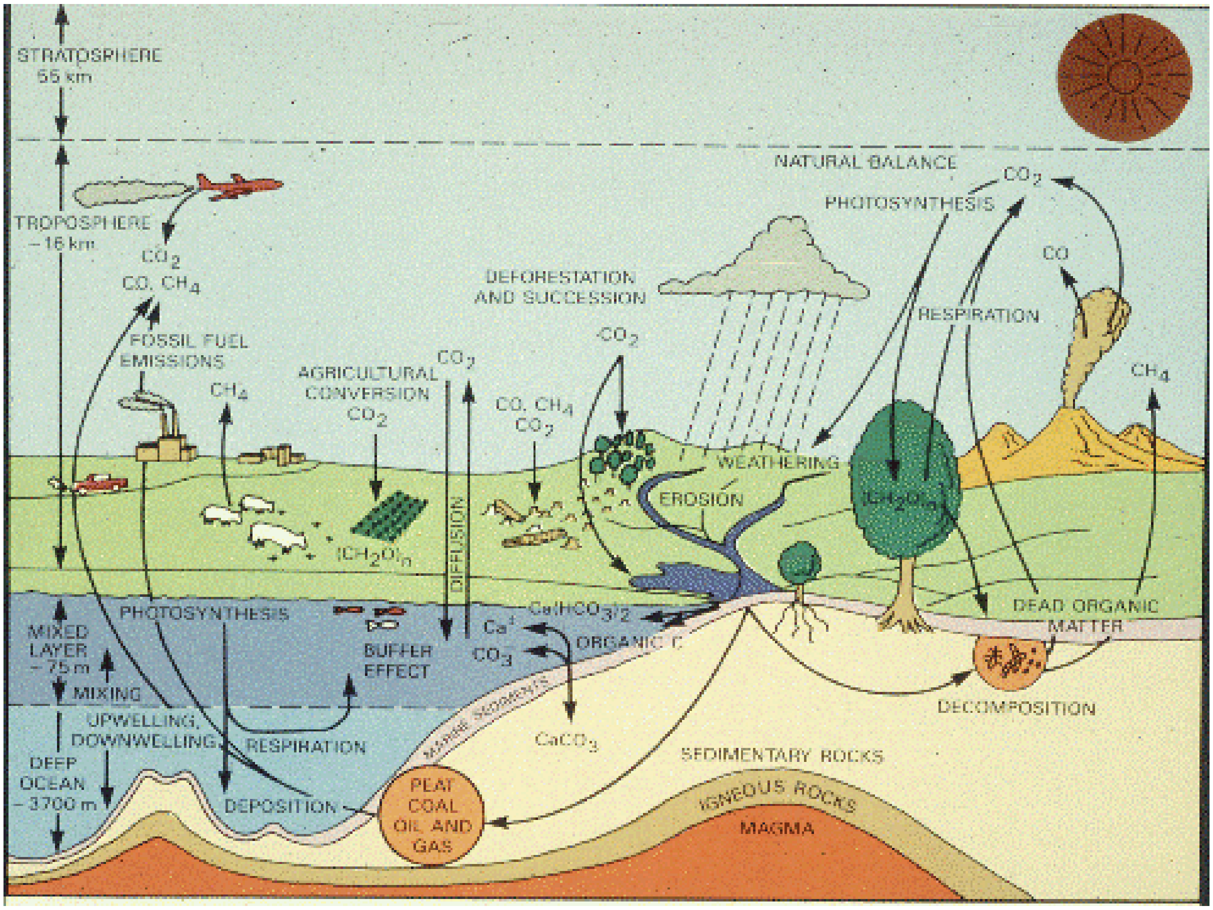


Figure 1.7 The Nitrogen Cycle

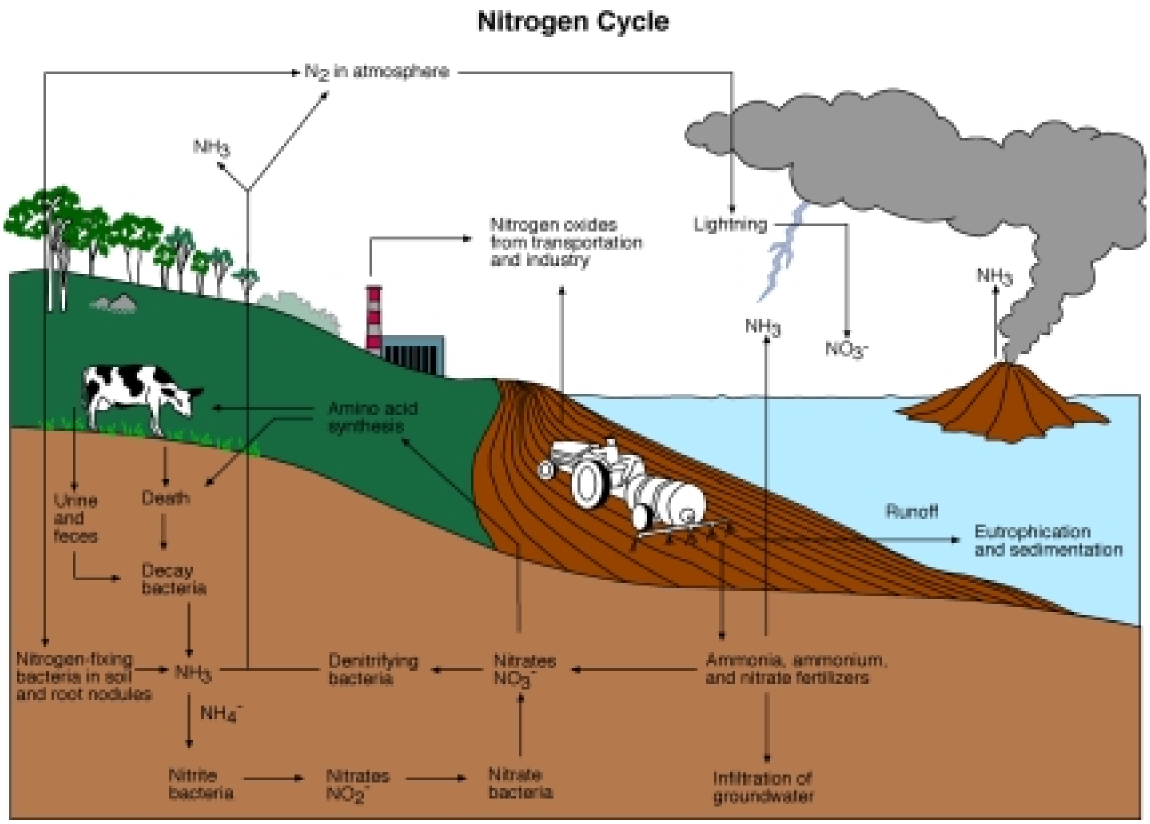


Figure 2.1 Toxicity of a Hypothetical Contaminant to the Sheepshead