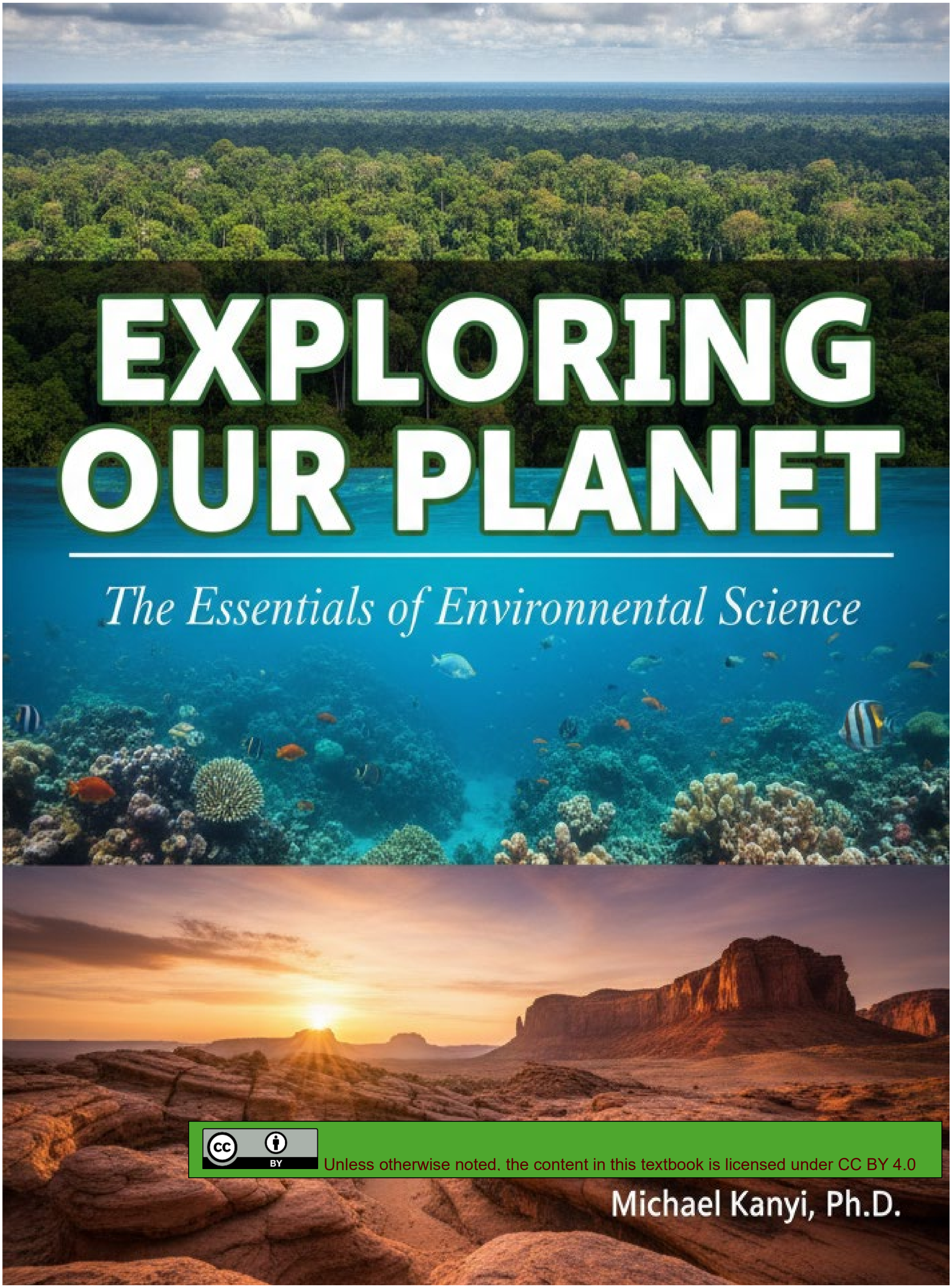

# EXPLORING OUR PLANET

*The Essentials of Environnental Science*



Michael Kanyi, Ph.D.

## Executive Summary

*Exploring Our Planet: The Essentials of Environmental Science* provides a comprehensive exploration of environmental science, emphasizing interdisciplinary approaches to address global ecological challenges. Authored by an expert in the field, the book integrates scientific principles, ecological dynamics, and socio-economic considerations to foster a holistic understanding of sustainability.

The text begins with an introduction to environmental science, outlining its interdisciplinary nature and key concepts such as the IPAT equation and the Tragedy of the Commons. It establishes the importance of studying environmental systems to address pressing issues like resource depletion and biodiversity loss. Chapter Two delves into the scientific foundations, covering matter, energy, thermodynamics, and the scientific method, with a focus on data measurement and machine learning applications in environmental research.

Subsequent chapters explore critical environmental processes and challenges. Chapter Three examines biogeochemical cycles, highlighting human impacts on carbon, nitrogen, phosphorus, and sulfur cycles, and their role in phenomena like eutrophication. Chapter Four addresses biodiversity conservation, detailing species diversity, human health implications, and strategies like protected preserves. Chapter Five focuses on ecosystem dynamics, including energy flow, photosynthesis, food webs, and ecological succession.

The book also tackles the human dimensions of environmental issues. Chapter Six analyzes population ecology, growth models, and demographic transitions, emphasizing factors like fertility and life expectancy. Chapter Seven explores natural resource management, covering renewable and non-renewable resources, desert ecology, and the HIPPCO framework (Habitat destruction, Invasive species, Population growth, Pollution, Climate change, Overexploitation). Chapter Eight investigates agriculture's environmental impact, advocating for sustainable practices like integrated pest management, organic farming, and aeroponics.

Water resources and pollution are the focus of Chapter Nine, addressing groundwater depletion, eutrophication, and the Clean Water Act. Chapter Ten discusses hazardous solid waste management, including recycling, incineration, and regulatory frameworks. Chapter Eleven covers air pollution, climate change, and ozone depletion, detailing greenhouse gas effects, acid rain, and adaptation strategies. Finally, Chapter Twelve examines environmental economics and policies, exploring market failures, externalities, and international agreements like the European Green Deal.

This book is an essential resource for students, researchers, and policymakers, offering a rigorous, data-driven approach to understanding and addressing environmental challenges. It underscores the urgency of sustainable practices and informed policymaking to ensure ecological and human well-being.

## About the Author

Dr. Michael G. Kanyi, a father of two, serves as a tenured Associate Professor and Coordinator of the Agriculture Program at Imperial Valley College (IVC). He holds a Ph.D. in Agricultural Communications and Education from Texas Tech University (2015) and completed postdoctoral research in the same field.

A dedicated member of the Association for International Agricultural and Extension Education (AIAEE), Dr. Kanyi focuses his research on nutrition, food security, agricultural education, and communication. His scholarly contributions appear in prominent peer-reviewed journals, including the *Journal of Nutrition Education and Behavior* and the *International Journal of Agricultural and Extension Education*.

Originally from Kenya, Dr. Kanyi was raised within the traditions of the Presbyterian Church, values he continues to uphold as guiding principles in his personal and professional life. Dr. Kanyi brings over two decades of expertise in teaching agricultural sciences. At IVC, he delivers a diverse curriculum encompassing Plant Science, Soil Science, Environmental Science, Entomology, and Agricultural Sales, while mentoring students transitioning to four-year institutions.

Beyond academia, Dr. Kanyi collaborates with USDA coordinators and plays a pivotal role in the USDA NextGen program, fostering the development of future agricultural leaders. He serves on the Research Advisory Committee at the University of California Desert Research and Extension Center (UC-DREC) and actively secures grants to advance agricultural innovation and education. In 2024, Dr. Kanyi was honored with the Western Region Certified Crop Advisers Honorarium for his outstanding contributions to the field.

# Contents

# Chapter One: Introduction to Environmental and Sustainability

## Objectives

- Define Environmental Science
- Explain sustainability.
- Describe ecology and ecosystem.

## What is environmental science?

**Environmental science** is the dynamic, interdisciplinary study of the interaction of living and non-living parts of the environment, with a special focus on the impact of humans on the environment. The study of environmental science includes the circumstances, objects, or conditions by which an organism or community is surrounded by and the complex ways in which they interact.

**Environmental stewardship** refers to the responsibility for environmental quality shared by all those whose actions affect the environment. This sense of responsibility is a value that can be reflected in the choices of individuals, companies, communities, and government organizations and shaped by unique environmental, social, and economic interests. The term environmental stewardship has been used to refer to such diverse actions as creating protected areas, replanting trees, limiting harvests, reducing harmful activities or pollution, creating community gardens, restoring degraded areas, or purchasing more sustainable products. It is applied to describe strict environmental conservation actions, active restoration activities, and/or the sustainable use and management of resources. Stewardship actions can also be taken at diverse scales, from local to global efforts, and in both rural and urban contexts.

## Environmental Science is Interdisciplinary

Environmental science includes disciplines in the physical sciences (like geology, soil science, physical geography, chemistry, and atmospheric sciences), life sciences (like ecology, conservation biology, restoration biology, and population biology), social sciences (like human geography, economics, law, political science, and anthropology), and humanities (philosophy, ethics). As such, environmental scientists are a diverse bunch. However, they all come together for the focus of studying and identifying past, current, and future environmental issues while also exploring solutions to the environmental issues and considering practical needs.

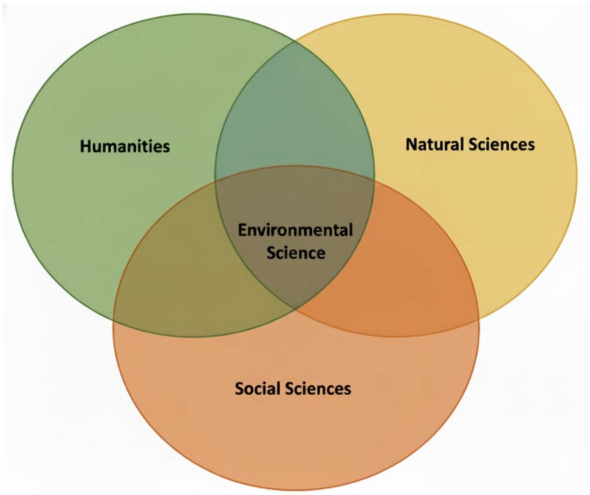


**Figure 1.1** Environmental science as an interdisciplinary between humanities, social sciences, and natural sciences (credit: LibreTexts).

Environmental science is inherently interdisciplinary, acting as a bridge between the natural sciences (physical/life), social sciences, and humanities to understand complex environmental systems and human impacts. It integrates physical, chemical, and biological knowledge with social, ethical, and economic perspectives to create sustainable solutions for global issues.

## The IPAT Equation

One way of measuring progress toward achieving sustainable goals can be through the application of the **IPAT equation**. This equation was designed to define the different ways that a variety of factors contribute to the environmental degradation, or impact, of a particular setting. Importantly, IPAT tells us that there are more ways we impact our environment than just through pollution:

$I = P \times A \times T$

- ***I*** *stand for* the impact on the environment.
- ***P*** is the size of the relevant human population
- ***A*** is the affluence (wealth and consumption) of the population.
- ***T*** is the technology available to the population

## Why Study Environmental Science?

The need for equitable, ethical, and sustainable use of Earth's resources by a global population that nears the carrying capacity of the planet requires us not only to understand how human behaviors affect the environment, but also the scientific principles that govern interactions between living and non-living.

Our future depends on our ability to understand and evaluate evidence-based arguments about the environmental consequences of human actions and technologies, and to make informed decisions based on those arguments.

From global climate change to habitat loss driven by human population growth and development, Earth is becoming a different planet, right before our eyes. The global scale and rate of environmental change are beyond anything in recorded human history. Our challenge is to acquire an improved understanding of Earth's complex environmental systems; systems characterized by interactions within and among their natural and human components that link local to global and short-term to long-term phenomena, and individual behavior to collective action. The complexity of environmental challenges demands that we all participate in finding and implementing solutions leading to long-term environmental sustainability.

## The Tragedy of the Commons

In his essay, The Tragedy of the Commons, Garrett Hardin (1968) looked at what happens when humans do not limit their actions by including the land as part of their ethic. The **tragedy of the commons** develops in the following way: Imagine a pasture open to all (the 'commons'). It is to be expected that each herdsman will try to keep as many cattle as possible on the commons. As rational beings, each herdsman seeks to maximize their gain. Adding more cattle increases their profit, and they do not suffer any immediate negative consequence because the commons are shared by all. The rational herdsman concludes that the only sensible course is to add another animal to their herd, and then another, and so forth.

However, this same conclusion is reached by every rational herdsman sharing the commons. Therein lies the tragedy: each person is locked into a system that compels them to increase their herd, without limit, in a world that is limited. Eventually this leads to the ruination of the commons. In a society that believes in freedom of the commons, freedom brings ruin to all because each person acts selfishly. Hardin went on to apply the situation to modern commons: overgrazing of public lands, overuse of public forests and parks, depletion of fish populations in the ocean, use of rivers as a common dumping ground for sewage and fouling the air with pollution.

The “Tragedy of the Commons” is applicable to what is arguably the most consequential environmental problem: global climate change. The atmosphere is common in which countries are dumping carbon dioxide from the burning of fossil fuels. Although we know that the generation of greenhouse gases will have damaging effects on the entire globe, we continue to burn fossil fuels. As a country, the immediate benefit from the continued use of fossil fuels is seen as a positive component (because of economic growth). All countries, however, will share the negative long-term effects.

**Some Indicators of Global Environmental Stress**

- **Forests** - Deforestation remains a main issue. 1 million hectares of forest were lost every year in the decade 1980-1990. The largest losses of forest area are taking place in the tropical moist deciduous forests, the zone best suited to human settlement and agriculture. Recent estimates suggest that nearly two-thirds of tropical deforestation is due to farmers clearing land for agriculture. There is increasing concern about the decline in forest quality associated with intensive use of forests and unregulated access.
- **Soil** - As much as 10% of the earth’s vegetated surface is now at least moderately degraded. Trends in soil quality and management of irrigated land raise serious questions about longer-term sustainability. It is estimated that about 20% of the world’s 250 million hectares of irrigated land are already degraded to the point where crop production is seriously reduced.
- **Fresh water** - Some 20% of the world’s population lacks access to safe water and 50% lacks access to safe sanitation. If current trends in water use persist, two-thirds of the world’s population could be living in countries experiencing moderate or high-water stress by 2025.
- **Marine fisheries** - 25% of the world’s marine fisheries are being fished at their maximum level of productivity and 35% are overfished (yields are declining). To maintain current per capita consumption of fish, global fish harvests must be increased; much of the increase might come through aquaculture which is a known source of water pollution, wetland loss and mangrove swamp destruction.
- **Biodiversity** is increasingly coming under threat from development, which destroys or degrades natural habitats, and from pollution from a variety of sources. The first comprehensive global assessment of biodiversity put the total number of species at close to 14 million and found that between 1% and 11% of the world’s species may be threatened by extinction every decade. Coastal

ecosystems, which host a very large proportion of marine species, are at great risk with perhaps one-third of the world's coasts at high potential risk of degradation and another 17% at moderate risk.

- **Atmosphere.** The Intergovernmental Panel on Climate Change has established that human activities are having a discernible influence on global climate. $CO_2$ emissions in most industrialized countries have risen during the past few years and countries generally failed to stabilize their greenhouse gas emissions at 1990 levels by 2000 as required by the Climate Change convention.
- **Toxic chemicals.** About 100,000 chemicals are now in commercial use and their potential impacts on human health and ecological function represent largely unknown risks. Persistent organic pollutants are now so widely distributed by air and ocean currents that they are found in the tissues of people and wildlife everywhere; they are of particular concern because of their high levels of toxicity and persistence in the environment.
- **Hazardous waste.** Pollution from heavy metals, especially from their use in industry and mining, is also creating serious health consequences in many parts of the world. Incidents and accidents involving uncontrolled radioactive sources continue to increase, and risks are posed by the legacy of contaminated areas left from military activities involving nuclear materials.
- **Domestic and industrial waste.** Domestic and industrial waste production continues to increase in both absolute and per capita terms, worldwide. In the developed world, per capita waste generation has increased threefold over the past 20 years; in developing countries, it is highly likely that waste generation will double during the next decade. The level of awareness regarding the health and environmental impacts of inadequate waste disposal remains rather poor; poor sanitation and waste management infrastructure is still one of the principal causes of death and disability for the urban poor.

The word **environment** describes living and non-living surroundings relevant to organisms. It incorporates physical, chemical, and biological factors and processes that determine the growth and survival of organisms, populations, and communities. All these components fit within the ecosystem concept to organize all the factors and processes that make up the environment. The ecosystem includes organisms and their environment within a specific area. Review the previous section for in-depth information regarding the Earth's ecosystems. Today, human activities influence all the Earth's ecosystems.

**Environmental science** studies all aspects of the environment in an **interdisciplinary** way. This means that it requires knowledge of various other subjects, including biology, chemistry, physics, statistics, microbiology, biochemistry, geology, economics, law, sociology, etc. It is a relatively new field of study that has evolved from the integrated use of many disciplines.

**Environmental engineering** is one of the fastest growing and most complex disciplines of engineering. Environmental engineers solve problems and design systems using knowledge of environmental concepts and ecology, thereby providing solutions to various environmental problems.

**Environmentalism**, in contrast, is a social movement through which citizens are involved in activism to further the protection of environmental landmarks and natural resources. This is not a field of science but incorporates some aspects of environmental knowledge to advance conservation and sustainability efforts.

**Sustainability** is derived from two Latin words: *sus* which means up, and *tenere* which means to hold. It is essentially the ability and potential of a resource to satisfy the present needs without compromising the ability of future generations to meet their needs.

There are three dimensions that sustainability seeks to integrate: economic, environmental, and social (including sociopolitical).

- Economic interests define the framework for making decisions, the flow of financial capital, and the facilitation of commerce, including the knowledge, skills, competences and other attributes embodied in individuals that are relevant to economic activity.
- Environmental aspects recognize the diversity and interdependence within living systems, the goods and services produced by the world's ecosystems, and the impacts of human waste.
- Social/Socio-political refers to interactions between institutions/firms and people, functions expressive of human values, aspirations and well-being, ethical issues, and decision-making that depends upon collective action.

The intersection of social and economic elements can form the basis of social "equitability." In the sense of enlightened management, "viability" is formed through consideration of economic and environmental interests. Between environment and social elements lies "bearability," the recognition that the functioning of societies is dependent on environmental resources and services. At the intersection of all three of these lies sustainability (Figure 1.2).

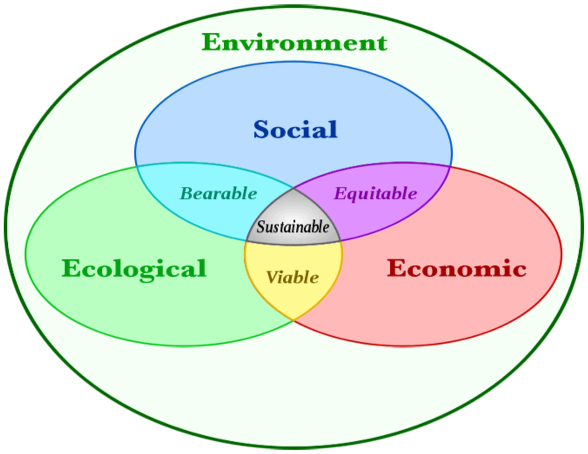


**Figure 1.2** Three dimensions that determine environmental sustainability (credit: Nicoguaro on Wikimedia Commons, Creative Commons Attribution 4.0)

The three main elements of the sustainability paradigm are thought of as equally important, however, tradeoffs occur depending on the local/global objective. For example, in some instances, it may be deemed necessary to degrade a particular ecosystem to facilitate commerce, or food production, or housing. The extent to which tradeoffs can be made before irreversible damage results is not always known, and in any case, there are definite limits on how much substitution among the three elements is wise (to date, humans have treated economic development as the dominant one of the three). This has led to the notion of strong sustainability, where tradeoffs among natural, human, and social capital are not allowed or are very restricted, and weak sustainability, where tradeoffs are unrestricted or have few limits. Whether or not one follows the strong or weak form of sustainability, it is important to understand that while economic and social systems are human creations, the environment is not. Rather, a functioning environment underpins both society and the economy.

## Concepts in Environmental Science

### *The Ecological Footprint*

The Ecological Footprint (EF), developed by Canadian ecologist and planner William Rees, is basically an accounting tool that uses land as the unit of measurement to assess per capita consumption, production, and discharge needs. It starts from the elementary assumption that ‘every category of energy and material consumption and waste discharge requires the productive or absorptive capacity of a finite area of land or water. If we (add up) all the land requirements for all categories of consumption and waste discharge by a defined population, the total area represents the Ecological Footprint of that population on Earth whether this area coincides with the population's home region.

Land is used as the unit of measurement for the simple reason that 'Land area not only captures planet Earth's finiteness, but it can also be seen as a proxy for numerous essential life support functions from gas exchange to nutrient recycling, land supports plants that are responsible for photosynthesis, the energy conduit for the web of life. Photosynthesis sustains all important food chains and maintains the structural integrity of ecosystems. Although the size of an Ecological Footprint, also termed Appropriated Carrying Capacity (ACC) would vary according to socioeconomic and technological factors one point is constant: the flows and capacities 'occupied' by one population are not available for another as these resources are finite. What does the Ecological Footprint tell us? Ecological footprint analysis can tell us in a vivid, ready-to-grasp manner how much of the Earth's environmental functions are needed to support human activities. It also makes visible the extent to which consumer lifestyles and behaviors are ecologically sustainable calculated that the Ecological Footprint of the average

American is conservatively, 5.1 hectares per capita of productive land. With roughly 7.4 billion hectares of the planet's total surface area of 51 billion hectares available for human consumption, if the current global population were to adopt American consumer lifestyles, we would need two additional planets to produce the resources, absorb the wastes, and provide general life support functions.

Ecological footprints have been calculated for numerous nations, cities, communities, and even individuals. The London-based IIED has calculated that London's ecological footprint is 120 times the size of the city. The footprint of the average Dutch person is slightly less at 3.3 hectares per capita but still import 'land services' fifteen times the territory of the Netherlands itself. The message of the ecological footprint is that lifestyles and behavior, industrial production and trade, institutions and politics must change. Humanity must learn to live off the income of the 'natural capital' and maintain natural stocks rather than continuing to mine them. Wackernagel and Rees suggest that one way would be to focus 'more on living locally than on consuming globally.

# Chapter Two: Scientific Principles of Matter, Energy and Scientific Method

## Learning Outcomes

After studying this chapter, you should be able to:

- Describe matter and elements.
- Describe the ways in which carbon is critical to life
- Explain energy and the different forms of energy.
- Describe the roles of cells in organisms.

## Matter

At its most fundamental level, life is made up of **matter**. Matter occupies space and has mass. All matters are composed of elements, substances that cannot be broken down or transformed chemically into other substances. Each element is made of atoms, each with a constant number of protons and unique properties. A total of 118 elements have been defined; however, only 92 occur naturally, and fewer than 30 are found in living cells. The remaining 26 elements are unstable and, therefore, do not exist for very long or are theoretical and have yet to be detected. Each element is designated by its chemical symbol (such as H, N, O, C, and Na) and possesses unique properties. These unique properties allow elements to combine and to bond with each other in specific ways.

An **atom** is the smallest component of an element that retains all the chemical properties of that element. For example, one hydrogen atom has all the properties of the element hydrogen, such as it exists as a gas at room temperature, and it bonds with oxygen to create a water molecule. Hydrogen atoms cannot be broken down into anything smaller while still retaining the properties of hydrogen. If a hydrogen atom were broken down into subatomic particles, it would no longer have the properties of hydrogen. At the most basic level, all organisms are made of a combination of elements. They contain atoms that combine to form molecules. In multicellular organisms, such as animals, molecules can interact to form cells that combine to form tissues, which make up organs. These combinations continue until entire multicellular organisms are formed.

At the most basic level, all organisms are made of a combination of **elements**. They contain atoms that combine to form **molecules**. In multicellular organisms, such as animals, molecules can interact to form cells that combine to form tissues, which make up organs. These combinations continue until entire multicellular organisms are formed. All atoms contain protons, electrons, and neutrons. The only exception is hydrogen (H), which is made of one proton and one electron. A **proton** is a positively charged particle that resides in the nucleus (the core of the atom) of an atom and has a mass of 1 and a charge of +1. An **electron** is a negatively charged particle that travels in space around the nucleus. In other words, it resides outside of the nucleus. It has a negligible mass and has a charge of –1.

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**Key properties of Helium**:

- Second-lightest and second-most abundant element in the universe
- Inert noble gas – does not react with other elements under normal conditions
- Lowest boiling point of any element (−268.9 °C), remains liquid even at absolute zero under normal pressure
- Used in cryogenics, balloons, deep-sea breathing mixtures (heliox), and as a coolant for superconducting magnets (e.g., in MRI machines)

Figure 2.1 shows the basic structure of Helium

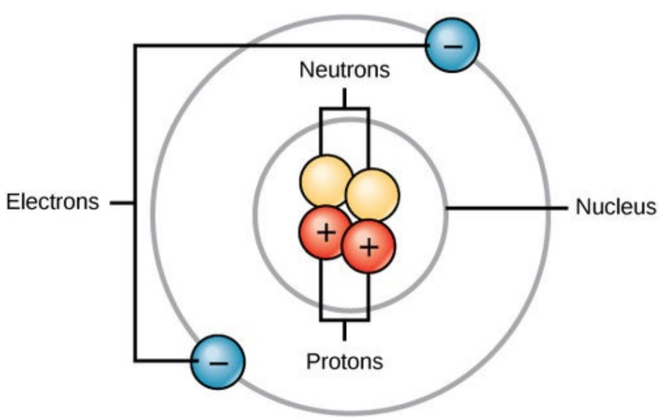


**Figure 2.1** Basic structure diagram showing the classic Bohr-type model of a helium atom. (credit: uen.pressbooks.pub). Atoms are made up of protons and neutrons located within the nucleus, and electrons surrounding the nucleus.

**Neutrons**, like protons, reside in the nucleus of an atom. They have a mass of 1 and no charge.

The positive (protons) and negative (electrons) charges balance each other in a neutral atom, which has a net zero charge. Each element contains a different number of protons and neutrons, giving it its own atomic number and mass number.

The **atomic number** of an element is equal to the number of protons that element contains.

The **mass number** is the number of protons plus the number of neutrons of that element. Therefore, it is possible to determine the number of neutrons by subtracting the atomic number from the mass number.

**Isotopes** are different forms of the same element that have the same number of protons, but a different number of neutrons. Some elements, such as carbon, potassium, and uranium, have naturally occurring isotopes. Carbon-12, the most common isotope of carbon, contains six protons and six neutrons. Therefore, it has a mass number of 12 (six protons and six neutrons) and an atomic number of 6 (which makes it carbon). Carbon-14 contains six protons and eight neutrons. Therefore, it has a mass of 14 (six protons and eight neutrons) and an atomic number of 6, meaning it is still the element carbon. These two alternate forms of carbon are isotopes. Some isotopes are unstable and will lose protons, other subatomic particles, or energy to form more stable elements. These are called **radioactive isotopes** or radioisotopes.

### Half-life and Decomposition

**Carbon dating**

Carbon-14 (14C) is a naturally occurring radioisotope that is created in the atmosphere by cosmic rays. This is a continuous process, so more 14C is always being created. As a living organism develops, the relative level of 14C in its body is equal to the concentration of 14C in the atmosphere. When an organism dies, it is no longer ingesting 14C, so the ratio will decline. 14C decays to 14N by a process called beta decay; it gives off energy in this slow process. After approximately 5,730 years, only one-half of the starting concentration of 14C will have been converted to 14N. The time it takes for half of the original concentration of an isotope to decay to its more stable form is called its half-life.

Because the half-life of 14C is long, it is used to age formerly living objects, such as fossils. Using the ratio of the 14C concentration found in an object to the amount of 14C detected in the atmosphere, the amount of the isotope that has not yet decayed can be determined. Based on this amount, the age of the fossil can be calculated to about 50,000 years. Isotopes with longer half-lives, such as potassium-40, are used to calculate the ages of older fossils. Carbon dating can be used to reconstruct the ecology of organisms living within the past 50,000 years.

**Figure 2.2** Fossil excavated for carbon dating.

The age of remains that contain carbon and are less than about 50,000 years old, such as this pygmy mammoth, can be determined using carbon dating. (credit: Bill Faulkner/ NPS)

## Chemical bonds

How elements interact with one another depends on how their electrons are arranged and how many openings for electrons exist at the outermost region where electrons are present in an atom. Electrons exist at energy levels that form shells around the nucleus. The closest shell can hold up to two electrons. The closest shell to the nucleus is always filled first, before any other shell can be filled. Hydrogen has one electron; therefore, it has only one spot occupied within the lowest shell. Helium has two electrons; therefore, it can completely fill the lowest shell with its two electrons. If you look at the periodic table, you will see that hydrogen and helium are the only two elements in the first row. This is because they only have electrons in their first shell. Hydrogen and helium are the only two elements that have the lowest shell and no other shells.

Not all elements have enough electrons to fill their outermost shells, but an atom is at its most stable when all the electron positions in the outermost shell are filled. Because of these vacancies in the outermost shells, we see the formation of chemical bonds, or interactions between two or more of the same or different elements that result in the formation of molecules. To achieve greater stability, atoms will tend to completely fill their outer shells and will bond with other elements to accomplish this goal by sharing electrons, accepting electrons from another atom, or donating electrons to another atom. Because the outermost shells of the elements with low atomic numbers (up to calcium, with atomic number 20) can hold eight electrons, this is referred to as the octet rule. An element can donate, accept, or share electrons with other elements to fill its outer shell and satisfy the octet rule.

When an atom does not contain equal numbers of protons and electrons, it is called an **ion**. Because the number of electrons does not equal the number of protons, each ion has a net **charge**. Positive ions are formed by losing electrons and are called **cations**. Negative ions are formed by gaining electrons and are called **anions**. Elemental anionic names are changed to end in -ide. For example, sodium only has one electron in its outermost shell. It takes less energy for sodium to donate that one electron than it does to accept seven more electrons to fill the outer shell. If sodium loses an electron, it now has 11 protons and only 10 electrons, leaving it with an overall charge of +1. It is now called a sodium ion.

**Ionic** and **covalent bonds** are strong bonds or interactions that require a larger energy input to break apart. When an element donates an electron from its outer shell, as in the sodium atom example above, a positive ion is formed. The element accepting the electron is now negatively charged. Because positive and negative charges attract, these ions stay together and form an **ionic bond**, or a bond between ions. The elements bond together with the electron from one element staying predominantly with the other element.

Another type of strong chemical bond between two or more atoms is a **covalent bond**. These bonds form when an electron is shared between two elements and are the strongest and most common form of chemical bond in living organisms. Covalent bonds form between the elements that make up the biological molecules in our cells. Unlike ionic bonds, covalent bonds do not dissociate in water. The hydrogen and oxygen atoms that combine to form water molecules are bound together by covalent bonds. The electron from the hydrogen atom divides its time between the outer shell of the hydrogen atom and the incomplete outer shell of the oxygen atom. To completely fill the outer shell of an oxygen atom, two electrons from two hydrogen atoms are needed, hence the subscript “2” in $H_2O$. The electrons are shared between the atoms, dividing their time between them to “fill” the outer shell of each. This sharing is a lower energy state for all the atoms involved than if they existed without their outer shells filled.

When polar covalent bonds containing a hydrogen atom form, the hydrogen atom in that bond has a slightly positive charge. This is because the shared electron is pulled more strongly toward the other element and away from the hydrogen nucleus. Because the hydrogen atom is slightly positive (δ+), it will be attracted to neighboring negative partial charges (δ–). When this happens, a weak interaction occurs between the δ+ charge of the hydrogen atom of one molecule and the δ– charge of the other molecule. This interaction is called a **hydrogen bond**. This type of bond is common; for example, the liquid nature of water is caused by the hydrogen bonds between water molecules. Hydrogen bonds give water the unique properties that sustain life. If it were not for hydrogen bonding, water would be a gas rather than a liquid at room temperature.

## Properties of water

**Water is crucial to sustaining life**

Do you ever wonder why scientists spend time looking for water on other planets? It is because water is essential to life; even minute traces of it on another planet can indicate that life could or did exist on that planet. Water is one of the more abundant molecules in living conditions and the one most critical to life as we know it. Approximately 60–70 percent of your body is made up of water. Without it, life simply would not exist.

- **The water is polar.** The hydrogen and oxygen atoms within water molecules form polar covalent bonds. The shared electrons spend more time associated with the oxygen atom than they do with hydrogen atoms. There is no overall charge to a water molecule, but there is a slight positive charge on each hydrogen atom and a slight negative charge on the oxygen atom. Because of these charges, the slightly positive hydrogen atoms repel each other and form the unique shape. Each water molecule attracts other water molecules because of the positive and negative charges in the different parts of the molecule. Water also attracts other polar molecules (such as sugars) that can dissolve in water and are referred to as hydrophilic ("water-loving").
- **Water stabilizes temperature.** The hydrogen bonds in water allow it to absorb and release heat energy more slowly than many other substances. Temperature is a measure of the motion (kinetic

energy) of molecules. As the motion increases, energy is higher and thus the temperature higher. Water absorbs a great deal of energy before its temperature rises. Increased energy disrupts the hydrogen bonds between water molecules. Because these bonds can be created and disrupted rapidly, water absorbs an increase in energy and temperature changes only minimally. This means that water moderates temperature changes within organisms and in their environments.

- **Water is an excellent solvent.** Because water is polar, with slightly positive and negative charges, ionic compounds and polar molecules can readily dissolve in it. Water is, therefore, what is referred to as a solvent—a substance capable of dissolving another substance. The charged particles will form hydrogen bonds with a surrounding layer of water molecules.
- **Water is cohesive.** Have you ever filled up a glass of water to the very top and then slowly added a few more drops? Before it overflows, the water forms a dome-like shape above the rim of the glass. This water can stay above the glass because of the property of cohesion. In cohesion, water molecules are attracted to each other (because of hydrogen bonding), keeping the molecules together at the liquid-air (gas) interface, although there is no more room in the glass. Cohesion gives rise to surface tension, the capacity of a substance to withstand rupture when placed under tension or stress. When you drop a small scrap of paper onto a droplet of water, the paper floats on top of the water droplet, although the object is denser (heavier) than the water. This occurs because of the surface tension that is created by water molecules. Cohesion and surface tension keep the water molecules intact and the item floating on the top. It is even possible to "float" a steel needle on top of a glass of water if you place it gently, without breaking the surface tension. These cohesive forces are also related to the water's property of adhesion, or the attraction between water molecules and other molecules. This is observed when water "climbs" up a straw placed in a glass of water. You will notice that the water appears to be higher on the sides of the straw than in the middle. This is because the water molecules are attracted to the straw and therefore adhere to it. Cohesive and adhesive forces are important for sustaining life. For example, because of these forces, water can flow up from the roots to the tops of plants to feed the plant.

## Buffers, pH, Acids, and Bases

The pH of a solution is a measure of its **acidity** or **alkalinity**. The pH scale ranges from 0 to 14. A change of one unit on the pH scale represents a change in the concentration of hydrogen ions by a factor of 10, a change in two units represents a change in the concentration of hydrogen ions by a factor of 100. Thus, small changes in pH represent large changes in the concentrations of hydrogen ions. Pure water is neutral. It is neither acidic nor basic and has a pH of 7.0. Anything below 7.0 (ranging from 0.0 to 6.9) is acidic, and anything above 7.0 (from 7.1 to 14.0) is alkaline. The blood in your veins is slightly alkaline (pH = 7.4). The environment in your stomach is highly acidic (pH = 1 to 2). Orange juice is mildly acidic (pH = approximately 3.5), whereas baking soda is basic (pH = 9.0). Acids are substances that provide hydrogen ions ($H^+$) and lower pH, whereas bases provide hydroxide ions ($OH^-$) and raise pH. The stronger the acid, the more readily it donates $H^+$. For example, hydrochloric acid and lemon juice are very acidic and readily give up $H^+$ when added to water. Conversely, bases are those substances that readily donate $OH^-$. The $OH^-$ ions combine with $H^+$ to produce water, which raises a substance's pH. Sodium hydroxide and many household cleaners are very alkaline and give up $OH^-$ rapidly when placed in water, thereby raising the pH.

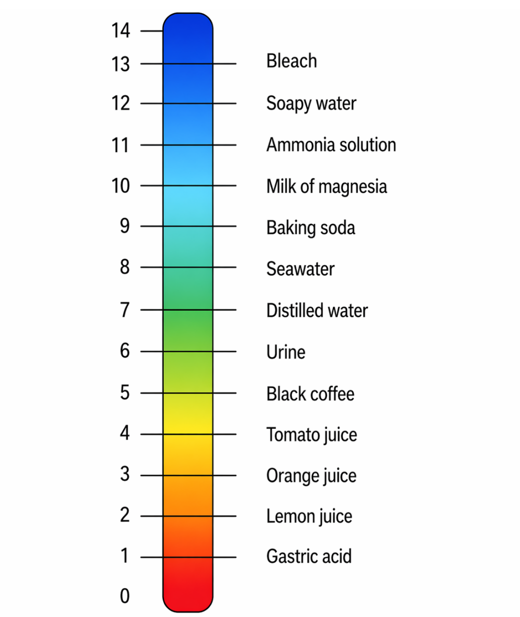


**Figure 2.3**. Common liquids and their ideal pH.  It illustrates the ideal pH of common liquids ranges from gastric acid (pH 1) to the acidic end, here signified by red, through bleach (pH 13) at the basic end, here signified by the color blue. In between are soapy water (12), ammonia solution (11), milk of magnesia (10), baking soda (9), seawater (9), distilled water (7), urine (6), black coffee (5), tomato juice (4), orange juice (3), and lemon juice (2). The color contrast is important to differentiate the liquids in

the pH spectrum. The pH scale ranges from 1.0 to 14.0 (credit: modification of work by Edward Stevens)

The pH scale measures the amount of hydrogen ions ($H^+$) in a substance.
How is it that we can ingest or inhale acidic or basic substances and not die? **Buffers** are the key. Buffers readily absorb excess $H^+$ or $OH^–$, keeping the pH of the body carefully maintained in the narrow range. Carbon dioxide is part of a prominent buffer system in the human body; it keeps the pH within the proper range. This buffer system involves carbonic acid ($H_2CO_3$) and bicarbonate ($HCO_3^–$) anion. If too much H+ enters the body, bicarbonate will combine with the $H^+$ to create carbonic acid and limit the decrease in pH. Likewise, if too much $OH^–$ is introduced into the system, carbonic acid will combine with it to create bicarbonate and limit the increase in pH. While carbonic acid is an important product in this reaction, its presence is fleeting because carbonic acid is released from the body as carbon dioxide gas each time we breathe. Without this buffer system, the pH in our bodies would fluctuate too much and we would fail to survive.

## Biological Molecules

The large molecules necessary for life that are built from smaller organic molecules are called **biological macromolecules**. There are four major classes of biological macromolecules (**carbohydrates**, **lipids**, **proteins**, and nucleic **acids**), and each is an important component of the cell and performs a wide array of functions. Combined, these molecules make up most of a cell's mass. Biological macromolecules are organic, meaning that they contain carbon. In addition, they may contain hydrogen, oxygen, nitrogen, phosphorus, sulfur, and additional minor elements.

## Carbon

**Carbon** is one of the abundant elements in living organisms. It is often said that life is "carbon-based." This means that carbon atoms, bonded to other **carbon** atoms or other elements, form the fundamental components of many, if not most, of the molecules found uniquely in living things. Other elements play important roles in biological molecules, but carbon certainly qualifies as the "foundation" element for molecules in living things. It is the bonding properties of carbon atoms that are responsible for their important role.

### *Carbon bonding*

Carbon contains four electrons in its outer shell. Therefore, it can form four covalent bonds with other atoms or molecules. The simplest organic carbon molecule is methane ($CH_4$), in which four hydrogen atoms bind to a carbon atom. A methane molecule ($CH_4$) consists of one central carbon atom covalently bonded to four hydrogen atoms, forming a tetrahedral shape with 109.5° bond angles, and is the simplest alkane, making up the primary component of natural gas and acting as a potent greenhouse gas.

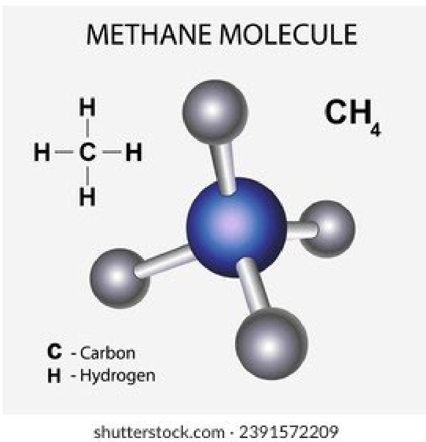


**Figure 2.4** Methane molecule (credit: Shutterstock.com).

Carbon can form four covalent bonds to create an organic molecule. Methane ($CH_4$) is considered the simplest carbon compound and molecule because it is the smallest possible stable hydrocarbon, featuring a single carbon atom bonded to four hydrogen atoms. As the first member of the alkane homologous series, it serves as the foundational structure for organic chemistry, featuring a tetrahedral geometry that maximizes the distance between its atoms.

## Lipids

**Lipids** include a diverse group of compounds that are united by a common feature. Lipids are hydrophobic ("water-fearing"), or insoluble in water, because they are nonpolar molecules. Lipids perform many different functions in a cell. Cells store energy for long-term use in the form of lipids called fats. Lipids also provide insulation from the environment for plants and animals. For example, they help keep aquatic birds and mammals dry because of their water-repelling nature. Lipids are also the building blocks of many hormones and are an important constituent of the plasma membrane. Lipids include fats, oils, waxes, phospholipids, and steroids.

## Proteins

**Proteins** are one of the most abundant organic molecules in living systems and have the most diverse range of functions of all macromolecules. They are all polymers of amino acids, arranged in a linear sequence. The functions of proteins are very diverse because there are 20 different chemically distinct amino acids that form long chains, and the amino acids can be in any order. For example, proteins can function as enzymes or hormones.

## Enzymes

**Enzymes**, which are produced by living cells, are catalysts in biochemical reactions (like digestion) and are usually proteins. Each enzyme is specific for the substrate (a reactant that binds to an enzyme) upon which it acts. Enzymes can function to break molecular bonds, to rearrange bonds, or to form new bonds.

## Nucleic acids

**Nucleic acids** are key macromolecules in the continuity of life. They carry the genetic blueprint of a cell and carry instructions for the functioning of the cell. The two main types of nucleic acids are deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). DNA is the genetic material found in all living organisms, ranging from single-celled bacteria to multicellular mammals. The other type of nucleic acid, RNA, is mostly involved in protein synthesis. DNA molecules never leave the nucleus but instead use an RNA intermediary to communicate with the rest of the cell. Other types of RNA are also involved in protein synthesis and its regulation. DNA and RNA are made up of monomers known as nucleotides. The nucleotides combine with each other to form a polynucleotide, DNA or RNA. Each nucleotide is made up of three components: a nitrogenous base, a pentose (five-carbon) sugar, and a phosphate group. Each nitrogenous base in a nucleotide is attached to a sugar molecule, which is attached to a phosphate group. DNA has a double-helical structure.

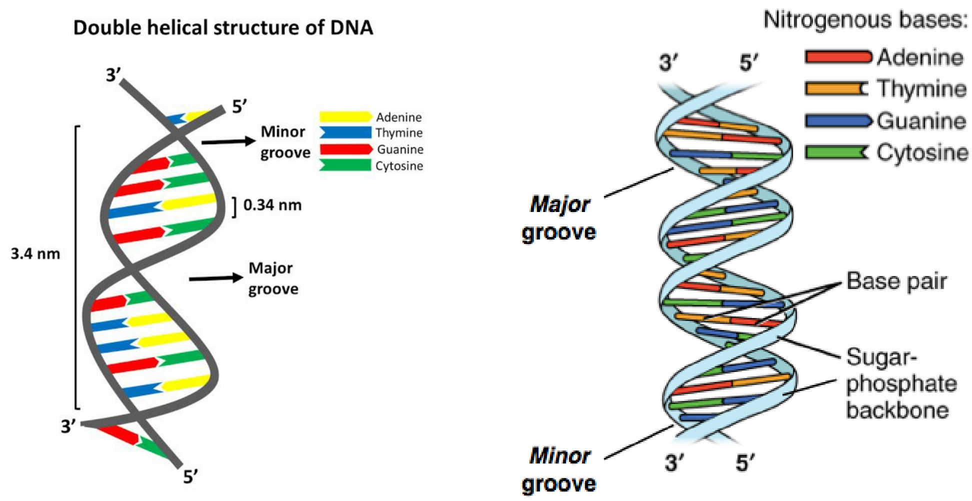


**Figure 2.5** DNA double-helical structure (credit: Khan Academy).

The double-helix model shows DNA as two parallel strands of intertwining molecules.
It is composed of two strands, or polymers, of nucleotides. The strands are formed with bonds between phosphate and sugar groups of adjacent nucleotides. The strands are bonded to each other at their bases with hydrogen bonds, and the strands coil about each other along their length, hence the "double helix" description, which means a double spiral. The alternating sugar and phosphate groups lie on the outside of each strand, forming the backbone of the DNA. The nitrogenous bases are stacked in the interior, like the steps of a staircase, and these bases pair; the pairs are bound to each other by hydrogen bonds. The bases pair in such a way that the distance between the backbones of the two strands is the same all along the molecule.

## What is Energy?

**Energy** is the ability of a system to do work. A system has done work if it has exerted a force on another system over some distance. When this happens, energy is transferred from one system to another. At least some of the energy is also transformed from one type to another during this process. One can keep track of how much energy transfers into or out of a system. There are two categories into which all energy falls: kinetic and potential. In a pendulum, through the swing, there is a constant change of potential energy (highest at the top of the swing) to kinetic energy (highest at the bottom of the swing).

## Potential and Kinetic Energy

**Kinetic energy** refers to types of energy associated with motion. For example, a rock rolling down a hill, the wind blowing through trees, water flowing over a dam, and a cyclist riding a bicycle are just a few examples of kinetic energy.

**Potential energy** is the energy possessed by objects that are at rest. Examples include a rock poised at the top of a hill and water stored behind a dam. Still water has potential energy; moving water, such as in a waterfall or a rapidly flowing river, has kinetic energy.

**Figure 2.7** Blocked water forming a large reservoir. When blocked behind a dam, water has potential energy. (credit: Pillip / Alamy Stock Photo).

In a hydroelectric system, water stored in a reservoir behind a dam possesses gravitational potential energy due to its height; when released, this energy converts to kinetic energy (motion) as it flows down through pipes (penstocks), spinning turbines, which then drive generators to create electricity, demonstrating the continuous conversion of potential to kinetic to electrical energy.


**Figure 2.8** Concept of potential and kinetic energy in a hydroelectric system (credit: BBC/Bitesize).

Water flows down through the penstock. It turns the blades of turbines as it passes through them. The spinning turbines turn generators that create electricity. Electricity passes through transformers so it can travel long distances efficiently. Potential energy is not only associated with the location of matter, but also with the structure of matter. Even a spring on the ground has potential energy if it is compressed; so, does a rubber band that is pulled taut.

**Chemical energy** describes the *potential* of a chemical substance to undergo a chemical reaction and transform other chemical substances; hence it is a form of potential energy.  Examples include energy stored in the food you eat and the gasoline that you put in your car. On a molecular level, the bonds that hold the atoms of molecules exist in a particular structure that has potential energy. Remember that anabolic cellular pathways require energy to synthesize complex molecules from simpler ones and catabolic pathways release energy when complex molecules are broken down. The fact that energy can be released by the breakdown of certain chemical bonds implies that those bonds have potential energy. In fact, there is potential energy stored within the bonds of all the food molecules we eat, which is eventually harnessed for use. This is because these bonds can release energy when broken. The type of potential energy that exists within chemical bonds, and is released when those bonds are broken, is called chemical energy. Chemical energy is responsible for providing living cells with energy from food. The release of energy occurs when the molecular bonds within food molecules are broken. Other examples of potential energy include the energy of water held behind a dam or a person about to skydive out of an airplane.

Living organisms need energy to perform life-sustaining "work" to survive. For nearly all living systems on Earth, the sun is the ultimate source of that energy. Over time, we humans have developed an understanding of energy that has allowed us to harness it for uses well beyond basic survival. The development and evolution of human society is largely attributed to our relationship with energy. The first major advancement in human understanding of energy was the mastery of fire for cooking and heating. Modern civilization is especially dependent on energy and some of its most distinct characteristics such as population growth, environmental impact and climate change are all consequences of energy use. We use energy to heat and light our homes; power our machinery; fuel our vehicles; produce plastics, pharmaceuticals, and synthetic fibers; and provide the comforts and conveniences to which we have grown accustomed in the industrial age. Societal complexity, affluence, and the gap between poor and rich people are all directly related to our level of energy consumption.

## Thermodynamics

Thermodynamics refers to the study of energy and energy transfer involving physical matter. The matter relevant to a particular case of energy transfer is called a system, and everything outside of that matter is called the surroundings. For instance, when heating a pot of water on the stove, the system includes the stove, the pot, and the water. Energy is transferred within the system (between the stove, pot, and water). There are two types of system: open and closed. In an open system, energy can be exchanged with its surroundings. The stovetop system is open because heat can be lost to the air. A closed system cannot exchange energy with its surroundings.

**Biological organisms are open systems**. Energy is exchanged between them and their surroundings as they use energy from the sun to perform photosynthesis or consume energy-storing molecules and release energy to the environment by doing work and releasing heat. Like all things in the physical world, energy is subject to physical laws. The laws of thermodynamics govern the transfer of energy in and among all systems in the universe. In general, energy is defined as the ability to do work, or to create some kind of change. Energy exists in different forms. For example, electrical energy, light energy, and heat energy are all different types of energy. To appreciate the way energy flows into and out of biological systems, it is important to understand two of the physical laws that govern energy.

The **first law of thermodynamics** states that the total amount of energy in the universe is constant and conserved. In other words, there has always been, and always will be, the same amount of energy in the universe. Energy exists in many different forms. According to the first law of thermodynamics, energy may be transferred from place to place or transformed into different forms, but it cannot be created or destroyed. The transfers and transformations of energy take place around us all the time. Light bulbs transform electrical energy into light and heat energy. Gas stoves transform chemical energy from natural gas into heat energy. Plants perform one of the most biologically useful energy transformations on earth: that of converting the energy of sunlight to chemical energy stored within organic molecules.

The challenge for all living organisms is to obtain energy from their surroundings in forms that they can transfer or transform into usable energy to do work. Living cells have evolved to meet this challenge. Chemical energy stored within organic molecules such as sugars and fats are transferred and transformed through a series of cellular chemical reactions into energy within molecules of ATP. Energy in ATP molecules is easily accessible to work. Examples of the types of work that cells need to do include building complex molecules, transporting materials, powering the motion of cilia or flagella, and contracting muscle fibers to create movement.

## Energy Transformations in Biological Systems

The process of **photosynthesis** is where **light energy from the sun** is captured by green plants and converted into **chemical energy** stored in glucose molecules. The chemical equation for this process is:

$$6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

Organisms, such as humans or animals, utilize this stored chemical energy. Through **cellular respiration**, glucose is broken down in the presence of oxygen to release **kinetic energy** for movement and other biological functions. The corresponding chemical equation is:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy (ATP)}$$

Together, these processes demonstrate the flow of energy through ecosystems, from sunlight to chemical bonds, and ultimately to mechanical work.

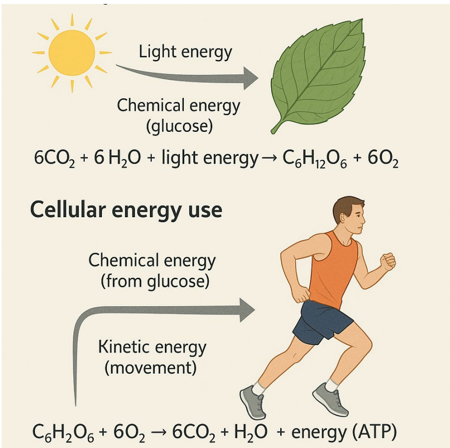


**Figure 2.9** Energy conversion (credit: AI)

The illustrations in figure 2.9 are some examples of energy transferred and transformed from one system to another and from one form to another. The food we consume provides our cells with the energy required to carry out bodily functions, just as light energy provides plants with the means to create the chemical energy they need. In this case, the person running indicates conversion of chemical energy to kinetic energy.

A living cell's primary tasks of obtaining, transforming, and using energy to do work may seem simple. However, the second law of thermodynamics explains why these tasks are harder than they appear. All energy transfers and transformations are never completely efficient. In every energy transfer, some amount of energy is lost in a form that is unusable. In most cases, this form is **heat energy**.

## Entropy

During the process of energy transformation, not all energy is used up due to disorder to lack of sufficient organization in any system. For example, when a light bulb is turned on, some of the energy being converted from electrical energy into light energy is lost as heat energy. Likewise, some energy is lost as heat energy during cellular metabolic reactions.

An important concept in physical systems is that of **order and disorder**. The more energy that is lost by a system to its surroundings, the less ordered and more random the system is. Scientists refer to the measure of randomness or disorder within a system as entropy. High entropy means high disorder and low energy. Molecules and chemical reactions have varying entropies as well. For example, entropy increases as molecules at a high concentration in one place diffuse and spread out. The second law of thermodynamics says that energy will always be lost as heat in energy transfers or transformations. Living things are highly ordered, requiring constant energy input to be maintained in a state of low entropy.

## The Scientific Method

The **scientific method** is a systematic, empirical process used to investigate natural phenomena, acquire new knowledge, or refine and expand existing knowledge. It is foundational to scientific research and ensures that investigations are objective, repeatable, and grounded in evidence. It ensures that investigations are objective, repeatable, and based on empirical evidence. The method is iterative in nature and provides a framework for testing hypotheses, minimizing bias, and building coherent theoretical models.

## Steps in the Scientific Method

### *Observation and Identification of a Problem*

Scientific inquiry begins with **careful observation** of the natural world. This phase involves recognizing patterns, anomalies, or phenomena that provoke curiosity or present a knowledge gap. Often, these observations are informed by existing literature, theoretical perspectives, or practical concerns. The goal is to precisely define the **research problem** or question in a way that is testable and specific.

*Example: A botanist observes that a certain plant species grows more vigorously in one region than another and seeks to understand why.*

### *Formulation of a Hypothesis*

A **hypothesis** is a tentative explanation or predictive statement that addresses the observed phenomenon. It must be **testable** and **falsifiable,** meaning it can be supported or refuted through empirical data. A strong hypothesis often takes the form of an "if-then" statement and is grounded in theoretical or empirical background.

*Example: If the plant receives more sunlight in Region A than in Region B, then it will exhibit greater growth due to increased photosynthetic activity.*

### *Experimentation and Data Collection*

The hypothesis is tested through a **controlled experiment** or systematic study. In a well-designed experiment, researchers manipulate one or more **independent variables** to observe the effect on

**dependent variables**, while controlling **confounding variables**. Data must be collected systematically using reliable and valid instruments or procedures.