Minnow in a 48-hour Acute Test

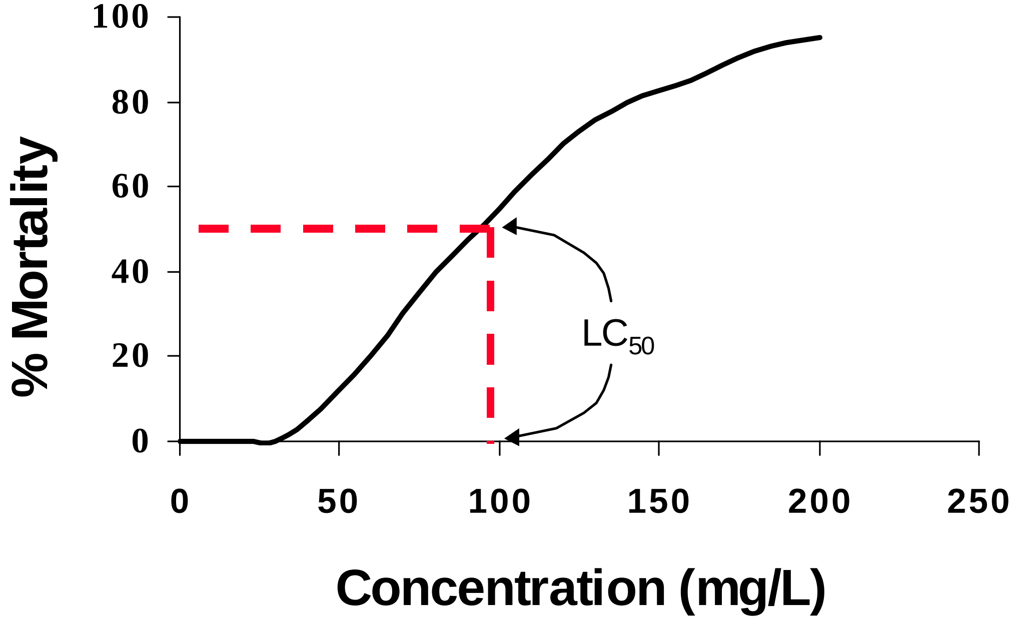


Figure 2.2 Effect of a Hypothetical Contaminant on Egg-laying by Sheepshead Minnows During a 75-day Chronic Test