Key characteristics of this stage include:

- **Replication:** Experiments should be repeatable by others.
- **Control groups:** Used to compare experimental groups.
- **Randomization:** Ensures impartial allocation of treatments.
- **Quantification:** Preferably data is quantitative for statistical analysis.

*Example: Grow identical plants under varying light intensities in controlled environments and measure their biomass over time.*

### *Analysis and Interpretation of Data*

After data collection, the next step is **statistical analysis** to determine whether the observed results support or refute the hypothesis. Depending on the nature of the data, researchers may use descriptive statistics (mean, median, standard deviation) and inferential statistics (t-tests, ANOVA, regression) to draw conclusions.

Interpretation involves evaluating:

- Statistical significance (e.g., p-values, confidence intervals)
- Trends or patterns in the data
- Possible sources of error or limitations
- Relevance of the findings to the original hypothesis

*Example: Statistical analysis confirms that plants grown under higher light levels have significantly greater biomass, supporting the hypothesis.*

### *Drawing Conclusions*

Based on data analysis, the researcher draws conclusions regarding the validity of the hypothesis. If the data **supports** the hypothesis, it gains credibility, but it has not proven that definitively, scientific knowledge is always **provisional**. If the data **does not support** the hypothesis, it must be revised or rejected. Researchers also assess whether results align with previous research and whether anomalies occurred that require further study. Additional hypotheses should be tested.

### *Dissemination or Communication of Findings*

Scientific knowledge is cumulative and collaborative. Thus, researchers must **communicate their results** to the scientific community through **peer-reviewed journals, conferences, or public reports**. A standard scientific paper includes an abstract, introduction, methodology, results, discussion, and references.

*Example: The botanist publishes a paper explaining how light intensity affects plant growth, contributing to ecological and agricultural sciences.*

#### *Replication*

Other researchers may **replicate the study** to confirm the findings or **extend** the research to new contexts.

### Theory Development

Repeated confirmations of a hypothesis under diverse conditions can lead to the development of broader **theories** or **models**, which explain related phenomena and offer predictive power.

*Example: Multiple studies corroborate the link between light and growth, supporting broader theories of photosynthesis and plant ecology.*

### The Iterative and Self-Correcting Nature of Science

One of the scientific method's strengths is its **self-correcting nature**. Scientific knowledge evolves as new evidence emerges, old hypotheses are refined, and new technologies allow deeper exploration. The method is not linear but **cyclical;** observations lead to hypotheses, which lead to experiments, which prompt further questions.

Moreover, the scientific method emphasizes:

- **Skepticism:** Results are not accepted until rigorously tested.
- **Transparency:** Methodologies and data must be open to scrutiny.
- **Objectivity:** Conclusions must be based on evidence, not personal belief.

### Observation

Scientific advances begin with **observations**. This involves noticing a pattern, either directly or indirectly from the literature. An example of a direct observation is noticing that there have been a lot of toads in your yard ever since you turned on the sprinklers, whereas an indirect observation would be reading a scientific study reporting high densities of toads in urban areas with watered lawns.

## Hypothesis and Prediction

The **hypothesis** is the expected answer to the question. The best hypotheses state the proposed direction of the effect (increases, decreases, etc.) and explain why the hypothesis could be true.

- OK hypothesis: Agent Orange influences rates of birth defects and disease.
- Better hypothesis: Agent Orange increases the incidence of birth defects and diseases.
- Best hypothesis: Agent Orange increases the incidence of birth defects and disease because these health problems have been frequently reported by individuals exposed to this herbicide.

If two or more hypotheses meet this standard, the simpler one is preferred.

**Predictions** stem from the hypothesis. The prediction explains what results would support hypothesis. The prediction is more specific than the hypothesis because it references the details of the experiment

Hypotheses and predictions must be testable to ensure that they are valid. For example, a hypothesis that depends on what a bear thinks are not testable, because it can never be known what a bear thinks. It should also be **falsifiable**, meaning that they have the capacity to be tested and demonstrated to be untrue. An example of an unfalsifiable hypothesis is "Botticelli's *Birth of Venus* is beautiful." There is no experiment that might show this statement to be false. To test a hypothesis, a researcher will conduct one or more experiments designed to eliminate one or more of the hypotheses. This is important. A hypothesis can be disproven, or eliminated, but it can never be proven. Science does not deal in proof like mathematics. If an experiment fails to disprove a hypothesis, then we find support for that explanation, but this is not to say that down the road a better explanation will not be found, or a more carefully designed experiment will be found to falsify the hypothesis.

Hypotheses are tentative explanations and are different from scientific theories. A **scientific theory** is a widely accepted, thoroughly tested and confirmed explanation for a set of observations or phenomena. Scientific theory is the foundation of scientific knowledge. In addition, in many scientific disciplines (less in biology) there are **scientific laws**, often expressed in mathematical formulas, which describe how elements of nature will behave under certain specific conditions, but they do not offer explanations for why they occur.

Next, a scientific study (experiment) is planned to test the hypothesis and determine whether the results match the predictions. Each experiment will have one or more variables.

The **independent variable** is what scientists hypothesize might be causing something else. In a manipulative experiment (see below), the independent variable is manipulated by the scientist.
The **dependent variable** is the response; the variable ultimately measured in the study. **Controlled variables** (confounding factors) might affect the dependent variable, but they are not the focus of the study. Scientists attempt to standardize the controlled variables so that they do not influence the results. In our previous example, exposure to Agent Orange is the independent variable. It is hypothesized to cause a change in health (likelihood of having children with birth defects or developing a disease), the dependent variable. Many other things could affect health, including diet, exercise, and family history. These are the controlled variables.

**There are two main types of scientific studies**:

- experimental studies (manipulative experiments) and
- observational studies.

In a **manipulative experiment**, the independent variable is altered by the scientists, who then observe the response. In other words, scientists apply treatment. An example would be exposing developing mice to TCDD and comparing the birth rate defects to a control group. The **control group** is a group of test subjects that are as similar as possible to all other test subjects, with the exception that they don't receive experimental treatment (those that do receive it are known as the experimental, treatment, or **test group**). The purpose of the control group is to establish what the dependent variable would be under normal conditions, in the absence of the experimental treatment. It serves as a baseline to which the test group can be compared.

In an **observational study**, scientists examine multiple samples with and without the presumed cause. An example would be monitoring the health of veterans who had varying levels of exposure to Agent Orange.
Scientific studies contain many **replicates.** Multiple samples ensure that any observed pattern is due to the treatment rather than naturally occurring differences between individuals. A scientific study should also be **repeatable**, meaning that if it is conducted again, following the same procedure, it should

reproduce the same general results. Additionally, multiple studies will ultimately test the same hypothesis.

## Results

Finally, the data are collected, and the results are analyzed. They also provide a criterion for deciding whether the pattern in the data is strong enough to support the hypothesis.

An observational study found that self-reported exposure to Agent Orange was positively correlated with incidence of multiple diseases in Korean veterans of the Vietnam War, including various cancers, diseases of the cardiovascular and nervous systems, skin diseases, and psychological disorders. Note that a **positive correlation** simply means that the independent and dependent variables both increase or decrease together, but further data, such as the evidence provided by manipulative experiments is needed to document a **cause-and-effect relationship**. (A **negative correlation** occurs when one variable increases as the other decreases.)

## Conclusion

Lastly, scientists make a conclusion regarding whether the data supports the hypothesis. In the case of Agent Orange, the data matches the prediction. Additionally, veterans exposed to Agent Orange had higher rates of certain diseases, further supporting the hypothesis. We can thus accept the hypothesis that Agent Orange increases the incidence of birth defects and disease. In practice, the scientific method is not as rigid and structured as it might first appear. Sometimes an experiment leads to conclusions that favor a change in approach; often, an experiment brings entirely new scientific questions to the puzzle. Many times, science does not operate in a linear fashion; instead, scientists continually draw inferences and generalize, finding patterns as their research proceeds. Even if the hypothesis was supported, scientists may continue to test it in different ways. For example, scientists explore the impacts of Agent Orange, examining long-term health impacts as Vietnam veterans age.

Figure 2.10 illustrates the steps of the scientific method in a flowchart format.

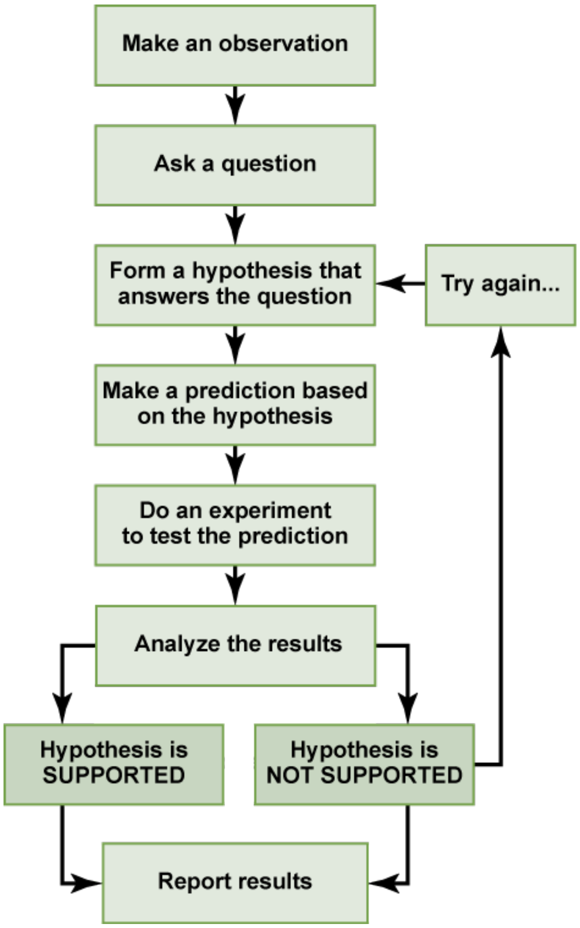


**Figure 2.10** Steps in the scientific method (credit: William McLellan, Creative Commons Attribution 4.0 International (CC BY 4.0)

The scientific method, as shown in Figure 2.10, is a series of defined steps that include experiments and careful observation. The steps are as follows: make an observation; ask a question; form a hypothesis that answers the question; make a prediction based on the hypothesis; do an experiment to test the prediction; analyze the results; and report the results. Whether the hypothesis is supported or not supported, the results are still reported. If a hypothesis is not supported by data, a new hypothesis can be proposed.

Scientific findings can influence decision making. In response to evidence regarding the effect of Agent Orange on human health, compensation is now available for Vietnam veterans who were exposed to Agent Orange and develop certain diseases. The use of Agent Orange is also banned in the U.S.

## Research Data

Understanding the different types of data (in statistics, marketing research, or data science) allows you to pick the data type that most closely matches your needs and goals. **Data**, **information**, **knowledge**, and **wisdom** (DIKW) are important terms which are common in research and related literature. Figure 2.11 provides a triangular pyramid divided into four horizontal layers labeled from bottom to top: Data, Information, Knowledge, and Wisdom. The bottom layer (Data) includes raw weather measurements such as hourly temperature, humidity, and precipitation readings. The next layer (Information) shows these readings organized over time. The third layer (Knowledge) explains a pattern where increasing humidity and decreasing temperature reduce the atmosphere's ability to hold moisture. The top layer (Wisdom) demonstrates applying this knowledge to predict the likelihood of rain. Dotted horizontal lines separate each level, and explanatory text appears alongside each layer.

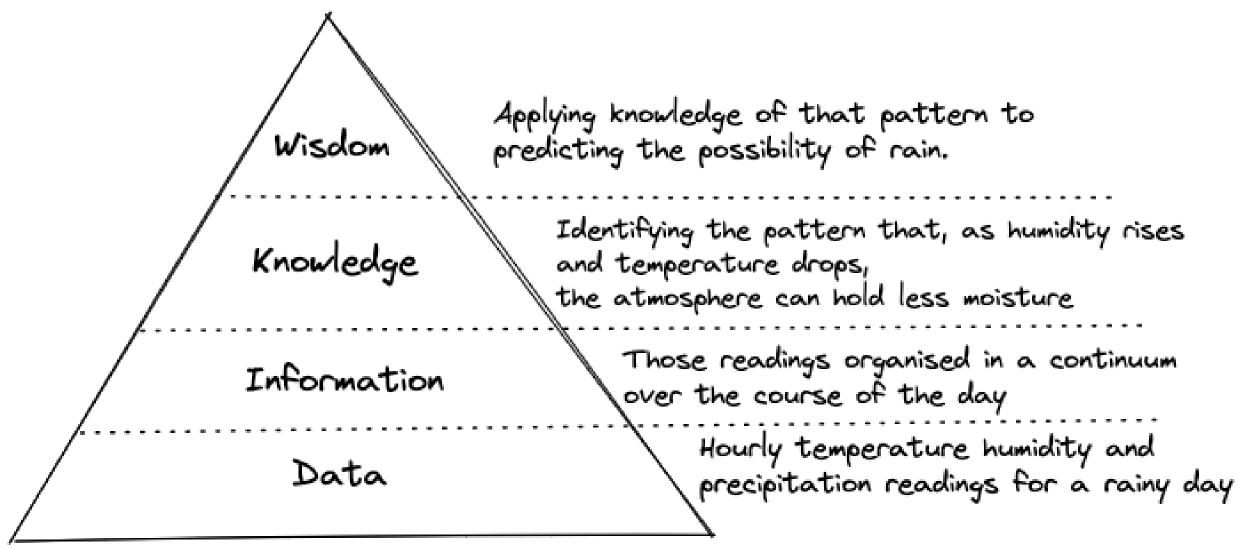


**Figure 2.11** The illustration represents DIKW **hierarchy,** foundational concept in science, data analysis, and decision-making. It shows how raw observations are transformed into meaningful action. (credit: Glaser, H. (2013, May 15).

## Data Measurement Levels

There are four data measurement levels. They are from lowest to highest.

1. Nominal
2. Ordinal
3. Interval
4. Ratio

Some academic authorities have proposed five levels. The lowest level in this is **string data**

## Nominal Data

Nominal data is used just for labeling variables, without any type of quantitative value. It is a qualitative form of data. The name 'nominal' comes from the Latin word "nomen" which means 'name'.
The nominal data just name a thing without applying it to order. The nominal data could just be called "labels."

**Examples of Nominal Data:**

- Gender (Women, Men)
- Hair color (Blonde, Brown, Brunette, Red, etc.)
- Marital status (Married, Single, Widowed)
- Ethnicity (Hispanic, Asian)

As you see from the examples there is no intrinsic ordering to the variables.
Eye color is a nominal variable having a few categories (Blue, Green, Brown) and there is no way to order these categories from highest to lowest.
An example of this could be color. You could encode yellow as 1 and blue as 2, but these numbers would have no specific value nor meaning. And such an encoding would not automatically make green equal to 1.5. When it comes to mathematical operations, there isn't much you can do here. One can only compute the mode (the most frequent value) of a nominal variable. Other measures, such as the mean or the median, make no sense.

## Ordinal Data

Ordinal data shows where a number is in order. This is the crucial difference from nominal types of data. Ordinal data is data which is placed into some kind of order by their position on a scale. Ordinal data may indicate superiority. However, **you cannot do arithmetic with ordinal numbers** because they only show sequence.

Ordinal variables are considered as "in between" qualitative and quantitative variables.
In other words, the ordinal data is qualitative data for which the values are ordered.

In comparison with nominal data, the second one is qualitative data for which the values cannot be placed in an order. We can also assign numbers to ordinal data to show their relative position. But we cannot do math with those numbers. For example: “first, second, third…etc.”

**Examples of Ordinal Data:**

- The first, second and third person in a competition.
- Letter grades: A, B, C, etc.
- When a company asks a customer to rate the sales experience on a scale of 1-10.
- Economic status: low, medium and high.

As the name suggests, **ordinal data** have **some order**. It allows you to rank the values, such as for education level: *elementary* is less than *high school*, which in turn is less than *university.* The ordering allows us to compute the median: if our dataset has 100 examples of each education level, it is correct to say that the median education is *high school.* From the definition of the median, this means that 50% of the examples have *high school* or *elementary* education, while the other 50% have *high school* or *university* education, which is correct and, maybe, an important insight. Calculating the mean, however, makes no sense for ordinal data. What is the average of a university and an elementary school anyway?

A note for the mathematically inclined reader: if you encode the levels of an ordinal variable with subsequent numbers, you can safely apply monotone transformations to it, such as taking the logarithm. This is because monotone transformations preserve order, and the order is all that matters here.

## Interval Data 📎

Interval data builds on top ordinal data. In addition to ordering the values, it also specifies that the intervals between subsequent values are the same. A good example of this is the temperature measured in degrees Celsius: the difference between 1 degree and 5 degrees is the same as between 20 and 24: it’s 4 degrees. Note that this was not the case for ordinal data: we cannot say that the difference between graduating from a high school versus from an elementary school only is the same as the one between a university and a high school.

In the case of interval type variables, in addition to the mode and the median, computing the arithmetic mean also makes sense. You can also apply linear transformations to interval data.

## Ratio Data ➗

Ratio data builds on top of interval data. The difference is that ratio type variables have a meaningful zero value. The examples are price, length, weight, amount of something, or temperature measured in Kelvin. The meaningful zero allows us to calculate ratios between two data points: we can say that 4 apples are twice as much as 2, or that $5 is half as expensive as $10. This was not the case for interval data: in the case of temperature measured in degrees Celsius, we cannot say 10 degrees is twice as warm as 5 degrees. Ratios make no sense for scales without a meaningful zero.

## Data Measurement Types: summary

The four data measurement types are neatly summarized for your convenience on the table below.

Table 1 Types of Data

| Data Measurement Type | Property | Central Tendency Measure | Allowed math transformations | Example |
|---|---|---|---|---|
| NOMINAL | grouping | mode | – | color |
| ORDINAL | order | mode, median | monotone transformations | education level |
| INTERVAL | equal intervals | mode, median, mean | linear transformations | temperature in °C |
| RATIO | meaningful zero | mode, median, mean | scaling transformations | price |

**Machine Learning**

How does it all relate to machine learning models, I hear you asking. There are two reasons why you should think carefully about what measurement types your variables are before typing .fit predict ():

- Model interpretability.
- Ease of learning.

Whether you are a researcher, professor, businessman, marketer, data scientist, or another professional who works with some kinds of data, you should familiarize yourself with the common classifications of data.

Why? Because the various data classifications allow you to correctly use measurements and thus to correctly make decisions.

## Qualitative vs Quantitative Data

### Quantitative data

Quantitative data seems to be the easiest to explain. It answers key questions such as "how many, "how much" and "how often."

Quantitative data can be expressed as a number or can be quantified. Simply put, it can be measured by numerical variables.

Quantitative data are easily amenable to statistical manipulation and can be represented by a wide variety of statistical types of graph and charts such as line, bar graph, scatter plot, etc.

**Examples of quantitative data:**

- Scores on tests and exams e.g. 85, 67, 90 etc.
- The weight of a person or a subject.
- Your shoe size.
- The temperature in a room.

There are 2 general types of quantitative data: discrete data and continuous data. We will explain them later in this article.

### Qualitative data

Qualitative data can't be expressed as a number and can't be measured in the same way as quantitative data. Qualitative data consists of words, pictures, and symbols, not numbers.

Qualitative data is also called categorical data because the information can be sorted by category, not by number. Qualitative data can answer questions such as "how this has happened" or and "why this has happened."

**Examples of qualitative data:**

- Colors e.g. the color of the sea
- Your favorite holiday destination such as Hawaii, New Zealand etc.
- Names as John, Patricia
- Ethnicity such as American Indian, Asian, etc.

## Discrete vs Continuous Data

As we mentioned above discrete and continuous data are the two key types of quantitative data. In statistics, marketing research, and data science, many decisions depend on whether the basic data is discrete or continuous.

## Discrete data

Discrete data is a count that involves only integers. The discrete values cannot be subdivided into parts. For example, the number of children in a class is discrete. You can count individuals. You can't count 1.5 kids. To put in other words, discrete data can take only certain values. The data variables cannot be divided into smaller parts. It has a limited number of possible values e.g. days of the month.

**Examples of discrete data:**

- The number of home runs in a baseball game.
- The number of test questions a student answered correctly
- The number of students in a class or the number of workers in a company.

## Continuous data

Continuous data is information that could be meaningfully divided into finer levels. It can be measured on a scale or continuum and can have almost any numeric value.

For example, you can measure your height at very precise scales, meters, centimeters, millimeters etc. You can record continuous data at so many different measurements, width, temperature, time, etc. This is where the key difference from discrete types of data lies.

The continuous variables can take any value between two numbers. For example, between 50 and 72 inches, there are literally millions of possible heights: 52.04762 inches, 69.948376 inches etc. A good great rule for defining if a data is continuous or discrete is that if the point of measurement can be reduced in half and still make sense, the data is continuous.

**Examples of continuous data:**

- The amount of time required to complete a project.
- The height of children.
- The square footage of a two-bedroom house.
- The speed of cars.

# Chapter Three: Energy and Biogeochemical Cycles

## Objectives

1. Explain the nature of matter and the biochemical cycles.
2. Describe ecological cycles

## Matter

Technically, **matter** is defined as anything that occupies space or has mass. **Mass** is resistance to acceleration. Put more simply, mass is like weight, but weight accounts for acceleration due to gravity. Matter moves between biotic and abiotic ecosystem components through biogeochemical cycles. Fully understanding these cycles requires a background in the particles that comprise matter, atoms.

## Biogeochemical Cycles

**Biogeochemical cycles**, also known as nutrient cycles, describe the movement of chemical elements through different media, such as the atmosphere, soil, rocks, bodies of water, and organisms. Biogeochemical cycles keep essential elements available to plants and other organisms. Energy flows directionally through ecosystems, entering as sunlight (or inorganic molecules for chemoautotrophs) and leaving as heat during energy transformation between trophic levels. Rather than flowing through an ecosystem, the matter that makes up organisms is conserved and recycled.

The **law of conservation of mass** states that matter is neither created nor destroyed. For example, after a chemical reaction, the mass of the products (ending molecules) will be the same as the mass of the reactants (starting molecules). The same is true in an ecosystem. Matter moves through different media, and atoms may react to form new molecules, but the amount of matter remains constant.

The biogeochemical cycles of four elements, carbon, nitrogen, phosphorus, and sulfur, are discussed below. The cycling of these elements is interconnected with the water. For example, the movement of water is critical for the leaching of sulfur and phosphorus into rivers, lakes, and oceans. Today, **anthropogenic** (human) activities are altering all major ecosystems and the biogeochemical cycles they drive.

## The Carbon Cycle

Carbon is the basic building block of all organic materials, and therefore, of living organisms. The carbon cycle is comprised of several interconnected cycles: one dealing with rapid carbon exchange among living organisms and the other dealing with the long-term cycling of carbon through geologic processes (figure 3.1. The overall effect is that carbon is constantly recycled in the dynamic processes taking place in the atmosphere, at the surface and in the crust of the earth. Most of the carbon resides as inorganic minerals in crustal rocks. Other **reservoirs** of carbon, places where carbon accumulates, include the oceans and atmosphere. Some of the carbon atoms in your body today may long ago have resided in a dinosaur's body or perhaps were once buried deep in the Earth's crust as carbonate rock minerals.

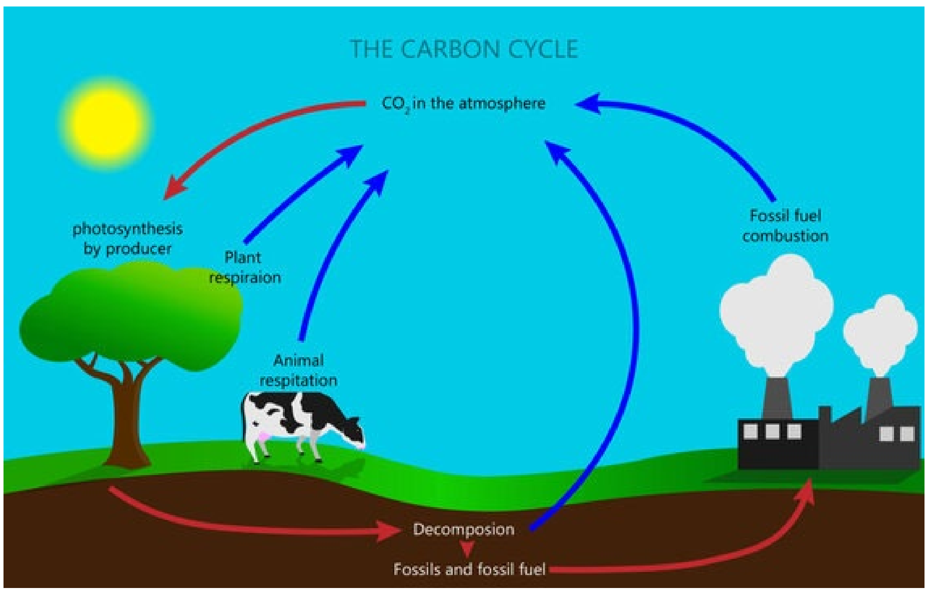


**Figure 3.1** Carbon Cycle. The carbon cycle involves $CO_2$ emissions from respiration, decomposition, and fossil fuel combustion, which plants absorb during photosynthesis to create organic carbon, forming the foundation of fossils and fossil fuels. (credit: U.S. Environmental Protection Agency. (n.d.). The carbon cycle [Diagram]. A Student's Guide to Global Climate Change. https://archive.epa.gov/climatechange/kids/basics/today/carbon-cycle.html).

Carbon dioxide in the atmosphere is converted to organic carbon through photosynthesis by terrestrial organisms (like trees) and marine organisms (like algae). Respiration by terrestrial organisms (like trees and deer) and marine organisms (like algae and fish) release carbon dioxide back into the atmosphere.

Additionally, microbes that decompose dead organisms release carbon dioxide through respiration. Weathering of terrestrial rocks also brings carbon into the soil. Carbon in the soil enters the water through leaching and runoff. It can accumulate into ocean sediments and reenter land through uplifting. Long-term storage of organic carbon occurs when matter from living organisms is buried deep underground and becomes fossilized. Volcanic activity and human emissions return carbon back into the carbon cycle.

### *Carbon cycles slowly between land and the ocean*

On land, carbon is stored in soil as organic carbon in the form of decomposing organisms or terrestrial rocks. Decomposed plants and algae are sometimes buried and compressed between layers of sediments. After millions of years fossil fuels such as coal, oil, and natural gas are formed. The **weathering** of terrestrial rock and minerals release carbon into the soil. Carbon-containing compounds in the soil can be washed into bodies of water, such as ocean, through **leaching.** Atmospheric carbon dioxide also dissolves in the ocean, reacting with water molecules to form carbonate ions ($CO_3^{2-}$). Some of these ions combine with calcium ions in seawater to form calcium carbonate ($CaCO_3$), a major component of the shells of marine organisms. These organisms eventually die and their shells form sediments on the ocean floor. Over geological time, the calcium carbonate forms limestone, which comprises the largest carbon reservoir on Earth.

Carbonate also precipitates in sediments, forming carbonate rocks, such as limestone. Carbon sediments from the ocean floor are taken deep within Earth by the process of **subduction**: the movement of one tectonic plate beneath another. The ocean sediments are subducted by the actions of **plate tectonics**, melted and then returned to the surface during volcanic activity. Plate tectonics can also cause **uplifting**, returning ocean sediments to land.

### *Carbon Cycles Quickly between Organisms and the Atmosphere*

Carbon dioxide is converted into glucose, an energy-rich organic molecule through **photosynthesis** by plants, algae, and some bacteria (figure 3.2). They can then produce other organic molecules like complex carbohydrates (such as starch), proteins and lipids, which animals can eat. Most terrestrial autotrophs obtain their carbon dioxide directly from the atmosphere, while marine autotrophs acquire it in the dissolved form (bicarbonate, $HCO_3^-$).


(a) (b) (c)

**Figure 3.2:** Images of autotrophs (a) Plants, (b) green algae, and (c) certain bacteria, called cyanobacteria
(credit a: Steve Hillebrand, U.S. Fish and Wildlife Service; credit b: "eutrophication hypoxia"/Flickr; credit c: NASA; scale-bar data from Matt Russell)

Green plants, algae, and certain bacteria, such as cyanobacteria, all can carry out photosynthesis. Algae can grow over enormous areas in water, at times completely covering the surface. Plants, animals, and other organisms break down these organic molecules during the process of **aerobic cellular respiration**, which consumes oxygen and releases energy, water and carbon dioxide. Carbon dioxide is returned to the atmosphere during gaseous exchange. Another process by which organic material is recycled is the decomposition of dead organisms. During this process, bacteria and fungi break down the complex organic compounds. Decomposers may respirate carbon dioxide, or other processes that release methane ($CH_4$).

**Photosynthesis** ($6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$) and **respiration** are reciprocal to one another regarding the cycling of carbon: photosynthesis removes carbon dioxide from the atmosphere and respiration returns it (Figure 3.3). A significant disruption of one process can therefore affect the amount of carbon dioxide in the atmosphere.

| Photosynthesis Equation | | | |
|---|---|---|---|
| Carbon dioxide + | Water —SUNLIGHT→ | Sugar + | Oxygen |
| $6CO_2$ | $6H_2O$ | $C_6H_{12}O_6$ | $6O_2$ |

**Figure 3.3** Photosynthesis equation (credit: National Park Service. (n.d.). Photosynthesis equation [Diagram]. In Biology basics educational resources. https://www.nps.gov).

This equation means that six molecules of carbon dioxide ($CO_2$) combine with six molecules of water ($H_2O$) in the presence of sunlight. This produces one molecule of glucose ($C_6H_{12}O_6$) and six molecules of oxygen ($O_2$). Cellular respiration is only one process that releases carbon dioxide. Physical processes, such as the eruption of volcanoes and release from **hydrothermal vents** (openings in the ocean floor) add carbon dioxide to the atmosphere. Additionally, the **combustion** of wood and fossil fuels releases carbon dioxide. The level of carbon dioxide in the atmosphere is greatly influenced by the reservoir of carbon in the oceans. The exchange of carbon between the atmosphere and water reservoirs influences how much carbon is found in each.

### *Importance of the Carbon Cycle*

The carbon cycle is crucially important to the biosphere. If not for the recycling processes, carbon might long ago have become completely sequestered in crustal rocks and sediments, and life would no longer exist (figure 3.4). Photosynthesis not only makes energy and carbon available to higher trophic levels, but it also releases gaseous oxygen ($O_2$). Gaseous oxygen is necessary for cellular respiration to occur. Photosynthetic bacteria were likely the first organisms to perform photosynthesis, dating back 2-3 billion years ago. Thanks to their activity, and a diversity of present-day photosynthesizing organisms, Earth's atmosphere is currently about 21% $O_2$. Also, this $O_2$ is vital for the creation of the ozone layer, which protects life from harmful ultraviolet radiation emitted by the sun. Ozone ($O_3$) is created from the breakdown and reassembly of $O_{2(g)}$.

Figure 3.4 shows a nurse log (a fallen decaying tree) in a temperate forest. The log is covered in moss and serves as a substrate for numerous young trees (mostly hemlocks) growing directly out of it, demonstrating ecological succession and the vital role of dead wood in forest regeneration hence carbon cycling.

**Figure 3.4** Green and brown organic matter in carbon cycle (credit: U.S. Fish and Wildlife Service. (n.d).

Decomposers will break down the organic compounds in this fallen tree at Cliffs of the Neuse State Park in Wayne County, North Carolina, releasing carbon dioxide into the atmosphere. Decomposition ensures that carbon dioxide will be available in the atmosphere for photosynthetic organisms, which then provide carbon for consumers. The global carbon cycle contributes substantially to the provisioning ecosystem services upon which humans depend. We harvest approximately 25% of the total biomass that is produced each year on the land surface to supply food, fuel, wood and fiber from croplands, pastures and forests. In addition, the global carbon cycle plays a key role in regulating ecosystem services because it significantly influences climate via its effects on atmospheric $CO_2$ concentrations.

## Human Alteration of the Carbon Cycle

Atmospheric $CO_2$ concentration increased from 280 parts per million (ppm) to 413 ppm between the start of industrial revolution in the late eighteenth century and 2020. This reflected a new flux in the global carbon cycle; anthropogenic $CO_2$ emissions, where humans release $CO_2$ into the atmosphere by burning fossil fuels and changing land use. Fossil fuel burning takes carbon from coal, gas, and oil reserves, where it would be otherwise stored on very long-time scales and introduces it into the active carbon cycle. Land use releases carbon from soil and plant biomass pools into the atmosphere, particularly through the process of deforestation for wood extraction or conversion of land to agriculture. In 2018, the additional flux of carbon into the atmosphere from anthropogenic sources was estimated to be 36.6 gigatons of carbon (GtC = 1 billion tons of carbon), a significant disturbance to the natural carbon cycle that had been in balance for several thousand years previously. High levels of carbon dioxide in the atmosphere cause warming that results in climate change.

## The Nitrogen Cycle

All organisms require nitrogen because it is an important component of nucleic acids, proteins, and other organic molecules. Getting nitrogen into living organisms is difficult. Plants and algae are not equipped to incorporate nitrogen from the atmosphere (where it exists as tightly bonded, triple covalent $N_2$) although this molecule comprises approximately 78 percent of the atmosphere. Because most of the nitrogen is stored in the atmosphere, the atmosphere is considered a reservoir of nitrogen. The nitrogen molecule ($N_2$) is quite inert. To break it apart so that its atoms can combine with other atoms requires the input of substantial amounts of energy. **Nitrogen fixation** is the process of converting nitrogen gas into ammonia ($NH_3$), which spontaneously becomes ammonium ($NH_4^+$). Ammonium is found in bodies of water and in the soil (Figure 3.5).

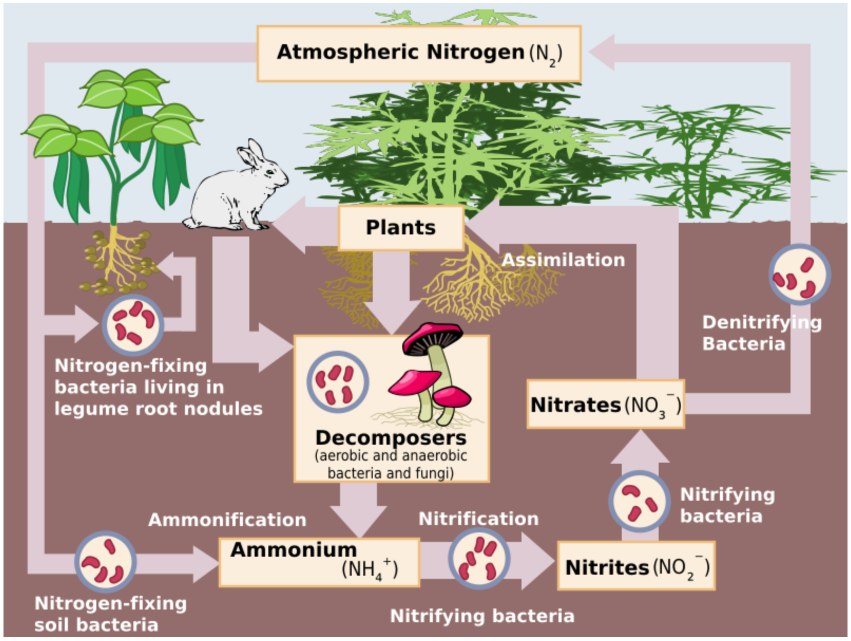


**Figure 3.5** Nitrogen cycle

(credit: "Nitrogen cycle" by Johann Dréo & Raeky is licensed under CC BY-SA 3.0)

In the nitrogen cycle, nitrogen-fixing bacteria in the soil or legume root nodules convert nitrogen gas ($N_2$) from the atmosphere to ammonium ($NH_4^+$). Nitrification occurs when bacteria convert ammonium to nitrites ($NO_2^-$) and then to nitrates ($NO_3^-$). Nitrates re-enter the atmosphere as nitrogen gas through denitrification by bacteria. Plants assimilate ammonium and nitrates, producing organic nitrogen, which is available to consumers. Decomposers, including aerobic and anaerobic bacteria and fungi, break down organic nitrogen and release ammonium through ammonification.

Three processes are responsible for most of the nitrogen fixation in the biosphere. The first is **atmospheric fixation** by lightning. The enormous energy of lightning breaks nitrogen molecules and enables their atoms to combine with oxygen in the air forming nitrogen oxides. These dissolve in rain, forming nitrates that are carried to the earth. Atmospheric nitrogen fixation probably contributes some 5-8% of the total nitrogen fixed. The second process is **industrial fixation.** Under great pressure, at a temperature of 600°C (1112°F), and with the use of a **catalyst** (which facilitates chemical reactions), atmospheric nitrogen and hydrogen can be combined to form ammonia ($NH_3$). Ammonia can be used directly as fertilizer, but most of it is further processed to urea and ammonium nitrate ($NH_4NO_3$).

The third process is **biological fixation** by certain free-living or symbiotic bacteria. Some form a symbiotic relationship with plants in the legume family, which include beans, peas, soybeans, alfalfa, and clovers. Some nitrogen-fixing bacteria even establish symbiotic relationships with animals, e.g., termites and "shipworms" (wood-eating bivalves). Nitrogen-fixing cyanobacteria are essential to maintaining the fertility of semi-aquatic environments like rice paddies. Although the first stable product of the process is ammonia, this is quickly incorporated into protein and other organic nitrogen compounds.

Ammonium is converted by bacteria and archaea into nitrites ($NO_2^-$) and then nitrates ($NO_3^-$) through the process of **nitrification**. Like ammonium, nitrites and nitrates are found in water and the soil. Some nitrates are converted back into nitrogen gas, which is released into the atmosphere. The process, called **denitrification**, is conducted by bacteria.
Plants and other producers directly use ammonium and nitrates to make organic molecules through the process of **assimilation**. This nitrogen is now available to consumers. Organic nitrogen is especially important to the study of ecosystem dynamics because many processes, such as primary production, are limited by the available supply of nitrogen. Consumers excrete organic nitrogen compounds that return to the environment. Additionally, dead organisms at each trophic level contain organic nitrogen. Microorganisms, such as bacteria and fungi, decompose these wastes and dead tissues, ultimately producing ammonium through the process of **ammonification.**

In marine ecosystems, nitrogen compounds created by bacteria, or through decomposition, collect in ocean floor sediments. It can then be moved to land in geological times by the uplift of Earth’s crust and thereby incorporated into terrestrial rock. Although the movement of nitrogen from rock directly into living systems has been traditionally seen as insignificant compared with nitrogen fixed from the atmosphere, a recent study showed that this process may indeed be significant and should be included in any study of the global nitrogen cycle.

Human activity can alter the nitrogen cycle by two primary means: the combustion of fossil fuels, which releases different **nitrogen oxides** into the atmosphere, and using artificial fertilizers in agriculture. Atmospheric nitrogen (other than $N_2$) is associated with several effects on Earth's ecosystems. Nitrogen oxides ($HNO_3$) can react in the atmosphere to form nitric acid, a form of **acid deposition**, also known as acid rain. Acid deposit damages healthy trees, destroys aquatic systems and erodes building materials such as marble and limestone. Like carbon dioxide, nitrous oxide ($N_2O$) causes warming resulting in climate change.

Humans are primarily dependent on the nitrogen cycle as a supporting ecosystem service for crop and forest productivity. Nitrogen fertilizers are added to enhance the growth of many crops and plantations (figure 3.6). The enhanced use of fertilizers in agriculture was a key feature of the green revolution that boosted global crop yields in the 1970s. The industrial production of nitrogen-rich fertilizers has increased substantially over time and now matches more than half of the input to the land from biological nitrogen fixation (90 megatons = 1 million tons of nitrogen each year). If the nitrogen fixation from legume crops is included, then the anthropogenic flux of nitrogen from the atmosphere to the land exceeds natural fluxes to the land.

Fertilizers are washed into lakes, streams, and rivers by surface runoff, resulting in saltwater and freshwater eutrophication, a process whereby nutrient runoff causes the overgrowth of algae, the depletion of oxygen, and death of aquatic fauna.

**Figure 3.6** Modern agricultural drone spraying chemicals over a well-established crop field Fertilizer containing nitrogen is conventionally applied at large scales in agriculture. (credit: Grok AI).

## The Phosphorus Cycle

Several forms of nitrogen (nitrogen gas, ammonium, nitrates, etc.) were involved in the nitrogen cycle, but phosphorus remains primarily in the form of the phosphate ion ($PO_4^{3-}$). Also, in contrast to the nitrogen cycle, there is no form of phosphorus in the atmosphere. Phosphorus is used to make nucleic acids and the phospholipids that comprise biological membranes.

Rocks are a reservoir for phosphorus, and these rocks have their origins in the ocean. Phosphate-containing Ocean sediments form primarily from the bodies of ocean organisms and from their excretions. However, volcanic ash, aerosols, and mineral dust may also be significant phosphate sources. This sediment then is moved to land over geologic time by the uplifting of Earth's surface (figure 3.7). The movement of phosphate from the ocean to the land and through the soil is extremely slow, with the average phosphate ion having an oceanic residence time between 20,000 and 100,000 years.

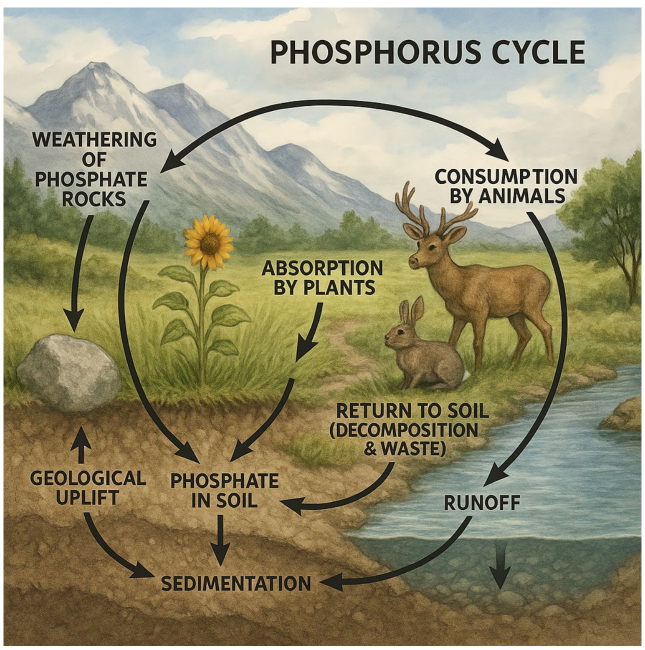


**Figure 3.7** Phosphorus cycle. (credit: Grok AI)

In nature, phosphorus exists as the phosphate ion ($PO_4^{3-}$). Phosphate enters the atmosphere from volcanic aerosols, which precipitate to Earth. Weathering of rocks also releases phosphate into the soil and water, where it becomes available to terrestrial food webs. Some of the phosphate from terrestrial food webs dissolves in streams and lakes, and the remainder enters the soil. Phosphate enters the ocean via surface runoff, groundwater flow, and river flow, where it becomes dissolved in ocean water or enters marine food webs. Some phosphate falls to the ocean floor where it becomes sediment. If uplifting occurs, this sediment can return to land. Marine birds play a unique role in the phosphorous cycle.

These birds take up phosphorous from ocean fish. Their droppings on land (guano) contain high levels of phosphorus and are sometimes mined for commercial use. Weathering of rocks releases phosphates into the soil and bodies of water. Plants can assimilate phosphate in the soil and incorporate it into organic molecules, making phosphorus available to consumers in terrestrial food webs. Waste and dead organisms are decomposed by fungi and bacteria, releasing phosphates back into the soil. Some phosphate leaches from the soil, entering rivers, lakes, and the ocean. Primary producers in aquatic food webs, such as algae and photosynthetic bacteria, assimilate phosphate, and organic phosphate is thus available to consumers in aquatic food webs. Like terrestrial food webs, phosphorus is reciprocally exchanged between phosphate dissolved in the ocean and organic phosphorus in marine organisms.

The movement of phosphorus from rock to living organisms is normally a very slow process, but some human activities speed up the process. Phosphate-bearing rock is often mined for use in the manufacture of fertilizers and detergents. This commercial production greatly accelerates the phosphorous cycle. In addition, runoff from agricultural land and the release of sewage into water systems can cause a local overload of phosphate. The increased availability of phosphate can cause overgrowth of algae. This reduces the oxygen level, causing eutrophication and the destruction of other aquatic species.

## Eutrophication and Dead Zones

**Eutrophication** occurs when excess phosphorus and nitrogen from fertilizer runoff or sewage causes excessive growth of algae. Algal blooms that block light and therefore kill aquatic plants in rivers, lakes, and seas. The subsequent death and decay of these organisms depletes dissolved oxygen, which leads to the death of aquatic organisms such as shellfish and fish. This process is responsible for **dead zones**, large areas in lakes and oceans near the mouths of rivers that are periodically depleted of their normal flora and fauna, and for massive fish kills, which often occur during the summer months (Figure 3.8). There are more than 500 dead zones worldwide. One of the worst dead zones is off the coast of the United States in the Gulf of Mexico. Fertilizer runoff from the Mississippi River basin created a dead zone, which reached its peak size of 8,776 square miles in 2017. Phosphate and nitrate runoff from fertilizers also negatively affect several lake and bay ecosystems including the Chesapeake Bay in the eastern United States.

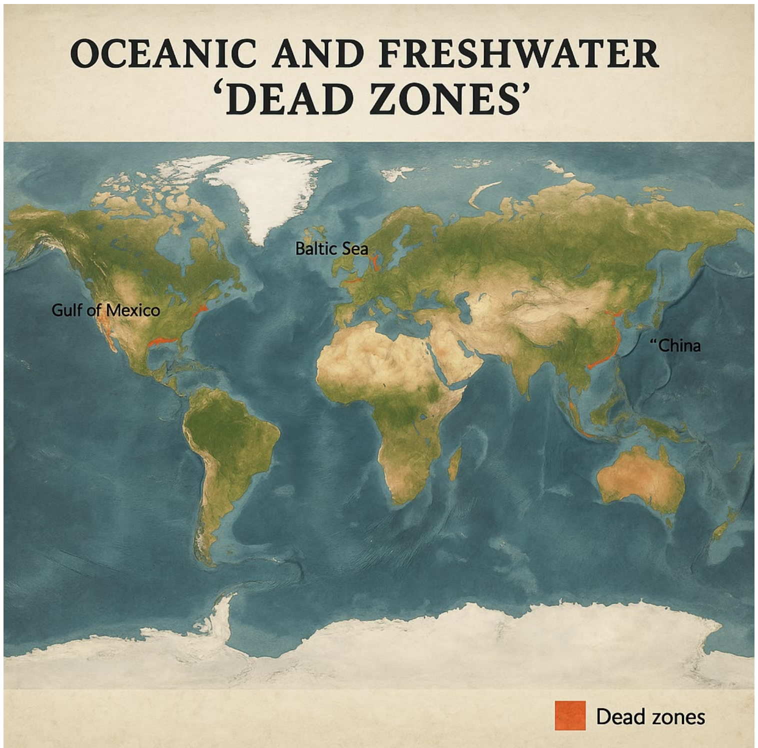


**Figure 3.8** Dead zones due to oxygen depletion. (credit: Grok AI)

Dead zones occur when phosphorus and nitrogen from fertilizers cause excessive growth of microorganisms, which depletes oxygen and kills fauna. This map shows dead zones around the world in 2024. Worldwide, large dead zones are found in coastal areas with high population density.

### *Everyday Connection: Chesapeake Bay*

The Chesapeake Bay has long been valued as one of the most scenic areas on Earth; it is now in distress and is recognized as a declining ecosystem. In the 1970s, the Chesapeake Bay was one of the first ecosystems to have identified dead zones, which continue to kill many fish and bottom-dwelling species, such as clams, oysters, and worms (figure 3.10). Several species have declined in the Chesapeake Bay due to surface water runoff containing excess nutrients from artificial fertilizer used on land.

The source of the fertilizers (with high nitrogen and phosphate content) is not limited to agricultural practices. There are many nearby urban areas and more than 150 rivers and streams empty into the bay that are carrying fertilizer runoff from lawns and gardens. Thus, the decline of Chesapeake Bay is a complex issue and requires the cooperation of industry, agriculture, and everyday homeowners.

The image (a) is a satellite image showing the Chesapeake Bay, an ecosystem affected by phosphate and nitrate runoff. Picture (b) shows a member of the Army Corps of Engineers holds a clump of oysters being used as a part of the oyster restoration effort in the bay.

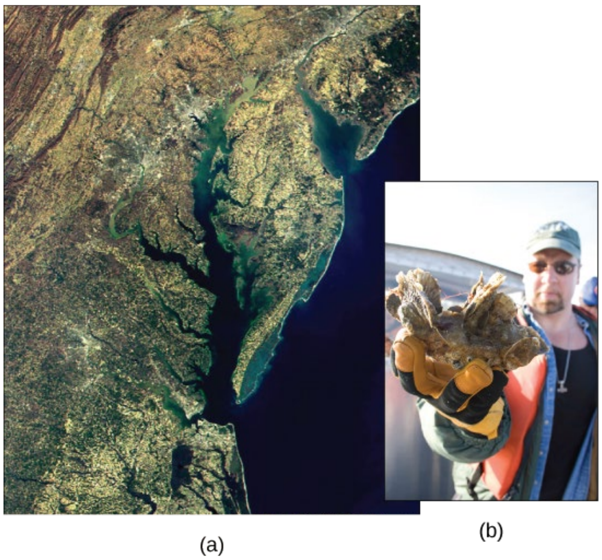


**Figure 3.9** Chesapeake Bay and a man holding an oyster. (credit (a): modification of work by NASA/MODIS; credit (b): modification of work by U.S. Army)

Of particular interest to conservationists is the oyster population; it is estimated that more than 200,000 acres of oyster reefs existed in the bay in the 1700s, but that number has now declined to only 36,000 acres. Oyster harvesting was once a major industry for Chesapeake Bay, but it declined 88 percent between 1982 and 2007. This decline was due not only to fertilizer runoff and dead zones but also to overexploitation. Oysters require a certain minimum population density because they must be near reproduce. Human activity has altered the oyster population and locations, greatly disrupting the ecosystem.

The restoration of the oyster population in Chesapeake Bay has been ongoing for several years with mixed success. Not only do many people find oysters good to eat, but they also clean up the bay. Oysters are filter feeders, and as they eat, they clean the water around them. In the 1700s, it was estimated that it took only a few days for the oyster population to filter the entire volume of the bay. Today, with changed water conditions, it is estimated that the present population would take nearly a year to do the same job.

Restoration efforts have been ongoing for several years by non-profit organizations, such as the Chesapeake Bay Foundation. The restoration goal is to find a way to increase population density so the oysters can reproduce more efficiently. Many disease-resistant varieties (developed at the Virginia Institute of Marine Science for the College of William and Mary) are now available and have been used in the construction of experimental oyster reefs. Efforts to clean and restore the bay by Virginia and Delaware have been hampered because much of the pollution entering the bay comes from other states, which stresses the need for inter-state cooperation to gain successful restoration. The new, hearty oyster strains have also spawned a new and economically viable industry, oyster aquaculture, which not only supplies oysters for food and profit but also has the added benefit of cleaning the bay.

## The Sulfur Cycle

Sulfur is an essential element for the molecules of living things. As part of the amino acid cysteine, it is critical to the three-dimensional shape of proteins. As shown in Figure 3.10, sulfur cycles among the oceans, land, and atmosphere. Atmospheric sulfur is found in the form of sulfur dioxide ($SO_2$), which enters the atmosphere in three ways: first, from the decomposition of organic molecules; second, from volcanic activity and geothermal vents; and third, from the burning of fossil fuels by humans.

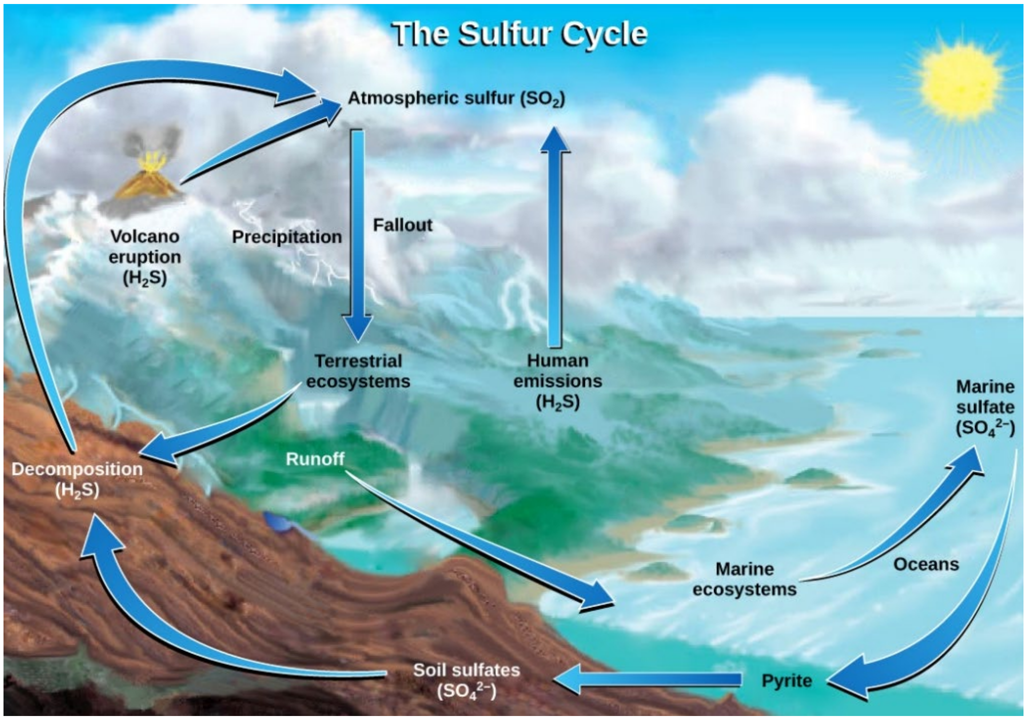


**Figure 3.10** Sulfur cycle. (credit: John M. Evans and Howard Perlman, USGS).

In the sulfur cycle, sulfur dioxide ($SO_2$) from the atmosphere is dissolved in precipitation as weak sulfuric acid or falls directly to Earth as fallout. This releases sulfates ($SO_4^{2-}$) into the soil and water. Soil sulfates can be carried as runoff into the water. Marine sulfate can form pyrite, and this can break down to release soil sulfates. Organisms in terrestrial and marine ecosystems assimilate sulfate, adding sulfur to organic molecules, such as proteins (not shown). Decomposition of these organisms returns sulfates to the soil. Microorganisms can convert sulfates to hydrogen sulfide ($H_2S$) and vice versa. Decomposition, volcanic eruptions, and human activities (including burning fossil fuels) can release hydrogen sulfide ($H_2S$) or sulfur dioxide into the atmosphere.