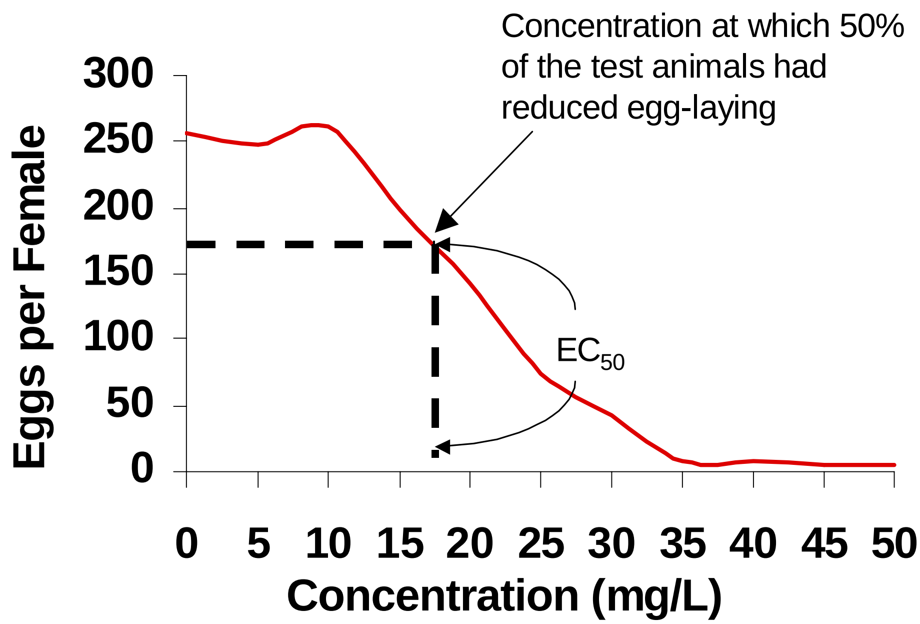


Figure 2.3 Egg-Laying by the Sheepshead Minnow When Exposed to a Hypothetical Contaminant During a 75-Day Exposure, Showing the No Observed Adverse Effect Concentration (NOAEC) and the Lowest Observed Adverse Effect Concentration (LOAEC)

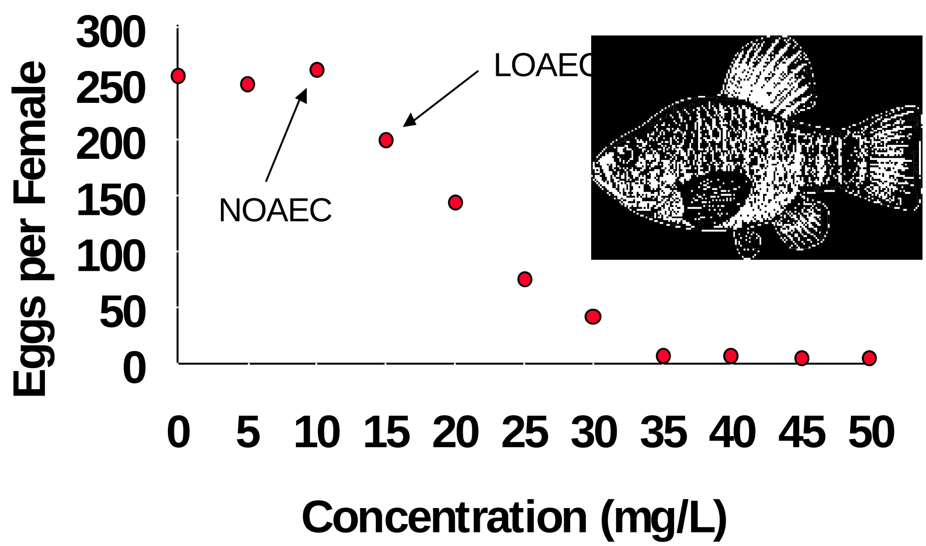


Table 1.1 Consumer types, trophic levels and food sources.

Consumer Type	Trophic Level	Food Source
Herbivores	Primary Consumer	Plants
Carnivores	Secondary or Higher Consumer	Animals
Omnivores	All Levels	Plants & Animals
Detritivores	Secondary or Higher Consumer	Detritus (Plant or Animal Material)

Table 2. 1 Bioconcentration factors in *Daphnia* for 4 chemicals.

Substance	Bioconcentration Factor
Benzo(a)pyrene	12,762
Bis (2-ethylhexyl) phthalate	5,200
Manganese chloride	911

Table 2.2 Lowest Observed Adverse Effect Concentrations (LOAEC) for Different Life Stages of Fathead Minnows Exposed to a Hypothetical Contaminant

Observed Effect	LOAEC (ppm)
Reduced Survival of Fry	9800
Reduced Growth of Fry	8300
Reduced Hatching Success	1760