On land, sulfur is deposited in four major ways: precipitation, direct fallout from the atmosphere, rock weathering, and geothermal vents. Atmospheric sulfur is found in the form of sulfur dioxide ($SO_2$), and as rain falls through the atmosphere, sulfur is dissolved in the form of weak sulfuric acid ($H_2SO_4$). Sulfur can also fall directly from the atmosphere in a process called **fallout**. Also, as sulfur-containing rocks weather, sulfur is released into the soil. These rocks originate from ocean sediments that are moved to land by the geologic uplifting of ocean sediments. Terrestrial ecosystems can then make use of

these soil sulfates ($SO_4^{2-}$), which enter the food web by being taken up by plant roots. When these plants decompose and die, sulfur is released back into the atmosphere as hydrogen sulfide ($H_2S$) gas.
Sulfur enters the ocean in runoff from land, from atmospheric fallout, and from hydrothermal vents. Some ecosystems rely on microorganisms using sulfur as a biological energy source (in contrast to ecosystems with photosynthetic producers). This sulfur then supports marine ecosystems in the form of sulfates. Human activities have played a major role in altering the balance of the global sulfur cycle. The burning of large quantities of fossil fuels, especially from coal, releases sulfur dioxide, which reacts with the atmosphere to form sulfuric acid. Like nitric acid, sulfuric acid contributes to acid deposition.

# Chapter Four: Biodiversity Conservation

## Objectives

- Describe biodiversity and the benefits of biodiversity to humans
- Explain the effects of habitat loss, exotic species, and hunting on biodiversity
- Identify the early and predicted effects of climate change on biodiversity
- Explain the legislative framework for conservation and effects of habitat restoration

Biodiversity is a broad term for biological variety, and it can be measured at several organizational levels. Traditionally, ecologists have measured biodiversity by considering both the number of species and the number of individuals in each of those species. However, biologists are using measures of biodiversity at several levels of biological organization (including genes, populations, and ecosystems) to help focus efforts to preserve the biologically and technologically important elements of biodiversity.

When biodiversity loss through extinction is thought of as the loss of the passenger pigeon, the dodo, or, even, the woolly mammoth there seems to be no reason to care about it because these events happened long ago. How is the loss practically important for the welfare of the human species? Would these species have made our lives any better? From the perspective of evolution and ecology, the loss of a particular individual species, with some exceptions, may seem unimportant, but the current accelerated extinction rate means the loss of tens of thousands of species within our lifetimes. Much of this loss is occurring in tropical rainforests like the one pictured in image above, which are especially high-diversity ecosystems that are being cleared for timber and agriculture. This is likely to have dramatic effects on human welfare through the collapse of ecosystems and in addition to added costs to maintain food production, clean air and water, and improve human health.

Biologists recognize that human populations are embedded in ecosystems and are dependent on them, just as is every other species on the planet. Agriculture began after early hunter-gatherer societies first settled in one place and heavily modified their immediate environment: the ecosystem in which they existed. This cultural transition has made it difficult for humans to recognize their dependence on living things other than crops and domesticated animals on the planet. Today our technology modifies out the extremes of existence and allows many of us to live longer, more comfortable lives, but ultimately the human species cannot exist without its surrounding ecosystems.

Ecosystems provide food and sustenance to humanity. This includes living plants that grow in soil ecosystems and the animals that eat these plants (or other animals) as well as photosynthetic organisms in the oceans and the other organisms that eat them. Our ecosystems have provided and will provide many of the medications that maintain our health, which are commonly made from compounds found in living organisms. Ecosystems provide our clean water, which is held in lake and river ecosystems or passes through terrestrial ecosystems on its way into groundwater.

## Types of Biodiversity

A common meaning of biodiversity is simply the number of species in a location or on Earth; for example, the American Ornithologists' Union lists 2078 species of birds in North and Central America. This is one measure of bird biodiversity on the continent. More sophisticated measures of diversity consider the relative abundances of species. For example, a forest with 10 equally common species of trees is more diverse than a forest that has 10 species of trees wherein just one of those species makes up 95 percent of the trees rather than them being equally distributed. Biologists have also identified alternate measures of biodiversity, some of which are important in planning how to preserve biodiversity.

### *Genetic and Chemical Biodiversity*

Genetic diversity is one alternate concept of biodiversity. **Genetic diversity** (or variation) is the raw material for adaptation in a species. A species' future potential for adaptation depends on the genetic diversity held in the genomes of the individuals in populations that make up the species. The same is true for higher taxonomic categories. A genus with very different types of species will have more genetic diversity than a genus with species that look alike and have similar ecologies. The genus with the greatest potential for subsequent evolution is the most genetically diverse one.

Most genes code for proteins, which in turn carry out the metabolic processes that keep organisms alive and reproducing. Genetic diversity can also be conceived of as **chemical diversity** in those species with different genetic makeups produce different assortments of chemicals in their cells (proteins as well as the products and byproducts of metabolism). This chemical diversity is important for humans because of the potential uses for these chemicals, such as medications. For example, the drug eptifibatide is derived from rattlesnake venom and is used to prevent heart attacks in individuals with certain heart conditions.

At present, it is far cheaper to discover compounds made by an organism than to imagine them and then synthesize them in a laboratory. Chemical diversity is one way to measure diversity that is important to human health and welfare. Through selective breeding, humans have domesticated animals, plants, and fungi, but even this diversity is suffering losses because of market forces and increasing globalism in human agriculture and migration. For example, international seed companies produce only a very few varieties of a given crop and provide incentives around the world for farmers to buy these few varieties while abandoning their traditional varieties, which are far more diverse. The human population depends on crop diversity directly as a stable food source and its decline is troubling biologists and agricultural scientists.

### *Ecosystem*

**An ecosystem** is a geographic area where biotic (plants, animals, microorganisms) and abiotic (sunlight, soil, water, climate) components interact as a functional unit

### *Ecosystems Diversity*

It is also useful to define **ecosystem diversity**: the number of different ecosystems on Earth or in a geographical area. Whole ecosystems can disappear even if some of the species might survive by adapting to other ecosystems. The loss of an ecosystem means the loss of interactions between species, the loss of unique features of coadaptation, and the loss of biological productivity that an ecosystem can create. An example of a largely extinct ecosystem in North America is the prairie ecosystem.
Prairies once spanned central North America from the boreal forest in northern Canada down into Mexico. They are now all but gone, replaced by crop fields, pasture lands, and suburban sprawl. Many of the species survive, but the hugely productive ecosystem that was responsible for creating our most productive agricultural soils is now gone. Consequently, their soils are now being depleted unless they are maintained artificially at greater expense. The decline in soil productivity occurs because the interactions in the original ecosystem have been lost; this was a far more important loss than the relatively few species that were driven extinct when the prairie ecosystem was destroyed.

A **terrestrial ecosystem** is a land-based community of organisms (plants, animals, microbes) interacting with their abiotic environment (soil, climate, atmosphere). Covering diverse biomes—including forests, grasslands, deserts, and tundra—these ecosystems are defined by distinct vegetation structures, temperature ranges, and precipitation levels.

**Marine ecosystems** are generally more biodiverse and nutrient rich.

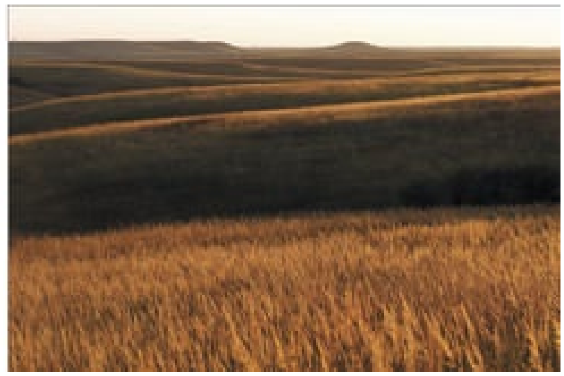

**Figure 4.1** Marine (left) and terrestrial (right) ecosystems. (Credit: Ocean Image Bank, NOAA Coral Reef Image Gallery).

**Key Aspects of Terrestrial Ecosystems:**

- **Biomes** are large, distinct geographical regions defined by climate, soil, and dominant vegetation, containing communities of plants and animals adapted to their environment. Key types include terrestrial (forest, desert, grassland, tundra) and aquatic (marine, freshwater) zones. These zones are driven by temperature and precipitation.

- **Types & Biomes:**
    - **Forests:** Dominated by trees (tropical rainforests, temperate deciduous, and boreal/taiga), covering ~31% of land.
    - **Grasslands/Savannas:** Areas dominated by grass with few trees.
    - **Deserts:** Arid regions with sparse vegetation and specialized wildlife.
    - **Tundra:** Cold, treeless environments with low-growing vegetation.
    - **Marine** biome is the largest in the world, covering roughly 70-75% of the Earth's surface and containing high levels of dissolved salt
    - **Others:** Chaparral, montane systems, and agricultural lands.

- **Key Components:** They rely on soil composition, water availability, and temperature to determine the types of vegetation and animal life that can thrive.
- **Ecological Functions:** Terrestrial ecosystems play a crucial role in carbon sequestration, nutrient cycling, and water purification.
- **Environmental Impact:** These systems are currently experiencing declining resilience due to climate change, deforestation, and land development.

## Species Diversity

Despite considerable effort, knowledge of the species that inhabit the planet is limited. A recent estimate suggests that the eukaryote species for which science has names, about 1.5 million species, account for less than 20 percent of the total number of eukaryote species present on the planet (8.7 million species, by one estimate). Estimates of numbers of prokaryotic species are largely guesses, but biologists agree that science has only just begun to catalog their diversity. Even with what is known, there is no centralized repository of names or samples of the described species; therefore, there is no way to be sure that the 1.5 million descriptions is an accurate number. It is a best guess based on the opinions of experts on different taxonomic groups. Given that Earth is losing species at an accelerating pace, science knows little about what is being lost.

There are various initiatives to catalog described species in accessible and more organized ways, and the internet is facilitating that effort. Nevertheless, at the current rate of species description, which according to the State of Observed Species[1] reports is 17,000–20,000 new species a year, it would take close to 500 years to describe all the species currently in existence. The task, however, is becoming increasingly impossible over time as **extinction** removes species from Earth faster than can be described.

Naming and counting species may seem an unimportant pursuit given the other needs of humanity, but it is not simply an accounting. Describing species is a complex process by which biologists determine an organism's unique characteristics and whether that organism belongs to any other described species. It allows biologists to find and recognize the species after the initial discovery to follow up on questions about its biology. Subsequent Quent research will produce the discoveries that make the species valuable to humans and to our ecosystems. Without a name and description, a species cannot be studied exhaustively and in a coordinated way by multiple scientists.

## Patterns of Biodiversity

Biodiversity is not evenly distributed on the planet. Lake Victoria contained almost 500 species of cichlids (only one family of fish is present in the lake) before the introduction of an exotic species in the 1980s and 1990s caused mass extinction. All these species were found only in Lake Victoria, which is to say they were endemic. **Endemic species** are found in only one location. For example, the blue jay is endemic to North America, while the Barton Springs salamander is endemic to the mouth of one spring in Austin, Texas. Endemics with highly restricted distributions, like the Barton Springs salamander, are particularly vulnerable to extinction.

Higher taxonomic levels, such as genera and families, can also be endemic.
Lake Huron contains about 79 species of fish, all of which are found in many other lakes in North America. What accounts for the difference in diversity between Lake Victoria and Lake Huron? Lake Victoria is a tropical lake, while Lake Huron is a temperate lake. Lake Huron in its present form is only about 7,000 years old, while Lake Victoria in its present form is about 15,000 years old. These two factors, latitude and age, are two of several hypotheses biogeographers have suggested to explain biodiversity patterns on Earth. One of the oldest observed patterns in ecology is that biodiversity in almost every taxonomic group of organism increases as latitude declines. In other words, biodiversity increases closer to the equator (Figure 4.2).

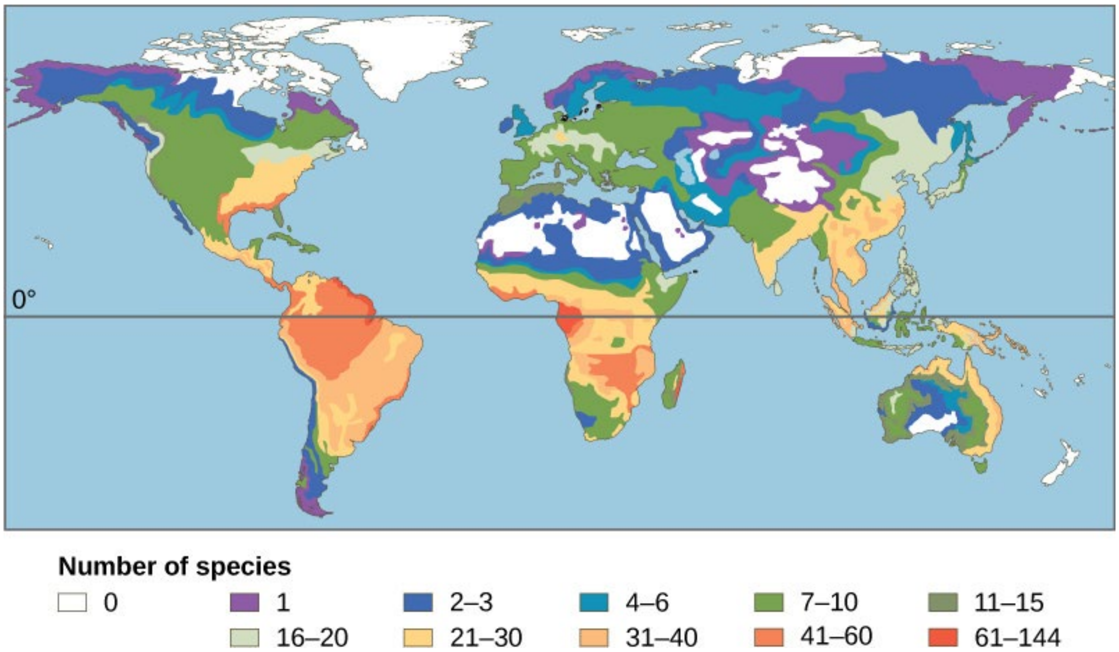


**Figure 4.2** Number of species. (credit: https://www.chegg.com/homework-help/questions-and-answers)

Figure 4.2 illustrates the number of amphibian species across the globe and shows the trend toward higher biodiversity at lower latitudes. It is not yet clear why biodiversity increases closer to the equator, but hypotheses include the greater age of the ecosystems in the tropics versus temperate regions, which were largely devoid of life or drastically impoverished during the last ice age. The greater age provides more time for speciation. Another possible explanation is the greater energy the tropics receive from the sun versus the lesser energy input in temperate and polar regions. But scientists have not been able to explain how greater energy input could translate into more species. The complexity of tropical ecosystems may promote speciation by increasing the **habitat heterogeneity**, or number of ecological niches, in the tropics relative to higher latitudes.

Greater heterogeneity provides more opportunities for coevolution, specialization, and perhaps greater selection pressures leading to population differentiation. However, this hypothesis suffers from some circularity; ecosystems with more species encourage speciation, but how did they get more species to begin with? The tropics have been perceived as being more stable than temperate regions, which have a pronounced climate and day-length seasonality. The tropics have their own forms of seasonality, such as rainfall, but they are generally assumed to be more stable environments, and this stability might promote speciation.

Regardless of the mechanisms, it is certainly true that biodiversity is greatest in the tropics. The number of endemic species is higher in the tropics. The tropics also contain more biodiversity hotspots. At the same time, our knowledge of the species living in the tropics is lowest and because of recent, heavy human activity the potential for biodiversity loss is greatest.

## Importance of Biodiversity

Loss of biodiversity eventually threatens other species. We do not impact directly because of their interconnectedness as species disappear from an ecosystem. Other species are threatened by the changes in available resources. Biodiversity is important to the survival and welfare of human populations because it has impacts on our health and our ability to feed ourselves through agriculture and harvesting populations of wild animals.

## Human Health

Many medications are derived from natural chemicals made by a diverse group of organisms. For example, many plants produce **secondary plant compounds**, which are toxins used to protect the plant from insects and other animals that eat them. Some of these secondary plant compounds also work as human medicines. Contemporary societies that live close to the land often have a broad knowledge of the medicinal uses of plants growing in their area. For centuries in Europe, older knowledge about the medical uses of plants was compiled in herbal books that identified the plants and their uses. Humans are not the only animals to use plants for medicinal reasons. The other great apes, orangutans, chimpanzees, bonobos, and gorillas have all been observed self-medicating with plants.

Modern pharmaceutical science also recognizes the importance of these plant compounds. Examples of significant medicines derived from plant compounds include aspirin, codeine, digoxin, atropine, and vincristine (Figure 4.3). Many medications were derived from plant extracts but are now synthesized. It is estimated that, at one time, 25 percent of modern drugs contained at least one plant extract. That number has probably decreased to about 10 percent as natural plant ingredients are replaced by synthetic versions of the plant compounds. Antibiotics, which are responsible for extraordinary improvements in health and lifespans in developed countries, are compounds largely derived from fungi and bacteria.

**Figure 4.3** Catharanthus roseus or the Madagascar periwinkle (credit: Forest and Kim Starr)

Catharanthus roseus, the Madagascar periwinkle, has various medicinal properties. Among other uses, it is a source of vincristine, a drug used in the treatment of lymphomas

In recent years, animal venoms and poisons have excited intense research for their medicinal potential. By 2007, the FDA had approved five drugs based on animal toxins to treat diseases such as hypertension, chronic pain, and diabetes. Another five drugs are undergoing clinical trials and at least six drugs are being used in other countries. Other toxins under investigation come from mammals, snakes, lizards, various amphibians, fish, snails, octopuses, and scorpions. Aside from representing billions of dollars in profits, these medications improve people's lives. Pharmaceutical companies are actively looking for new natural compounds that can function as medicines. It is estimated that one third of pharmaceutical research and development is spent on natural compounds and that about 35 percent of new drugs brought to market between 1981 and 2002 were from natural compounds.

Finally, it has been argued that humans benefit psychologically from living in a biodiverse world. The chief proponent of this idea is entomologist E. O. Wilson. He argues that human evolutionary history has adapted us to living in a natural environment and that built environments generate stresses that affect human health and well-being. There is considerable research into the psychologically regenerative benefits of natural landscapes that suggest the hypothesis may hold some truth.

### Agricultural Biodiversity

Since the beginning of human agriculture more than 10,000 years ago, human groups have been breeding and selecting crop varieties. This crop diversity matched the cultural diversity of highly subdivided populations of humans. For example, potatoes were domesticated beginning around 7,000 years ago in the central Andes of Peru and Bolivia. The people in this region traditionally lived in relatively isolated settlements separated by mountains. The potatoes grown in that region belong to seven species and the number of varieties is likely in the thousands. Each variety has been bred to thrive at elevations and soil and climate conditions. The diversity is driven by the diverse demands of the dramatic elevation changes, the limited movement of people, and the demands created by crop rotation for different varieties that will do well in different fields.

Every plant, animal, and fungus that has been cultivated by humans has been bred from original wild ancestor species into diverse varieties arising from the demands for food value, adaptation to growing conditions, and resistance to pests. The potato demonstrates a well-known example of the risks of low crop diversity: during the tragic Irish potato famine (1845–1852 AD), the single potato variety grown in Ireland became susceptible to a potato blight, wiping out the crop. The loss of the crop led to famine, death, and mass emigration. Resistance to disease is a chief benefit to maintaining crop biodiversity and lack of diversity in contemporary crop species carries similar risks. Seed companies, which are the source of most crop varieties in developed countries, must continually breed new varieties to keep up with evolving pest organisms. These same seed companies, however, have participated in the decline of the number of varieties available as they focus on selling fewer varieties in more areas of the world replacing traditional local varieties.

The ability to create new crop varieties relies on the diversity of varieties available and the availability of wild forms related to the crop plant. These wild forms are often the source of new gene variants that can be bred with existing varieties to create varieties with new attributes. Loss of wild species related to a crop will mean the loss of potential in crop improvement. Maintaining the genetic diversity of wild species related to domesticated species ensures our continued supply of food. Since the 1920s, government agriculture departments have maintained seed banks of crop varieties to maintain crop diversity.

In 2008, the Svalbard Global seed Vault, located on Spitsbergen Island, Norway, (Figure 4.4) began storing seeds from around the world as a backup system to the regional seed banks. The Svalbard seed vault is deep into the rock of the arctic island. Conditions within the vault are maintained at ideal temperature and humidity for seed survival, but the deep underground location of the vault in the arctic means that failure of the vault's systems will not compromise the climatic conditions inside the vault.

**Figure 4.4** The Svalbard Global Seed Vault. (credit: Michael Major)
The Svalbard Global Seed Vault is a storage facility for seeds of Earth's diverse crops. (credit: Mari Tefre, Svalbard Global Seed Vault). The Svalbard seed vault is located on Spitsbergen Island in Norway, which has an arctic climate. Why might an arctic climate be good for seed storage?

Although crops are largely under our control, our ability to grow them is dependent on the biodiversity of the ecosystems in which they are grown. That biodiversity creates the conditions under which crops can grow through what are known as ecosystem services, valuable conditions or processes that are carried out by an ecosystem. Although some agricultural soils are rendered sterile using controversial pesticide treatments, most contain a huge diversity of organisms that maintain nutrient cycles, breaking down organic matter into nutrient compounds that crops need for growth. These organisms also maintain soil texture that affects water and oxygen dynamics in the soil that are necessary for plant growth. Replacing the work of these organisms in forming arable soil is practically not possible. These kinds of processes are called ecosystem services. They occur within ecosystems, such as soil ecosystems, because of the diverse metabolic activities of the organisms living there, but they provide benefits to human food production, drinking water availability, and breathable air.

Other key ecosystem services related to food production are plant pollination and crop pest control. It is estimated that honeybee pollination within the United States brings in $1.6 billion per year; other pollinators contribute up to $6.7 billion. Over 150 crops in the United States require pollination to produce. Many honeybee populations are managed by beekeepers who rent out their hives' services to farmers. Honeybee populations in North America have been suffering large losses caused by a syndrome known as colony collapse disorder, a new phenomenon with an unclear cause. Other pollinators include a diverse array of other bee species and various insects and birds. Loss of these species would make growing crops requiring pollination impossible, increasing dependence on other crops.

Finally, humans compete for their food with crop pests, most of which are insects. Pesticides control these competitors, but these are costly and lose their effectiveness over time as pest populations adapt. They also lead to collateral damage by killing non-pest species as well as beneficial insects like honeybees and risking the health of agricultural workers and consumers. Moreover, these pesticides may migrate from the fields where they are applied and do damage to other ecosystems like streams, lakes, and even the ocean.

Ecologists believe that the bulk of the work in removing pests is done by predators and parasites of those pests, but the impact has not been well studied. A review found that in 74 percent of studies that looked for an effect of landscape complexity (forests and fallow fields near to crop fields) on natural enemies of pests, the greater the complexity, the greater the effect of pest-suppressing organisms. Another experimental study found that introducing multiple enemies of pea aphids (an important alfalfa pest) increased the yield of alfalfa significantly. This study shows that a diversity of pests is more effective at control than one single pest. Loss of diversity in pest enemies will inevitably make it more difficult and costly to grow food. The world's growing human population faces significant challenges in the increasing costs and other difficulties associated with producing food.

### Wild Food Sources

In addition to growing crops and raising animals, humans obtain food resources from wild populations, primarily wild fish populations. For about one billion people, aquatic resources provide the main source of animal protein. But since 1990, production from global fisheries has declined. Despite considerable effort, few fisheries on Earth manage sustainability.

Fishery extinctions rarely lead to complete extinction of the harvested species, but rather to a radical restructuring of the marine ecosystem in which a dominant species is so over-harvested that it becomes a minor player, ecologically. In addition to humans losing the food source, these alterations affect many other species in ways that are difficult or impossible to predict. The collapse of fisheries has dramatic and long-lasting effects on local human populations that work in the fishery. In addition, the loss of an inexpensive protein source to populations that cannot afford to replace it will increase the cost of living and limit societies in other ways. In general, the fish taken from fisheries have shifted to smaller species and the larger species are overfished.

### Habitat Loss

Humans rely on technology to modify their environment and replace certain functions that were once performed by the natural ecosystem. Other species cannot do this. Elimination of their habitat, whether it is a forest, coral reef, grassland, or flowing river, will kill the individuals in the species. Remove the entire habitat within the range of a species and, unless they are one of the few species that do well in human-built environments, the species will become extinct. Consider the exceptional biodiversity of Sumatra: it is home to one species of orangutan, a species of critically endangered elephant, and the Sumatran tiger, but half of Sumatra's Forest is now gone.

The neighboring island of Borneo, home to the other species of orangutan, has lost a similar area of forest. Forest loss continues in protected areas of Borneo. The orangutan in Borneo is listed as endangered by the International Union for Conservation of Nature (IUCN), but it is simply the most visible of thousands of species that will not survive the disappearance of the forests of Borneo. The forests are removed for timber and to plant palm oil plantations (Figure below). Palm oil is used in many products including food products, cosmetics, and biodiesel in Europe. A 5-year estimate of global forest cover loss for the years from 2000 to 2005 was 3.1 percent. These represent the extinction of species unique to those areas. An oil palm plantation in Sabah province Borneo, Malaysia, replaces native forest habitat that a variety of species depended on to live (Figure 4.5).

**Figure 4.5** Oil palm plantation in Sabah province Borneo, Malaysia (credit: Lian Pin Koh)

Habitat destruction can affect ecosystems other than forests. Rivers and streams are important ecosystems and are frequently the target of habitat modification through building and from damming or water removal. Damming of rivers affects flows and access to all parts of a river. Altering a flow regime can reduce or eliminate populations that are adapted to seasonal changes in flow. For example, an estimated 91 percent of river lengths in the United States have been modified with damming or bank modifications. Many fish species in the United States, especially rare species or species with restricted distributions, have seen declines caused by river damming and habitat loss. Research has confirmed that species of amphibians that must carry out parts of their life cycles in both aquatic and terrestrial habitats are at greater risk of population decline and extinction because of the increased likelihood that one of their habitats or access between them will be lost. This is of particular concern because amphibians have been declining in numbers and going extinct more rapidly than many other groups for a variety of possible reasons.

### Overharvesting and the Tragedy of Commons

Overharvesting is a serious threat to many species, but particularly to aquatic species. There are many examples of regulated fisheries (including hunting of marine mammals and harvesting of crustaceans and other species) monitored by fisheries scientists that have nevertheless collapsed. The western Atlantic cod fishery is the most spectacular in recent collapse. While it was a hugely productive fishery for 400 years, the introduction of modern factory trawlers in the 1980s and the pressure on the fishery led to it becoming unsustainable.

The causes of fishery collapse are both economic and political in nature. Most fisheries are managed as a common resource, available to anyone willing to fish, even when the fishing territory lies within a country's territorial waters.

### Tragedy of Commons

The tragedy of the commons describes a situation where a shared resource is depleted or damaged because individual self-interest overrides the collective good. It's a social trap where short-term gains for individuals lead to long-term harm for the community. Common resources are subject to an economic pressure known as the **tragedy of the commons**, in which fishers have little motivation to exercise restraint in harvesting a fishery when they do not own the fishery. The general outcome of harvests of resources held in common is their overexploitation. While large fisheries are regulated to attempt to avoid this pressure, it still exists in the background.

This overexploitation is exacerbated when access to the fishery is open and unregulated and when technology gives fishers the ability to overfish. In a few fisheries, the biological growth of the resource is less than the potential growth of the profits made from fishing if that time and money were invested elsewhere. In these cases, whales are an example, economic force that will drive toward fishing the population to extinction. For the most part, fishery extinction is not equivalent to biological extinction, the last fish of a species is rarely fished out of the ocean. But there are some instances in which true extinction is a possibility. Whales have slow-growing populations and are at risk of complete extinction through hunting. Also, there are some species of sharks with restricted distributions that are at risk of extinction. The groupers are another population of generally slow-growing fish that, in the Caribbean, includes several species that are at risk of extinction from overfishing.

Coral reefs are extremely diverse marine ecosystems that face peril from several processes. Reefs are home to 1/3 of the world's marine fish species, about 4000 species, despite making up only one percent of marine habitat. Most home marine aquaria house coral reef species that are wild-caught organisms, not cultured organisms. Although no marine species is known to have been driven extinct by pet trade, there are studies showing that populations of some species have declined in response to harvesting, indicating that the harvest is not sustainable at those levels. There are also concerns about the effect of pet trade on some terrestrial species such as turtles, amphibians, birds, plants, and even the orangutans.

**Bush meat** is the generic term used for wild animals killed for food. Hunting is practiced throughout the world, but hunting practices, particularly in equatorial Africa and parts of Asia, are believed to threaten several species with extinction. Traditionally, bush meat in Africa was hunted to feed families directly; however, recent commercialization of the practice now has bush meat available in grocery stores, which has increased harvest rates to the level of unsustainability. Additionally, human population growth has increased the need for protein foods that are not being met by agriculture. Species threatened by the bush meat trade are mostly mammals including many monkeys and the great apes living in the Congo basin.

## Exotic Species

**Exotic species** are species that have been intentionally or unintentionally introduced by humans into an ecosystem in which they did not evolve. Human transportation of people and goods, including the intentional transport of organisms for trade, has dramatically increased the introduction of species into new ecosystems. These new introductions are sometimes at distances that are well beyond the capacity of the species to ever travel itself and outside the range of the species' natural predators.

Most exotic species introductions probably fail because of the low number of individuals introduced or poor adaptation to the ecosystem they enter. Some species, however, have characteristics that can make them especially successful in a new ecosystem. These exotic species often undergo dramatic population increases in their new habitat and reset the ecological conditions in the new environment, threatening the species that exist there. When this happens, the exotic species also becomes an invasive species. Invasive species can threaten other species through competition for resources, predation, or disease.

Lakes and islands are particularly vulnerable to threats of extinction from introduced species. In Lake Victoria, the intentional introduction of the Nile perch was largely responsible for the extinction of about 200 species of cichlids. The accidental introduction of the brown tree snake via aircraft from the Solomon Islands to Guam in 1950 has led to the extinction of three species of birds and three to five species of reptiles' endemic to the island. Several other species are still threatened. The brown tree snake is adept at exploiting human transportation to migrate; one was even found on an aircraft arriving in Corpus Christi, Texas. Constant vigilance on the part of airport, military, and commercial aircraft personnel is required to prevent the snake from moving from Guam to other islands in the Pacific, especially Hawaii. Islands do not make up a large area of land on the globe, but they do contain a disproportionate number of endemic species because of their isolation from mainland ancestors.

Many introductions of aquatic species, both marine and freshwater, have occurred when ships have dumped ballast water taken on at a port of origin into waters at a destination port. Water from the port of origin is pumped into tanks on a ship empty of cargo to increase stability. The water is drawn from the ocean or estuary of the port and typically contains living organisms such as plant parts, microorganisms, eggs, larvae, or aquatic animals. The water is then pumped out before the ship takes on cargo at the destination port, which may be on a different continent. The zebra mussel was introduced to the Great Lakes from Europe prior to 1988 in ship ballast. The zebra mussels in the Great Lakes have cost the industry millions of dollars in cleanup costs to maintain water intake and other facilities.

The mussels have also altered the ecology of the lakes dramatically. They threaten native mollusk populations, but have also benefited some species, such as smallmouth bass. The mussels are filter feeders and have dramatically improved water clarity, which in turn has allowed aquatic plants to grow along shorelines, providing shelter for young fish where it did not exist before. The European green crab, *Carcinus maenas*, was introduced to San Francisco Bay in the late 1990s, likely in ship ballast water, and has spread north along the coast to Washington. The crabs have been found to dramatically reduce the abundance of native clams and crabs with resulting increases in the prey of native crabs.

Invading exotic species can also be disease organisms. It now appears that the global decline in amphibian species recognized in the 1990s is, in some part, caused by the fungus *Batrachochytrium dendrobatidis*, which causes the disease **chytridiomycosis.** There is evidence that the fungus is native to Africa and may have been spread throughout the world by transport of a commonly used laboratory and pet species: the African clawed frog, *Xenopus laevis*. It may well be that biologists themselves are responsible for spreading this disease worldwide. The North American bullfrog, *Rana catesbeiana*, which has also been widely introduced as a food animal, but which easily escapes captivity, survives most infections of *B. dendrobatidis* and can act as a reservoir for the disease.

**Figure 4.6** Limosa harlequin frog (*Atelopus limosus*) (credit: Brian Gratwicke)

This Limosa harlequin frog (Atelopus limosus), an endangered species from Panama, died from a fungal disease called chytridiomycosis. The red lesions are symptomatic of the disease.

Early evidence suggests that another fungal pathogen, *Geomyces destructans*, introduced from Europe is responsible for **white-nose syndrome**, which infects cave-hibernating bats in eastern North America and has spread from a point of origin in western New York State. The disease has decimated bat populations and threatens extinction of species already listed as endangered: the Indiana bat, *Myotis sodalis*, and potentially the Virginia big-eared bat, *Corynorhinus townsendii virginianus*. How the fungus was introduced is unknown, but one logical presumption would be that recreational cavers unintentionally brought the fungus on clothes or equipment from Europe.

**Figure 4.7** Brown bat in Greeley Mine, Vermont, suffering from white-nose syndrome. (credit: modification of work by Marvin Moriarty, USFWS).

## Climate Change

Climate change, and specifically the anthropogenic warming trend presently underway, is recognized as a major extinction threat, particularly when combined with other threats such as habitat loss. Anthropogenic warming of the planet has been observed and is hypothesized to continue due to past and continuing emission of greenhouse gases, primarily carbon dioxide and methane, into the atmosphere caused by the burning of fossil fuels and deforestation.

These gases decrease the degree to which Earth can radiate heat energy created by the sunlight that enters the atmosphere. The changes in climate and energy balance caused by increasing greenhouse gases are complex and our understanding of them depends on predictions generated from detailed computer models. Scientists generally agree that the present warming trend is caused by humans and some of the likely effects include dramatic and dangerous climate changes in the coming decades. However, there is still debate and a lack of understanding about specific outcomes. Scientists disagree about the likely magnitude of the effects on extinction rates, with estimates ranging from 15 to 40 percent of species committed to extinction by 2050.

Scientists do agree that climate change will alter regional climates, including rainfall and snowfall patterns, making habitats less hospitable to the species living in them. The warming trend will shift colder climates toward the north and south poles, forcing species to move with their adapted climate norms, but also to face habitat gaps along the way. The shifting ranges will impose new competitive regimes on species as they find themselves in contact with other species do not present in their historic range. One such unexpected species is the contact between polar bears and grizzly bears. Previously, these two species had separate ranges. Now, their ranges are overlapping and there are documented cases of these two species mating and producing viable offspring. Changing climates also throw off the delicate timing adaptations that species have to seasonal food resources and breeding times. Scientists have already documented many contemporary mismatches to shifts in resource availability and timing. Range shifts are already being observed: for example, on average, European bird species ranges have moved 91 km (56.5 mi) northward. The same study suggested that the optimal shift based on warming trends was double that distance, suggesting that the populations are not moving quickly enough. Range shifts have also been observed in plants, butterflies, other insects, freshwater fishes, reptiles, amphibians, and mammals.

Climate gradients will also move up mountains, eventually crowding species higher in altitude and eliminating the habitat for those species adapted to the highest elevations. Some climates will completely disappear. The rate of warming appears to accelerate in the arctic, which is recognized as a serious threat to polar bear populations that require sea ice to hunt seals during the winter months: seals are the only source of protein available to polar bears. A trend to decreasing sea ice coverage has occurred since observations began in the mid-twentieth century. The rate of decline observed in recent years is far greater than previously predicted by climate models (Figure 4.8).


**Figure 4.8** The effect of global warming and retreat of Grinnell Glacier. (credit: USGS, GNP)

The effect of global warming can be seen in the continuing retreat of the Grinnell Glacier. The mean annual temperature in Glacier National Park has increased 1.33°C since 1900. The loss of a glacier results in the loss of summer meltwaters, sharply reducing seasonal water supplies and severely affecting local ecosystems.

Finally, global warming will raise ocean levels due to meltwater from glaciers and the greater volume occupied by warmer water. Shorelines will be inundated, reducing island size, which will influence some species, and several islands will disappear entirely. Additionally, the gradual melting and subsequent refreezing of the poles, glaciers, and higher elevation mountains, a cycle that has provided freshwater to environments for centuries, will be altered. This could result in an overabundance of salt water and a shortage of fresh water.

### *Conservation of Biodiversity*

The threats to biodiversity at the genetic, species, and ecosystem levels have been recognized for some time. In the United States, the first national park with land set aside to remain in a wilderness state was Yellowstone Park in 1890. However, attempts to preserve nature for various reasons have occurred for centuries. Today, the main efforts to preserve biodiversity involve legislative approaches to regulate human and corporate behavior, setting aside protected areas, and habitat restoration.

### *Changing Human Behavior*

Legislation has been enacted to protect species throughout the world. The legislation includes international treaties as well as national and state laws. The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) treaty came into force in 1975. The treaty, and the national legislation that supports it, provides a legal framework for preventing "listed" species from being transported across nations' borders, thus protecting them from being caught or killed in the first place when the purpose involves international trade. The listed species that are protected to one degree or another by the treaty number some 33,000. The treaty is limited in its reach because it only deals with the international movement of organisms or their parts. It is also limited by various countries' ability or willingness to enforce the treaty and supporting legislation. The illegal trade in organisms and their parts is probably a market in hundreds of millions of dollars.

Within many countries there are laws that protect endangered species and that regulate hunting and fishing. In the United States, the Endangered Species Act was enacted in 1973. When an at-risk species is listed by the Act, the U.S. Fish & Wildlife Service is required by law to develop a management plan to protect the species and bring it back to sustainable numbers. The Act, and others like it in other countries, is a useful tool, but it suffers because it is often difficult to get a species listed, or to get an effective management plan in place once a species is listed. Additionally, species may be controversially taken off the list without necessarily having had a change in their situation. More fundamentally, the approach to protecting individual species rather than entire ecosystems (although the management plans commonly involve protection of the individual species' habitat) is both inefficient and focuses efforts on a few highly visible and often charismatic species, perhaps at the expense of other species that go unprotected.

The Migratory Bird Treaty Act (MBTA) is an agreement between the United States and Canada that was signed into law in 1918 in response to declines in North American bird species caused by hunting. The Act now lists over 800 protected species. It makes it illegal to disturb or kill the protected species or distribute their parts (much of the hunting of birds in the past was for their feathers). Examples of protected species include northern cardinals, the red-tailed hawk, and the American black vulture.

Global warming is expected to be a major driver of biodiversity loss. Many governments are concerned about the effects of anthropogenic global warming, primarily on their economies and food resources. Since greenhouse gas emissions do not respect national boundaries, the effort to curb them is an international one. The international response to global warming has been mixed. The Kyoto Protocol, an international agreement that came out of the United Nations Framework Convention on Climate Change that committed countries to reducing greenhouse gas emissions by 2012, was ratified by some countries, but spurned by others. Two countries that were especially important in terms of their potential impact that did not ratify the Kyoto protocol were the United States and China. Some goals for reduction in greenhouse gases were met and exceeded by individual countries, but, worldwide, the effort to limit greenhouse gas production is failing. The intended replacement for the Kyoto Protocol has not materialized because governments cannot agree on timelines and benchmarks. Meanwhile, the resulting costs to human societies and biodiversity predicted by most climate scientists will be high.

As already mentioned, the non-profit, non-governmental sector plays a large role in conservation effort both in North America and around the world. The approaches range from species-specific organizations to the broadly focused IUCN and Trade Records Analysis of Flora and Fauna in Commerce (TRAFFIC). Nature Conservancy takes a novel approach. It purchases land and protects it to set up preserves for ecosystems. Ultimately, human behavior will change when human values change. At present, the growing urbanization of the human population is a force that mitigates against valuing biodiversity, because many people no longer encounter natural environments and the species that inhabit them.

## Conservation in Preserves

Establishment of wildlife and ecosystem preserves is one of the key tools in conservation efforts (Figure 4.9) A preserve is an area of land set aside with varying degrees of protection for the organisms that exist within the boundaries of the preserve. Preserves can be effective for protecting both species and ecosystems, but they have some serious drawbacks.

National parks, such as Grand Teton National Park in Wyoming, help conserve biodiversity. (credit: Don DeBold)

**Figure 4.9** Grand Teton National Park in Wyoming (credit: Don DeBold).

A simple measure of success in setting aside preserves for biodiversity protection is to set a target percentage of land or marine habitat to protect. However, a more detailed preserve design and choice of location is usually necessary because of the way protected lands are allocated and how biodiversity is distributed: protected lands tend to contain less economically valuable resources rather than being set aside specifically for the species or ecosystems at risk. In 2003, the IUCN World Parks Congress estimated that 11.5 percent of Earth's land surface was covered by preserves of various kinds. This area is greater than previous goals; however, it only represents 9 out of 14 recognized major biomes and research has shown that 12 percent of all species live outside preserves; these percentages are much higher when threatened species are considered and when only high-quality preserves are considered. For example, high quality preserves include only about 50 percent of threatened amphibian species.

The conclusion must be that either the percentage of areas protected must be increased, the percentage of high-quality preserves must be increased, or preserves must be targeted with greater attention to biodiversity protection. Researchers argue that more attention to the latter solution is required.

**A biodiversity hotspot** is a conservation concept developed by Norman Myers in 1988. Hotspots are geographical areas that contain high numbers of endemic species. The purpose of the concept was to identify important locations on the planet for conservation efforts, a kind of conservation triage. By protecting hotspots, governments can protect a larger number of species. The original criteria for a hotspot included the presence of 1500 or more species of endemic plants and 70 percent of the area disturbed by human activity. There are now 34 biodiversity hotspots that contain large numbers of endemic species, which include half of Earth's endemic plants.

Conservation International has identified 34 biodiversity hotspots. Although these cover only 2.3 percent of the Earth's surface, 42 percent of the terrestrial vertebrate species and 50 percent of the world's plants are endemic to those hotspots.

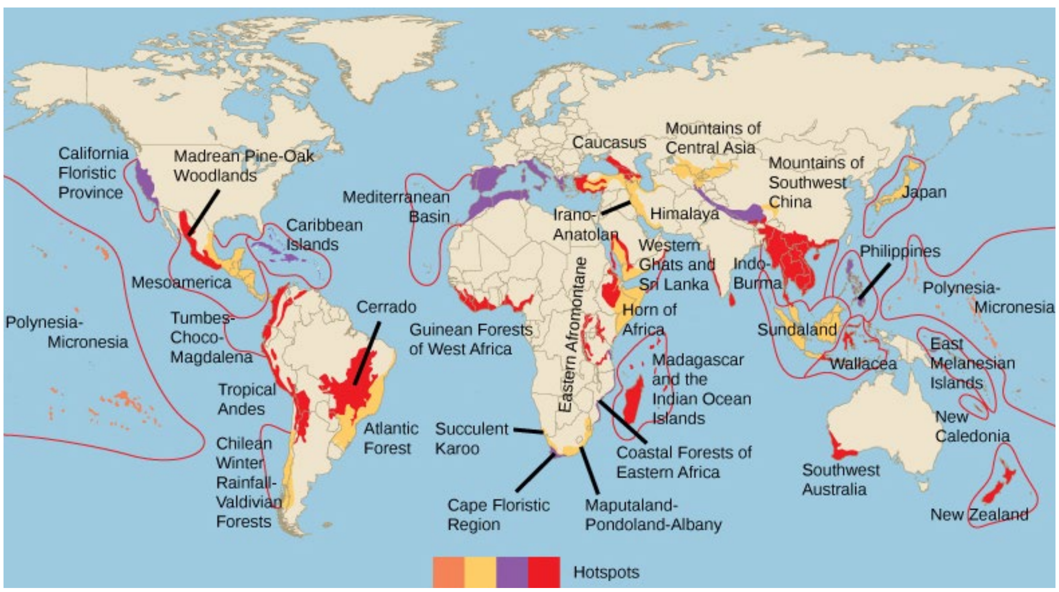


**Figure 4.10** Conservation International's 34 biodiversity hotspots. (credit: thecrospite.com).

There has been extensive research into optimal preserve designs for maintaining biodiversity. The fundamental principles behind much of the research have come from the seminal theoretical work of Robert H. MacArthur and Edward O. Wilson published in 1967 on island biogeography. This work sought to understand the factors affecting biodiversity on islands. Conservation preserves can be seen as "islands" of habitat within "an ocean" of non-habitat. In general, large preserves are better because they support more species, including species with large home ranges; they have more core areas of optimal habitat for individual species; they have more niches to support more species; and they attract more species because they can be found and reached more easily.

Preserves perform better when there are partially protected buffer zones around them of suboptimal habitat. The buffer allows organisms to exit the boundaries of the preserve without immediate negative consequences from hunting or lack of resources. One large preserve is better than the same area of several smaller preserves because there is more core habitat unaffected by less hospitable ecosystems outside the preserve boundary. For this same reason, preserves in the shape of a square or circle will be better than a preserve with many thin "arms." If preserves must be smaller, then providing wildlife corridors between them so that species and their genes can move between the preserves; for example, preserves along rivers and streams will make the smaller preserves behave more like a large one. All these factors are taken into consideration when planning the nature of a preserve before the land is set aside.

In addition to the physical specifications of a preserve, there are a variety of regulations related to the use of a preserve. These can include anything from timber extraction, mineral extraction, regulated hunting, human habitation, and nondestructive human recreation. Many of the decisions to include these other uses are made based on political pressures rather than conservation considerations. On the other hand, in some cases, wildlife protection policies have been so strict that subsistence-living indigenous populations have been forced from ancestral lands that fell within a preserve. In other cases, even if a preserve is designed to protect wildlife, if the protection is not or cannot be enforced, the preserve status will have little meaning in the face of illegal poaching and timber extraction. This is a widespread problem with preserves in the tropics. Some of the limitations on preserves as conservation tools are evident from the discussion of preserve design. Political and economic pressures typically make preserves smaller, never larger, so setting aside areas that are large enough is difficult. Enforcement of protections is also a significant issue in countries without the resources or political will to prevent poaching and illegal resource extraction.

Climate change will create inevitable problems with the location of preserves as the species within them migrate to higher latitudes as the habitat of the preserve becomes less favorable. Planning for the effects of global warming on future preserves or adding new preserves to accommodate the changes expected from global warming is in progress but will only be as effective as the accuracy of the predictions of the effects of global warming on future habitats.

Finally, an argument can be made that conservation preserves reinforce the cultural perception that humans are separate from nature, can exist outside of it, and can only operate in ways that do damage to biodiversity. Creating preserves reduces the pressure on human activities outside the preserves to be sustainable and non-damaging to biodiversity. Ultimately, the political, economic, and human demographic pressures will degrade and reduce the size of conservation preserves if the activities outside them are not altered to be less damaging to biodiversity.

### *Habitat Restoration*

Habitat restoration holds considerable promise as a mechanism for maintaining or restoring biodiversity. Of course, once a species has become extinct, its restoration is impossible. However, restoration can improve the biodiversity of degraded ecosystems. Reintroducing wolves, a top predator, to Yellowstone National Park in 1995 led to dramatic changes in the ecosystem that increased biodiversity. The wolves (Figure 4.12) function to suppress elk and coyote populations and provide more abundant resources to the guild of carrion eaters. Reducing elk populations has allowed revegetation of riparian (the areas along the banks of a stream or river) areas, which has increased the diversity of species in that habitat. Suppression of coyotes has increased the species previously suppressed by this predator. The number of species of carrion eaters has increased because of the predatory activities of the wolves. In this habitat, the wolf is a keystone species, meaning a species that is instrumental in maintaining diversity within an ecosystem.

Removing a keystone species from an ecological community causes a collapse in diversity. The results from the Yellowstone experiment suggest that restoring a keystone species effectively can have the effect of restoring biodiversity in the community. Ecologists have argued for the identification of keystone species where possible and for focusing protection efforts on these species. It makes sense to return the keystone species to the ecosystems where they have been removed. Wolves have been identified as a keystone species.

**Figure 4.11** Gibbon wolf pack in Yellowstone National Park (credit: Doug Smith, NPS)

Other large-scale restoration experiments underway involve dam removal. In the United States, since the mid-1980s, many aging dams are being considered for removal rather than replacement because of shifting beliefs about the ecological value of free-flowing rivers. The measured benefits of dam removal include restoration of naturally fluctuating water levels (often the purpose of dams is to reduce variation in river flows), which leads to increased fish diversity and improved water quality. In the Pacific Northwest, dam removal projects are expected to increase populations of salmon, which is considered a keystone species because it transports nutrients to inland ecosystems during its annual spawning migrations.

### ***The Role of Zoos and Captive Breeding***

Zoos have sought to play a role in conservation efforts both through captive breeding programs and education. The transformation of the missions of zoos from collection and exhibition facilities to organizations that are dedicated to conservation is ongoing. In general, it has been recognized that, except in some specific targeted cases, captive breeding programs for endangered species are inefficient and often prone to failure when the species are reintroduced to the wild. Zoo facilities are far too limited to contemplate captive breeding programs for the numbers of species that are now at risk. Education, on the other hand, is a potential positive impact of zoos on conservation efforts, particularly given the global trend to urbanization and the consequent reduction in contact between people and wildlife. Several studies have been carried out to look at the effectiveness of zoos in people's attitudes and actions regarding conservation; at present, the results tend to be mixed.

# Chapter Five: Ecology and Energy Flow in the Ecosystem

Objectives

- Describe ecology and the related terms
- Explain energy flow in ecosystem

***Ecology*** is a scientific discipline that delves into the intricate relationships between living organisms and their environments. It seeks to unravel the complex web of interactions that shape the natural world, from the smallest microorganisms to the vast ecosystems that cover our planet. This field of study examines the flow of energy, the cycling of nutrients, and the interdependence of species within various ecological communities.

***Ecosystems*** represent the dynamic and interconnected tapestry of life, encompassing the living organisms within a particular environment and their interactions with the abiotic components that shape their existence. These complex systems range from the smallest microcosms, such as a pond or a forest, to the expansive landscapes of oceans and continents. Understanding ecosystems involves unraveling the intricate relationships between plants, animals, microorganisms, and their physical surroundings.

***Biotic interactions*** refer to the relationships among organisms.
They can be **intraspecific** (between members of the same species) or **interspecific** (between members of different species). When at least one of the interactants is harmed, the relationship is called an **antagonism.**

**Trophic interactions**, in which one species consumes another, are antagonisms. Some biological interactions are brief, such as predation. In others, species are closely associated with long periods of **commensalism**. Such associations are called **symbiotic** ("living together"). One species always benefits from a symbiosis, but the other may be harmed (parasitism), unaffected (commensalism), or benefited (mutualism). Some experts considered all parasitism, parasitism, and mutualisms to be symbiotic, but others only consider interactions in which species are living together in a close association (such as when one species lives on or in the other) as symbiotic.

- **Competition** is another antagonism in which species at the same trophic level (that eat the same things) interact through using the same resources.

- **Facilitations** are interactions in which at least one species benefit, and neither is harmed.
- **Commensalism** is a type of facilitation that occurs when one species benefits from interaction, while the other neither benefit or is harmed.
- **Mutualisms** are interactions where both species benefit from the interaction.
- **Predation** is an association where one species (predator) kills and eats another species (prey).

A **keystone species** is one whose presence has inordinate influence in maintaining the prevalence of various species, the ecological community's structure, and sometimes its biodiversity.

## Energy in Ecosystems

Virtually every task performed by living organisms requires energy. Nutrients and other molecules are imported into the cell to meet these energy demands. For example, energy is required for the synthesis and breakdown of molecules, as well as the transport of molecules into and out of cells. In addition, processes such as ingesting and breaking down food, exporting waste and toxins, and movement of the cell all require energy.

Scientists use the term bioenergetics to describe the concept of energy flow through living systems, such as cells. Cellular processes such as the building and breaking down of complex molecules occur through stepwise chemical reactions. Some of these chemical reactions are spontaneous and release energy, whereas others require energy to proceed. Together, all the chemical reactions that take place inside cells, including those that consume or generate energy, are referred to as the cell's metabolism.

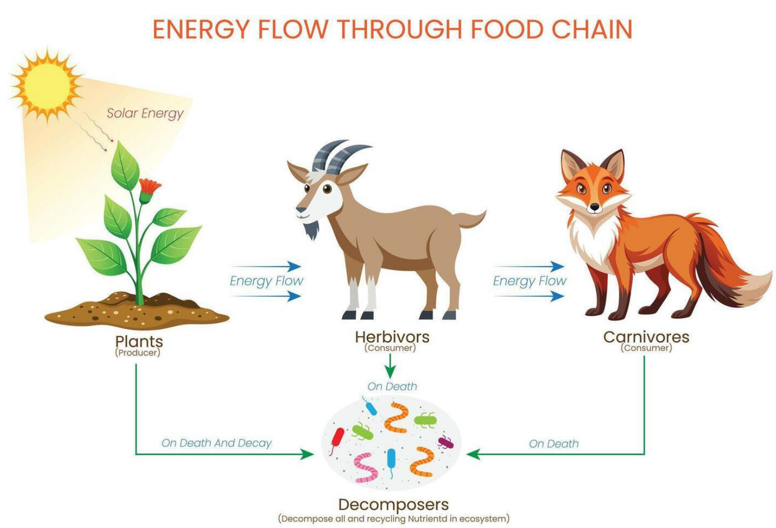


**Figure 5.1** Energy flow from the sun. (credit: papiamajumder143423176/Vecteezy)

Ultimately, most life forms get their energy from the sun. Plants use photosynthesis to capture sunlight, and herbivores eat the plants to obtain energy. Carnivores eat the herbivores, and eventually decomposition of plant and animal material contributes to the nutrient pool.

Some organisms can carry out photosynthesis, whereas others cannot. An autotroph is an organism that can produce its own food. The Greek roots of the word autotroph mean “self” (auto) “feeder” (troph). Plants are the best-known autotrophs, but others exist, including certain types of bacteria and algae. Oceanic algae contribute enormous quantities of food and oxygen to global food chains. More specifically, plants are photoautotrophs, a type of autotroph that uses sunlight and carbon from carbon dioxide to synthesize chemical energy in the form of carbohydrates. All organisms carrying out photosynthesis require sunlight. Chemoautotrophs are organisms that use inorganic molecules as an energy source. Chemoautotrophs are much less abundant than photoautotrophs and are often found in extreme environments such as near deep-seafloor hydrothermal vents.

The energy stored in carbohydrate molecules from photosynthesis passes through the food chain. The predator that eats these deer is getting energy that originated in the photosynthetic vegetation that the deer consumed. **Heterotrophs** are organism’s incapable of photosynthesis that must therefore obtain energy and carbon from food by consuming other organisms. The Greek roots of the word *heterotroph* mean “other” (*hetero*) “feeder” (*troph*), meaning that their food comes from other organisms. Even if the organism being consumed is another animal, it traces its stored energy back to autotrophs and the process of photosynthesis. Humans are heterotrophs, as are all animals and fungi. Heterotrophs depend on autotrophs, either directly or indirectly. For example, a deer obtains energy by eating plants. A wolf eating a deer obtains energy that originally came from the plants eaten by that deer. Using this reasoning, all food eaten by humans can be traced back to **autotrophs** that carry out photosynthesis.

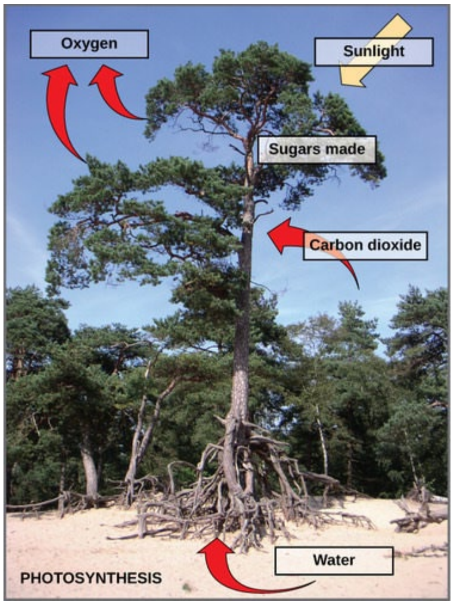


**Figure 5.2** Photosynthesis in autotrophs

Photosynthesis uses solar energy, carbon dioxide, and water to release oxygen and to produce energy-storing sugar molecules. Photosynthesis requires sunlight, carbon dioxide, and water as starting reactants. After the process is complete, photosynthesis releases oxygen and produces carbohydrate molecules, most commonly glucose. These sugar molecules contain the energy that living things need to survive. The complex reactions of photosynthesis can be summarized by the chemical equation shown below. Although the equation looks simply, the many steps that take place during photosynthesis are quite complex. In plants, photosynthesis takes place primarily in the chloroplasts of leaves. Chloroplasts have a double (inner and outer) membrane. Within the chloroplast is a third membrane that forms stacked, disc-shaped structures called thylakoids. Embedded in the thylakoid membrane are molecules of chlorophyll, a pigment (a molecule that absorbs light) through which the entire process of photosynthesis begins.

$6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$

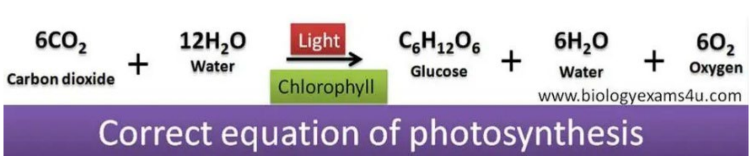


**Figure 5.3** Photosynthesis equation (credit: biologyexams4u.com).

This equation means that six molecules of carbon dioxide ($CO_2$) combine with six molecules of water ($H_2O$) in the presence of sunlight. This produces one molecule of glucose ($C_6H_{12}O_6$) and six molecules of oxygen ($O_2$).

## The Two Parts of Photosynthesis

Photosynthesis takes place in two stages: the light-dependent reactions and the Calvin cycle. In the light-dependent reactions chlorophyll absorbs energy from sunlight and then converts it into chemical energy with the aid of water. The light-dependent reactions release oxygen as a byproduct from the splitting of water. In the Calvin cycle, the chemical energy derived from the light-dependent reactions drives both the capture of carbon in carbon dioxide molecules and the subsequent assembly of sugar molecules.

## The Global Significance of Photosynthesis

The process of photosynthesis is crucially important to the biosphere. It creates $O_2$, which is important for two reasons. The molecular oxygen in Earth's atmosphere was created by photosynthetic organisms; without photosynthesis there would be no $O_2$ to support cellular respiration needed by complex, multicellular life.  Photosynthetic bacteria were likely the first organisms to perform photosynthesis, dating back 2-3 billion years ago. Thanks to their activity, and a diversity of present-day photosynthesizing organisms, Earth's atmosphere is currently about 21% $O_2$. Also, this $O_2$ is vital for the creation of the ozone layer, which protects life from harmful ultraviolet radiation emitted by the sun. Ozone ($O_3$) is created from the breakdown and reassembly of $O_2$.

It provides energy for nearly all ecosystems.  By transforming light energy into chemical energy, photosynthesis provides the energy used by organisms, whether those organisms are plants, grasshoppers, wolves, or fungi. The only exceptions are found in very rare and isolated ecosystems, such as near deep sea hydrothermal vents where organisms get energy that originally came from minerals, not the sun. It provides the carbon needed for organic molecules. Organisms are primarily made of two things: water and organic molecules, the latter being carbon based.  Through the process of carbon fixation, photosynthesis takes carbon from $CO_2$ and converts it into sugars (which are organic). Carbon in these sugars can be re-purposed to create the other types of organic molecules that organisms need, such as lipids, proteins, and nucleic acids. For example, the carbon used to make your DNA was once $CO_2$ used by photosynthetic organisms.

(a) (b)

**Figure 5.4** A tidal pool ecosystem (a) in Matinicus Island, Maine, is a small ecosystem, while the (b) Amazon rainforest in Brazil is a large ecosystem. (credit a: modification of work by Jim Kuhn; credit b: modification of work by Ivan Mlinaric).

Desert ecosystems, like all ecosystems, can vary greatly (Figure 5.5).

(a) (b)

**Figure 5.5** The desert in (a) Saguaro National Park, Arizona, has abundant plant life, while the rocky desert of (b) Boa Vista Island, Cape Verde, Africa, is devoid of plant life. (credit a: modification of work by Jay Galvin; credit b: modification of work by Ingo Wölbern)

## Food Chains and Food Webs

A food chain is a linear sequence of organisms through which nutrients and energy pass as one organism eats another. The levels in the food chain are producers, primary consumers, higher-level consumers, and finally decomposers. These levels are used to describe ecosystem structure and dynamics. There is a single path through a food chain. Each organism in a food chain or food web occupies a specific trophic level (energy level).

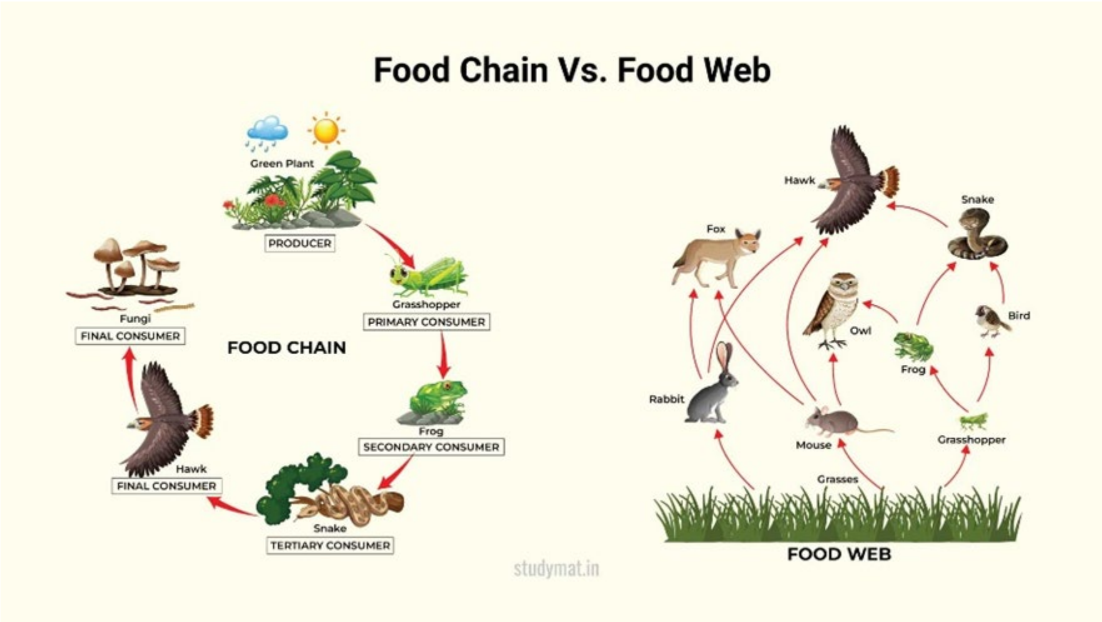


**Figure 5.6** Food chain and food web. This figure illustrates a food chain which represents a single, linear pathway of energy flow while a food web consists of many interconnected food chains. (credit: studymat.in).

In many ecosystems, the base, or foundation, of the food chain consists of photosynthetic organisms (plants or phytoplankton), which are called producers. The organisms that consume the producers are herbivores called primary consumers. Secondary consumers are usually carnivores that eat the primary consumers. Tertiary consumers are carnivores that eat other carnivores. Higher-level consumers feed on the next lower trophic levels, and so on, up to the organisms at the top of the food chain. In the Lake Ontario food chain, the Chinook salmon is the apex consumer at the top of this food chain.

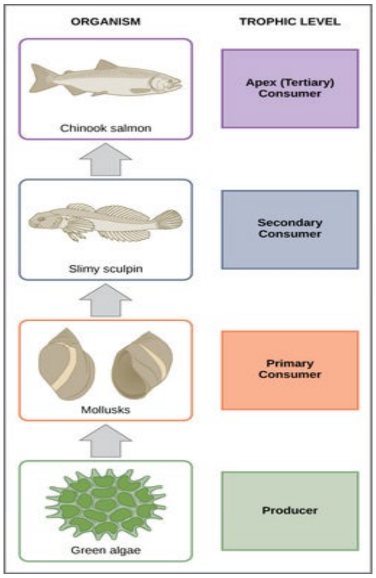


**Figure 5.7** Trophic levels (credit: Ecosystems chapter, Khan academy stuff).
Energy and nutrients flow from photosynthetic green algae at the base to the top of the food chain: the Chinook salmon. (credit: modification of work by National Oceanic and Atmospheric Administration/NOAA).

One major factor that limits the number of steps in a food chain is energy. Energy is lost at each trophic level and between trophic levels as heat and in the transfer to decomposers. The loss of energy between trophic levels is illustrated by the pioneering studies of Howard T. Odum in the Silver Springs, Florida, ecosystem in the 1940s. Some of the data from this study is shown below. The primary producers generated 20,819 kcal/$m^2$/yr (kilocalories per square meter per year), the primary consumers generated 3368 kcal/$m^2$/yr, the secondary consumers generated 383 kcal/$m^2$/yr, and the tertiary consumers only generated 21 kcal/$m^2$/yr. Thus, there is little energy remaining for another level of consumers in this ecosystem.

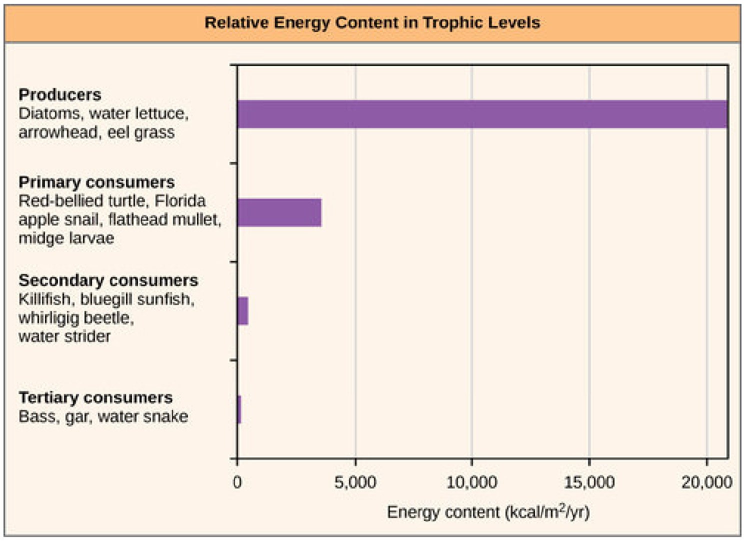


**Figure 5.8** Amount of energy at each trophic level (credit: Biology LibreTexts).

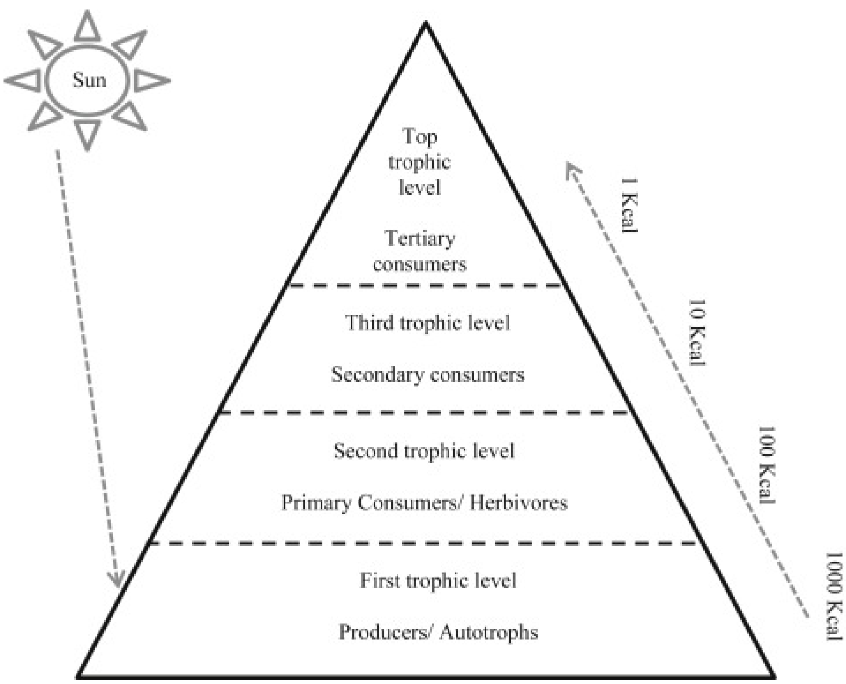


**Figure 5.9** Trophic/energy levels in a triangle

(credit: https://bio.libretexts.org/Courses/Gettysburg).

Each trophic level has less energy available, and usually, but not always, supports a smaller mass of organisms at the next level.

There is one problem when using food chains to describe most ecosystems. Even when all organisms are grouped into appropriate trophic levels, some of these organisms can feed at more than one trophic level. In addition, species feed on and are eaten by more than one species. In other words, the linear model of ecosystems, the food chain, is a hypothetical and overly simplistic representation of ecosystem structure. A holistic model, which includes all the interactions between different species and their complex interconnected relationships with each other and with the environment, is a more accurate and descriptive model for ecosystems. A food web is a concept that accounts for the multiple trophic (feeding) interactions between each species (Figure 5.10).

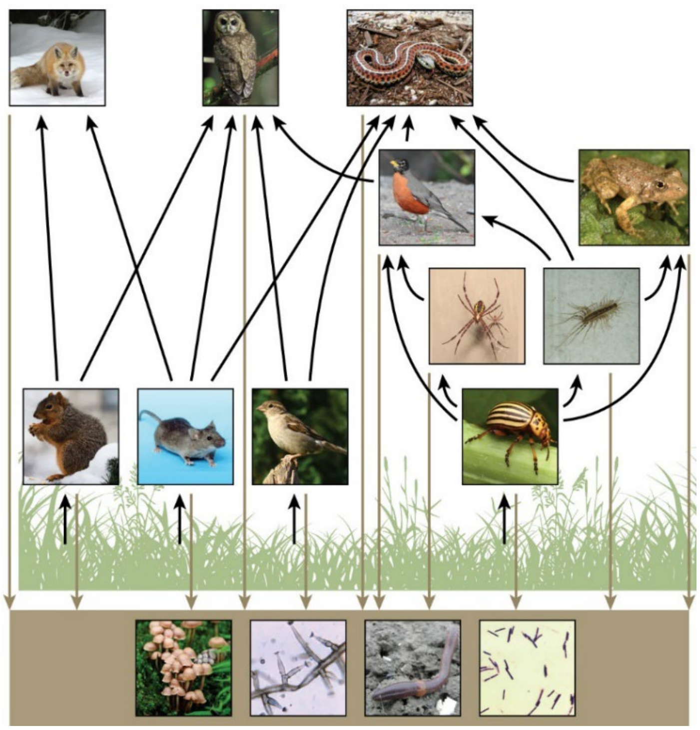

**Figure 5.10** Food web (credit: https://bio.libretexts.org/Courses/Gettysburg)

This food web (Figure 5.10) shows the interactions between organisms across trophic levels. The direction of the arrows is important. It shows the direction of the flow of energy whose original source is the sun. Arrows point from an organism that is consumed to the organism that consumes it. All the producers and consumers eventually become nourishment for the decomposers (fungi, mold, earthworms, and bacteria in the soil).

Two general types of food webs are often shown interacting within a single ecosystem. A grazing food web has plants or other photosynthetic organisms at its base, followed by herbivores and various carnivores. A detrital food web consists of a base of organisms that feed on decaying organic matter (dead organisms), including decomposers (which break down dead and decaying organisms) and detritivores (which consume organic detritus). These organisms are usually bacteria, fungi, and invertebrate animals that recycle organic material back into the biotic part of the ecosystem as they themselves are consumed by other organisms.

## Productivity within Trophic Levels

Productivity within an ecosystem can be defined as the percentage of energy entering the ecosystem incorporated into biomass at a particular trophic level. Biomass is the total mass, in a unit area at the time of measurement, of living or previously living organisms within a trophic level. Ecosystems have characteristic amounts of biomass at each trophic level. For example, in the English Channel ecosystem the primary producers account for a biomass of 4 $g/m^2$ (grams per meter squared), while the primary consumers exhibit a biomass of 21 $g/m^2$.

Since all organisms need to use some of this energy for their own functions (like respiration and resulting metabolic heat loss) scientists often refer to the net primary productivity of an ecosystem.

Net primary productivity is the energy that remains in the primary producers after accounting for the organisms' respiration and heat loss. Net productivity is then available to the primary consumers at the next trophic level. In our Silver Spring example, 13,187 of the 20,810 $kcal/m^2/yr$ were used for respiration or were lost as heat, leaving 7,632 $kcal/m^2/yr$ of energy for use by the primary consumers.

## Primary productivity provides energy to the ecosystem

**Gross primary productivity** is the rate at which solar or chemical energy is captured and converted into chemical bonds by producers in an area. Producers use energy for their own respiration, growth, and reproduction. When energy that is assimilated by producers and converted into producer biomass in an area is called **net primary productivity** (NPP). NPP includes all energy that is not respired.

NPP = GPP – Respiration (Both GPP and NPP are expressed in units of Joules (J) / $m^2$ / year).

However, photosynthesis is not a very efficient process. Only 1% of solar energy is captured and used by photosynthesis, which is **gross primary productivity**.

## Secondary production

Herbivores consume only a fraction of the total producer biomass available. They can only digest a portion of the energy they consume. Secondary production is the amount of assimilated energy converted into new biomass (growth and reproduction) by herbivores.

The image below shows that a rabbit consumes cabbage (primary production provided by the producers), a process called **consumption**. A small proportion of consumed energy that is excreted or regurgitated is the egested energy. The portion of consumed energy that the rabbit digests and absorbs is called assimilated energy (assimilation; analogous to GPP for producers). The rabbit uses a portion of assimilated energy for respiration, which is called respirated energy. The remaining assimilated energy can be used for ***growth and reproduction***, which is called net secondary productivity.

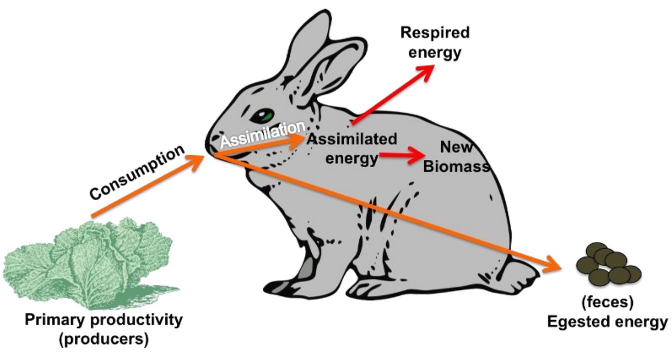


**Figure 5.11** Energy flow with a living organism (Credit: Dr. Ching-Yu Huang)..

This diagram in figure 5.11 shows a rabbit (primary consumer) that consumes the cabbage (producer). The consumed energy is either excreted as waste (egested energy; non-assimilated energy) or converted into assimilated energy (including respired energy and biomass; secondary productivity) (Credit: Dr. Ching-Yu Huang).

## The efficiency of energy transfers within organisms

**Consumption efficiency** is the percentage of energy (J for joules) or biomass at a trophic level that is consumed by the next higher trophic level.

$$\text{Consumption efficiency} = \frac{\text{Consumed energy (J)}}{\text{Net production energy of the next lower trophic level (J)}}$$

**Primary productivity** is the energy content in producers that is available to the organisms of the next trophic level (which is primary consumers; herbivores). Secondary productivity is the available energy content in the primary consumer to the next trophic level (i.e. secondary consumer, carnivores). You will use primary productivity as "Net production energy of the next lower trophic level" in the equation above, when you are calculating the consumption efficiency for primary consumer. And you will use secondary productivity as "Net production energy of the next lower trophic level" in the equation above, when you are calculating the consumption efficiency for secondary consumer.

The percentage of energy consumed by an organism that is assimilated in the body of the consumer (i.e., material that is not egested) is called **assimilation efficiency**. It is calculated based on the amount of assimilated energy divided by the consumed energy.

$$\text{Assimilation efficiency} = \frac{\text{Assimilated energy (J)}}{\text{Consumed energy (J)}}$$

**Assimilation efficiency** varies among trophic levels. Primary consumers (i.e. herbivores) tend to have lower efficiencies than secondary consumers because animal tissues are more digestible than plant tissues (contain many undigestible materials, such as fibers and lignin).

**Net production efficiency** is the percentage of assimilated energy that is used for *growth* and *reproduction.* You may also consider that net production efficiency is the percentage of assimilated energy that remains after an organism's respiration.

$$\text{Net production efficiency} = \frac{\text{Net production energy (J)}}{\text{Assimilated energy (J)}}$$

Net production efficiency (NPE) allows ecologists to quantify how efficiently organisms of a particular trophic level incorporate the energy they receive into biomass. Thus, net production efficiency measures how efficiently each trophic level is used and incorporates the energy from its food into biomass to fuel the next trophic level.

For active homeothermic animals, they spend significant amount of energy to maintain body temperature, move, circulate blood, and osmoregulate, so their net production efficiency can be as low as 1%. In general, cold-blooded animals (ectotherms), such as invertebrates, fish, amphibians, and reptiles, use less of the energy they obtain for respiration and heat than warm-blooded animals (endotherms), such as birds and mammals. The extra heat generated in endotherms, although an advantage in terms of the activity of these organisms in colder environments, is a major disadvantage in terms of net production efficiency. Therefore, many endotherms must eat more often than ectotherms to get the energy they need for survival. In general, NPE for ectotherms is an order of magnitude (10x) higher than for endotherms. For example, the NPE for a caterpillar eating leaves has been measured at 18 percent, whereas the NPE for a squirrel eating acorns may be as low as 1.6 percent.

The inefficiency of energy use by warm-blooded animals has broad implications for the world's food supply. It is widely accepted that the meat industry uses large amounts of crops to feed livestock, and because the NPE is low, much of the energy from animal feed is lost. For example, it costs about 1¢ to produce 1000 dietary calories (kcal) of corn or soybeans, but approximately $0.19 to produce a similar number of calories growing cattle for beef consumption. The same energy content of milk from cattle is also costly, at approximately $0.16 per 1000 kcal. Much of this difference is due to the low NPE of cattle. Thus, there has been a growing movement worldwide to promote the consumption of non-meat and non-dairy foods so that less energy is wasted feeding animals for the meat industry.

## Ecological Efficiency: (The Transfer of Energy between Trophic Levels)

As illustrated in the Silver Springs ecosystem, large amounts of energy are lost from the ecosystem from one trophic level to the next level as energy flows from the primary producers through the various trophic levels of consumers and decomposers. The main reason for this loss is the second law of thermodynamics, which states that whenever energy is converted from one form to another, there is a tendency toward disorder (**entropy**) in the system. In biologic systems, this means a great deal of energy is lost as metabolic heat when the organisms from one trophic level consume the next level. In the Silver Springs ecosystem example, we see that the primary consumers produced 1103 kcal/m$^2$/yr from the 7618 kcal/m$^2$/yr of energy available to them from the primary producers.

The measurement of energy transfer efficiency between two successive trophic levels is termed the ecological efficiency and is defined by the formula:
Ecological efficiency (also called food chain efficiency) is the percentage of net production from one trophic level compared to the next lower trophic level.

$$\text{Ecological efficiency} = \frac{\text{Net production energy of a trophic level (J)}}{\text{Net production energy of the next lower trophic level (J)}}$$

**Ecological efficiency** incorporates consumption, assimilation, and net production efficiency. Because energy is lost at each of these processes, ecological efficiency is usually low, ranging from 5% to 20%. However, 10% is used as a rule of thumb.

For example, in Silver Springs, the ecological efficiency between the first two trophic levels was approximately 14.8 percent. The low efficiency of energy transfer between trophic levels is usually the major factor that limits the length of food chains observed in a food web. The fact is, after four to six energy transfers, there is not enough energy left to support another trophic level. In the Lake Ontario example, only three energy transfers occurred between the primary producer, (green algae), and the apex consumer (Chinook salmon).

Ecologists have many different methods of measuring energy transfers within ecosystems. Some transfers are easier or more difficult to measure depending on the complexity of the ecosystem and how much access scientists have to observe the ecosystem. In other words, some ecosystems are more difficult to study than others, and sometimes the quantification of energy transfers must be estimated.

## Modeling Energy Flow: Ecological Pyramids

The structure of ecosystems can be visualized with ecological pyramids, which were first described by the pioneering studies of Charles Elton in the 1920s. Ecological pyramids show the relative amounts of various parameters (such as number of organisms, energy, and biomass) across trophic levels. Pyramids of numbers can be either upright or inverted, depending on the ecosystem. As shown at the bottom of this section, a typical grassland during the summer has a base of many plants and the numbers of organisms decrease at each trophic level. However, during the summer in a temperate forest, the base of the pyramid consists of few trees compared with the number of primary consumers, mostly insects. Because trees are large, they have great photosynthetic capability and dominate other plants in this ecosystem to obtain sunlight. Even in smaller numbers, primary producers in forests are still capable of supporting other trophic levels.

Another way to visualize ecosystem structure is with pyramids of biomass. This pyramid measures the amount of energy converted into living tissue at the different trophic levels. Using the Silver Springs ecosystem example, this data exhibits an upright biomass pyramid, whereas the pyramid from the

English Channel example is inverted. The primary producers) of the Silver Springs ecosystem make up a large percentage of the biomass found there. However, the phytoplankton in the English Channel example make up less biomass than the primary consumers, the zooplankton. These two pyramids are included in the figure at the end of this section. As with inverted pyramids of numbers, this inverted pyramid is not due to a lack of productivity from the primary producers but results from the high turnover rate of the phytoplankton. The phytoplankton is consumed rapidly by the primary consumers, thus minimizing their biomass at any point in time. However, phytoplankton reproduces quickly, thus they can support the rest of the ecosystem.

Pyramid ecosystem modeling can also be used to show energy flow through the trophic levels. Notice that these numbers are the same as those used in the energy flow compartment diagrams. Pyramids of energy are always upright, and an ecosystem without sufficient primary productivity cannot be supported. All types of ecological pyramids are useful for characterizing ecosystem structure. However, in the study of energy flow through the ecosystem, pyramids of energy are the most consistent and representative models of ecosystem structure.

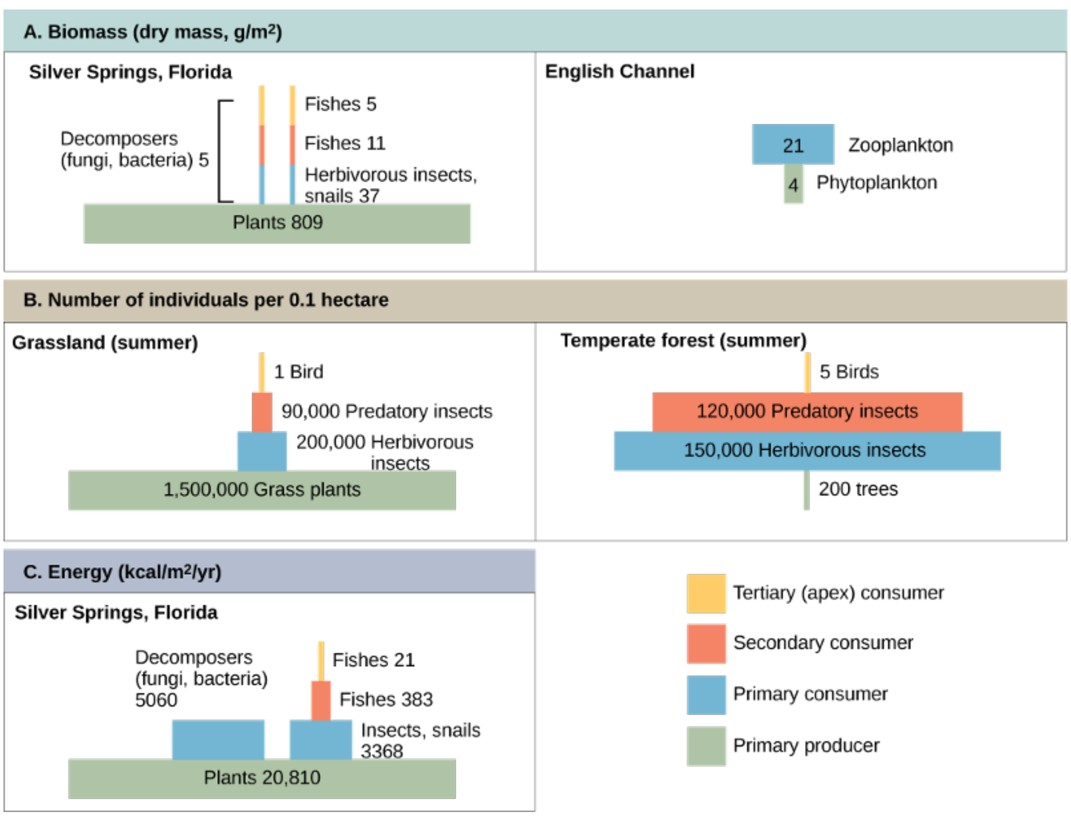

**Figure 5.12** Ecological pyramids depict the (a) biomass, (b) number of organisms, and (c) energy in each trophic level in aquatic (Silver Spring and English Channel ecosystems) and terrestrial ecosystems (grassland and temperate forest). (credit: OpenStax. (2016). *46.2D: Ecological Pyramids*. In *Biology 2e*. OpenStax, Rice University).

## Consequences of Food Webs: Biological Magnification

One of the most important consequences of ecosystem dynamics in terms of human impact is biomagnification. Biomagnification is the increasing concentration of persistent, toxic substances in organisms at each successive trophic level. These are substances that are lipid soluble and are stored in the fat reserves of each organism. Many substances have been shown to biomagnify, including classical studies with the pesticide dichlorodiphenyltrichloroethane (DDT), which were described in the 1960s bestseller *Silent Spring* by Rachel Carson. DDT was a commonly used pesticide before its dangers to apex consumers, such as the bald eagle, became known. DDT and other toxins are taken in by producers and passed on to successive levels of consumers at increasingly higher rates.  As bald eagles feed on contaminated fish, their DDT levels rise. It was discovered that DDT caused the eggshells of birds to become fragile, which contributed to the bald eagle being listed as an endangered species under U.S. law. The use of DDT was banned in the United States in the 1970s.

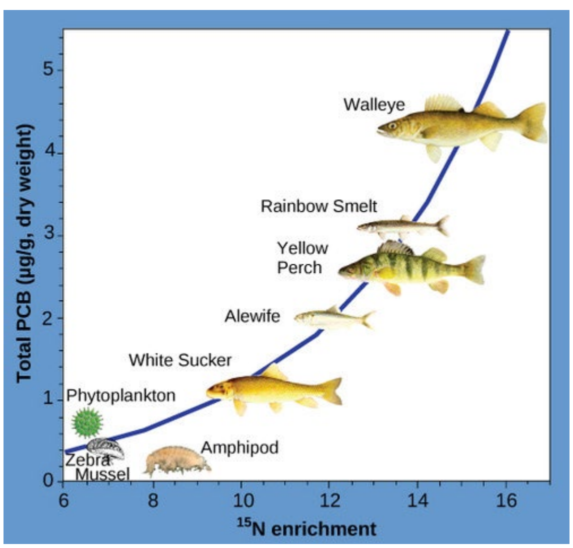


**Figure 5.13** Concentration of chemicals in various sea depths (credit: University of Minnesota. (n.d.). *Energy flow through ecosystems*. In *Introductory Biology: Evolutionary and Ecological Perspectives*. University of Minnesota Libraries Publishing).

Figure 5.13 shows the PCB concentrations found at the various trophic levels in the Saginaw Bay ecosystem of Lake Huron. Notice that the fish in the higher trophic levels accumulate more PCBs than those in lower trophic levels. (credit: Patricia Van Hoof, NOAA). Another substance that biomagnifies is **polychlorinated biphenyl** (PCB), which was used as coolant liquids in the United States until its use was banned in 1979. PCB was best studied in aquatic ecosystems where predatory fish species accumulated very high concentrations of the toxin that otherwise exists at low concentrations in the environment. As illustrated in a study performed by the NOAA in the Saginaw Bay of Lake Huron of the North American Great Lakes PCB concentrations increased from the producers of the ecosystem (phytoplankton) through the different trophic levels of fish species. The apex consumer, the walleye, has more than four times the number of PCBs compared to phytoplankton. Also, research found that birds that eat these fish may have PCB levels that are at least ten times higher than those found in the lake fish.

Other concerns have been raised by the biomagnification of heavy metals, such as mercury and cadmium, in certain types of seafood. The United States Environmental Protection Agency recommends that pregnant women and young children should not consume any swordfish, shark, king mackerel, or tilefish because of their high mercury content. These individuals are advised to eat fish low in mercury: salmon, shrimp, pollock, and catfish. Biomagnification is a good example of how ecosystem dynamics can affect our everyday lives, even influencing the food we eat.

## Consequences of Food Webs: Trophic Cascades

The interdependence of organisms in an ecosystem through the food webs means that changes to one type of organism can affect other organisms. For example, in the example of the Silver Springs ecosystem, if one of the primary producers, such as the eelgrass, died off in the area, the primary consumers would eat more of the other primary producers, decrease in abundance due to lack of food or some combination of the two. What is less obvious is that a change in one trophic level (such as a secondary consumer) may have indirect effects on a non-adjacent trophic level (such as primary producers). This is called a trophic cascade. One classic example of the importance of trophic cascades is seen in the ecological role of wolves in Yellowstone National Park. Watch the video below to learn more.

The impact of the wolves in Yellowstone Park on lower trophic levels is an example of top-down control, the higher trophic level has impacts on multiple lower trophic levels. This type of control was originally thought to be rare but may be more common than we think. Some systems exhibit bottom-up control in which the primary producers control the abundance at the upper trophic levels. In these instances, the growth of the primary producers is typically limited by some resources, such as nutrients or water, and increasing the amount of that resource would increase the biomass of the primary producer and the upper trophic levels.

## Community Dynamics

**Community dynamics** are the changes in community structure and composition over time, often following environmental disturbances such as volcanoes, earthquakes, storms, fires, and climate change. Communities with a relatively constant number of species are said to be at equilibrium. The equilibrium is dynamic with species identities and relationships changing over time but maintaining relatively constant numbers. Following disturbance, the community may or may not return to the equilibrium state.

## Succession

**Succession** describes the sequential appearance and disappearance of species in a community over time after a severe disturbance. In primary succession, newly exposed or newly formed rock is colonized by living organisms. In **secondary succession**, a part of an ecosystem is disturbed, and remnants of the previous community remain. In both cases, there is a sequential change in species until a more-or-less permanent community develops.

## Primary Succession and Pioneer Species

**Primary succession** occurs when new land is formed, or when the soil and all life is removed from pre-existing land. An example of the former is the eruption of volcanoes on the Big Island of Hawaii, which results in lava that flows into the ocean and continually forms new land. From this process, approximately 32 acres of land are added to the Big Island each year. An example of pre-existing soil being removed is through the activity of glaciers. The massive weight of the glacier scours the landscape down to the bedrock as the glacier moves. This removes any original soil and leaves exposed rock once the glacier melts and retreats.

In both cases, the ecosystem starts with bare rock that is devoid of life. New soil is slowly formed as weathering and other natural forces break down the rock and lead to the establishment of hearty organisms, such as lichens and some plants, which are collectively known as **pioneer species** (figure 5.14) because they are the first to appear. These species help to further break down the mineral-rich rock into soil where other, less hardy but more competitive species, such as grass, shrubs, and trees, will grow and eventually replace the pioneer species. Over time the area will reach an equilibrium state, with a set of organisms quite different from the pioneer species.

**Figure 5.14** Pioneer species in primary succession
During primary succession in lava on Maui, Hawaii, succulent plants are the pioneer species. (credit: Forest and Kim Starr).

The relationship between pioneer species and the more competitive (late-successional) species illustrates the complexity of biotic interactions. Pioneer species facilitate the growth of the late-successional species, and this initially appears to be a commensalism. However, the late-successional species later outcompeted the pioneer species, shifting the interaction to competition.

## Secondary Succession

A classic example of secondary succession occurs in forests cleared by wildfire, or by clearcut logging. Wildfires will burn most vegetation, and unless the animals can flee the area, they are killed. Their nutrients, however, are returned to the ground in the form of ash. Thus, although the community has been dramatically altered, there is a soil ecosystem present that provides a foundation for rapid recolonization. Before the fire, the vegetation was dominated by tall trees with access to the major plant energy resource: sunlight. Their height gave them access to sunlight while also shading the ground and other low-lying species. After the fire, though, these trees are no longer dominant. Thus, the first plants to grow back are usually annual plants followed within a few years by quickly growing and spreading grasses and other pioneer species. Due, at least in part, to changes in the environment brought on by the growth of grass and shrubs, over many years shrubs emerge along with small trees. These organisms are called **intermediate species**.

Eventually, over 150 years or more, the forest will reach its equilibrium point and resemble the community before the fire. This equilibrium state is referred to as the **climax community**, which will remain until the next disturbance. The climax community is typically characteristic of a given climate and geology.

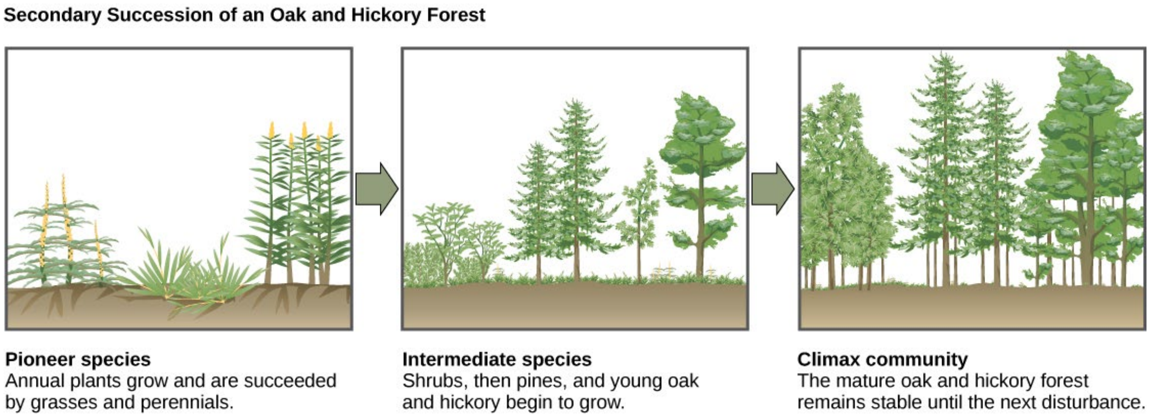


**Figure 5.15** Succession (credit: OpenStax. (2020). *Biology 2e*. OpenStax, Rice University. Retrieved from https://openstax.org/books/biology-2e/pages/45-6-community-ecology).

Succession in an oak and hickory forest. Secondary succession occurs when a disturbance (reduction in biomass) occurs, but the entire community does not die as a result of the disturbance. First, pioneer species grow. These include annual plants, which are succeeding by perennial grasses and other perennials. Next, intermediate species grow. These include shrubs followed by pines and young oak and hickory. Finally, the climax community is established, which consists of mature oak and hickory trees. These remain intact until the next disturbance.

## Terms

**Autotroph:** an organism capable of synthesizing its own food molecules from smaller inorganic molecules

**Apex consumer:** an organism at the top of the food chain

**Biomagnification:** an increasing concentration of persistent, toxic substances in organisms at each trophic level, from the producers to the apex consumers

**Biome:** a large-scale community of organisms, primarily defined on land by the dominant plant types that exist in geographic regions of the planet with similar climatic conditions

**Chemoautotroph:** an organism capable of synthesizing its own food using energy from inorganic molecules

**Detrital food web:** a type of food web that is supported by dead or decaying organisms rather than by living autotrophs; these are often associated with grazing food webs within the same ecosystem

**Ecosystem:** a community of living organisms and their interactions with their abiotic environment

**Equilibrium:** the steady state of a system in which the relationships between elements of the system do not change

**Food chain:** a linear sequence of trophic (feeding) relationships of producers, primary consumers, and higher-level consumers

**Food web:** a web of trophic (feeding) relationships among producers, primary consumers, and higher-level consumers in an ecosystem

**Grazing food web:** a type of food web in which the producers are either plants on land or phytoplankton in the water; often associated with a detrital food web within the same ecosystem

**Gross primary productivity:** the rate at which photosynthetic producers incorporate energy from the Sun

**Net primary productivity:** the energy that remains in the producers after accounting for the organisms' respiration and heat loss

**Photoautotroph:** an organism that uses sunlight as an energy source to synthesize its own food molecules

**Primary consumer:** the trophic level that obtains its energy from the producers of an ecosystem

**Producer:** the trophic level that obtains its energy from sunlight, inorganic chemicals, or dead or decaying organic material

**Resilience (ecological resilience):** the speed at which an ecosystem recovers equilibrium after being disturbed

**Ecological resistance):** the ability of an ecosystem to remain at equilibrium despite disturbances

**Secondary consumer:** a trophic level in an ecosystem, usually a carnivore that eats a primary consumer

**Tertiary consumer:** a trophic level in an ecosystem, usually carnivores that eat other carnivores

**Trophic level:** the position of a species or group of species in a food chain or a food web.

# Chapter Six: Human Population and Demography

## Objectives

- Explain the impact of population density on the natural environment.
- Use exponential and logistic equations to predict population growth rate.
- Compare the environmental conditions represented that apply to the exponential growth model vs. the logistic growth model.

## What is Population Ecology?

***Ecology*** is a sub-discipline of biology that studies the interactions between organisms and their environments. A population is a group of interbreeding individuals (individuals of the same species) living and interacting in each area at a given time. These individuals rely on the same resources and are influenced by the same environmental factors.

**Population ecology,** therefore, is the study of how individuals of a particular species interact with their environment and change over time. The study of any population usually begins by determining how many individuals of a particular species exist, and how closely associated they are with each other. A population can be characterized by its **population size** (***N***), defined as the total number of individuals, and its **population**, the number of individuals of a particular species within a
specific area or volume (units are number of individuals/unit area or unit volume).
Population *size* and *density* are the two main characteristics used to describe a population. For example, larger populations may be more stable and able to persist better than smaller populations because of the greater amount of genetic variability, and their potential to adapt to the environment or changes in the environment. On the other hand, a member of a population with a low population density (more spread out in the habitat) will have access to adequate food and space but might have more difficulty finding a mate to reproduce. Other characteristics of a population include **dispersion;** the way individuals are spaced within the area; **age structure;** the number of individuals in different age groups; **sex ratio;** the proportion of males to females; and **growth;** change in population size (increase or decrease) over time.

## Terms Common terminologies used in population ecology

**Age-sex structure**: The composition of a population as determined by the number or proportion of males and females in each age category. The age-sex structure of a population is the cumulative result of past trends in fertility, mortality, and migration. Information on age-sex composition is essential for the description and analysis of many other types of demographic data.

**Birth Rate** (or crude birth rate): The number of live births per 1,000 population in a given year. Not to be confused with the growth rate.

**Carrying Capacity**: The maximum sustainable size of a resident population of a given species in a supporting ecosystem.

**Fecundity**: The physiological capacity of a woman to produce a child.

**Fertility**: The actual reproductive performance of an individual, a couple, a group, or a population. The term fertility is used instead of natality when births are put in relation with the number of women of fertile age. The fertility of a generation can be summarized by completed fertility and mean age at childbirth, whereas the total period fertility rate measures the fertility rate for the year.

**General Fertility Rate**: The number of live births per 1,000 women ages 15-44 or 15-49 years each year.

**Growth Rate**: The number of persons added to (or subtracted from) a population in a year due to natural increase and net migration expressed as a percentage of the population at the beginning of the period.

**Life expectancy**: The average number of years a person of a given age expects to live if current mortality trends were to continue for the rest of that person's life. Most cited as life expectancy at birth.

**Population density** is the average number of people per square kilometer of the territorial area, calculated by dividing the population (time point or average) of a certain residential area to the area of that territory.

**Total fertility rate (TFR)** reflects the average number of live births that would be born per woman (or a group of women) during the childbirth period if the woman (or a group of women) passes age-specific fertility rates observed in a given reference period during the reproductive period (aged 15 to 49). The average number of children born to each woman over her lifetime if she were to follow prevailing patterns, or in simpler terms, the average number of children born to each woman.

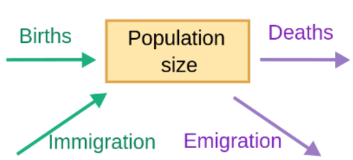


**Figure 6.1** Determinants of population size. (credit: OpenStax. (2020). *Introduction to Sociology 3e*. OpenStax, Rice University).

## Population Growth Models

Populations change over time and space as individuals are added through birth or immigrate (arrive from outside the population), and others die or emigrate (depart from the population to another location). Populations grow and shrink, and the age and gender composition also change through time and in response to changing environmental conditions. Some populations, for example, trees in a mature forest, are relatively constant over time while others, such as deer utilizing the forest, change frequently. Using idealized models, population ecologists can predict how the size of a particular population will change over time under different conditions.

## Exponential Growth

Charles Darwin, in his theory of natural selection, was greatly influenced by the English clergyman Thomas Malthus. Malthus published a book (An Essay on the Principle of Population) in 1798 stating that populations with unlimited natural resources grow very rapidly but once population size exceeds available resources, population growth decreases dramatically. This accelerating pattern of increasing population size is called **exponential growth,** meaning that the population is increasing by a fixed percentage each year. When plotted (visualized) on a graph showing how the population size increases over time, the result is a J-shaped curve (Figure 6.2). Each member of a population contributes to the population's growth by a certain amount (***r***) and as the population gets larger, there are more individuals contributing to growth by that same amount (the fixed percentage). In nature, exponential growth only occurs if there are no external limits such as food, space, and enemies.

One example of exponential growth is seen in bacteria. Bacteria are prokaryotes (organisms whose cells lack a nucleus and other membrane-bound organelles) that reproduce by binary fission (each individual cell splits into two new cells). This process of reproduction takes about an hour for many bacterial species. If 100 bacteria are placed in a large flask with an unlimited supply of nutrients (so the nutrients will not become depleted), after an hour, there is one round of fission and each organism divides, resulting in 200 organisms - an increase of 100. In another hour, each of the 200 organisms divides, producing 400 - an increase of 200 organisms. After the third hour, there should be 800 bacteria in the flask - an increase of 400 organisms. After ½ a day and 12 of these cycles, the population would have increased from 100 cells to more than 24,000 cells.

When the population size, *N*, is plotted over time, a J-shaped growth curve is produced This shows that the number of individuals added during each reproduction generation is accelerating – increasing at a faster rate.

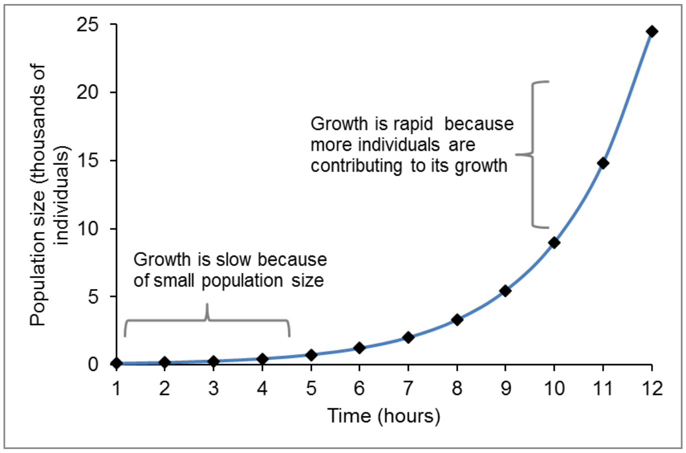


**Figure 6.2** J-shaped curve of exponential population growth (credit: CK-12 Biology Concepts).

The "J" shaped curve of exponential growth for a hypothetical population of bacteria. The population starts out with 100 individuals and after 11 hours there are over 24,000 individuals. As time goes on and the population size increases, the rate of increase also increases (each step up becomes bigger). In this figure "r" is positive.

This type of growth can be represented with a mathematical function known as the **exponential growth model:**

***G = r * N (or G =rN, also dN/dt = rN).***

**In this equation.**

***G*** (or ***dN/dt***) is the *population growth rate*; it refers to the number of individuals added to the population per time interval time.

***r*** is the *per capita rate of increase* (also referred to as *per capita growth rate*). It refers to the average contribution toward the population's growth made by each individual in a population; per capita means "per person."

***N*** is the *population size*, the number of individuals in the population at a particular time.

## Logistic Growth

Exponential growth cannot continue indefinitely because resources (food, water, shelter) will become limited. Exponential growth may occur in environments where there are few individuals and plentiful resources, but soon or later, the population gets large enough that individuals run out of vital resources such as food or living space, slowing the growth rate. Most natural populations exhibit what we call **logistic growth.** In logistic growth a population grows nearly exponentially at first when the population is very small and resources are plentiful, but growth rate slows down as the population size gets close to the limit of the environment and resources begin to be in short supply. In logistic growth, the population size finally stabilizes (zero population growth rate) at the maximum population size that can be supported by the environment (**carrying capacity**). This means that the number of individuals added to the population equals the amount removed, which keeps the population size the same (stable). This results in a characteristic S-shaped growth curve (**Figure 6.2**). The mathematical function or logistic growth model is represented by the following equation:

$\boldsymbol{G} = \boldsymbol{r} * \boldsymbol{N} * [\mathbf{1} - \mathbf{N}/\mathbf{K}]$

**In this equation;**

***G, r, N*** are the same as in the exponential growth model

***K*** is the *carrying capacity* – the maximum population size that a particular environment can support or sustain ("carry").

In the exponential growth model, population growth rate is mainly dependent on *N* so that each new individual that is added to the population contributes equally to the growth of the population as those individuals previously in the population because per capita rate of increase is fixed. In the logistic growth model, an individual's contribution to population growth rate depends on the amount of resources available (K). As the number of individuals (N) in a population increases, fewer resources are available to everyone. As resources diminish, each individual on average produces fewer offspring than when resources are plentiful, causing the birth rate of the population to decrease.

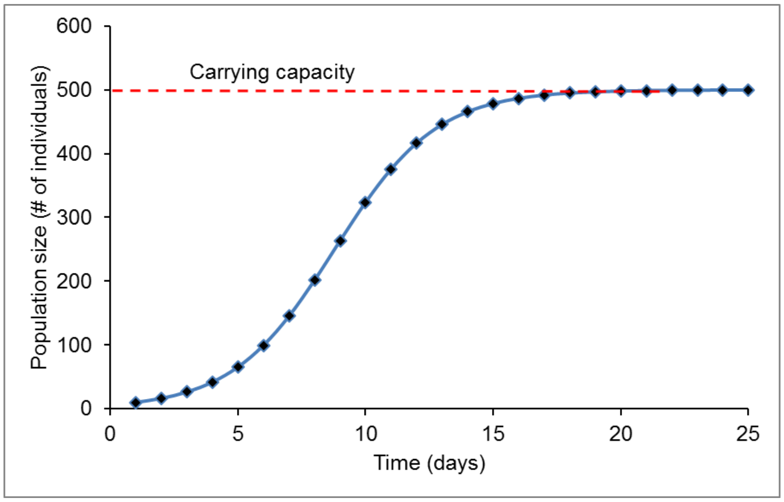


**Figure 6.3** Logistic growth and carrying capacity of a hypothetical bacteria population (credit: OpenStax. (2020). *Biology 2e*. OpenStax, Rice University).

The population starts out with 10 individuals and then reaches the carrying capacity of the habitat, which is 500 individuals. An **S-shaped** curve such as the one in figure 6.3 is the idealized curve of logistic growth but most natural populations do not exhibit population sizes that fall perfectly along this curve. Yeast, a microscopic fungus used to make bread and alcoholic beverages, exhibits the classical S-shaped logistic growth curve when grown in a test tube. Notice that the points representing population size at different time intervals do not all fall perfectly along the line, but most are on or very close to the line. As the population grows, the nutrients needed for growth become depleted and growth levels off. In the real world, however, there are variations to this idealized curve. For example, a population of harbor seals may exceed the carrying capacity for a short time, causing resources to be unable to support the population. This overshoot of the carrying capacity would cause the population to fall below the carrying capacity for a brief time period and as more resources become available, the population grows again (Figure 6.4). This fluctuation in population size continues to occur as the population oscillates/cycles around its carrying capacity. Still, even with this oscillation, the logistic model is exhibited.

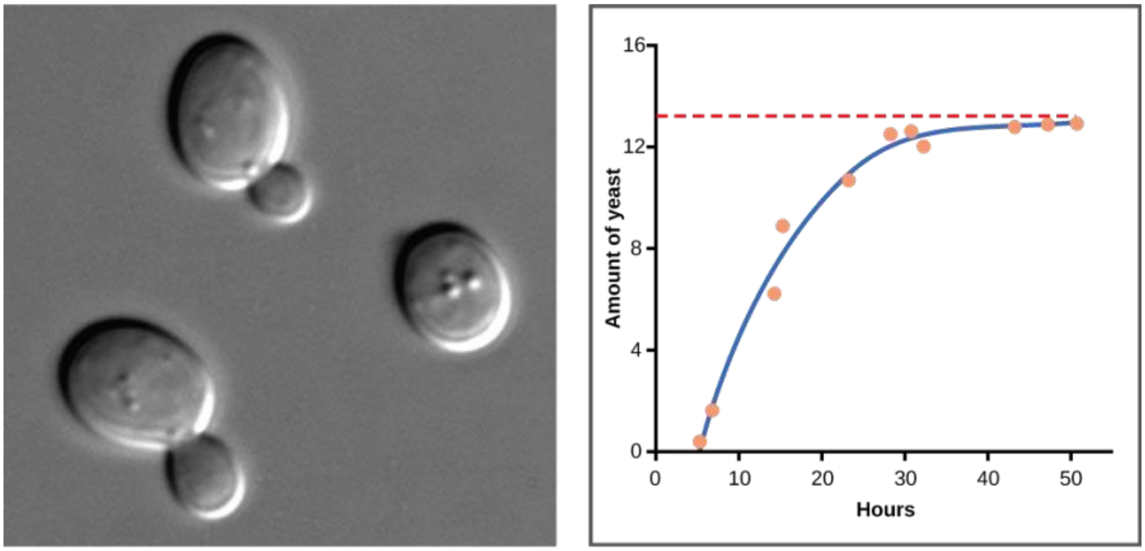


**Figure 6.4** Yeast versus time of growth in hours (credit: credit: OpenStax. (2020). *Biology 2e*. OpenStax, Rice University).

The graph in figure 6.4 shows the amount of yeast versus time of growth in hours. The curve rises steeply and then plateaus at the carrying capacity. Data points tightly follow the curve. The image is a micrograph (microscope image) of yeast cells.

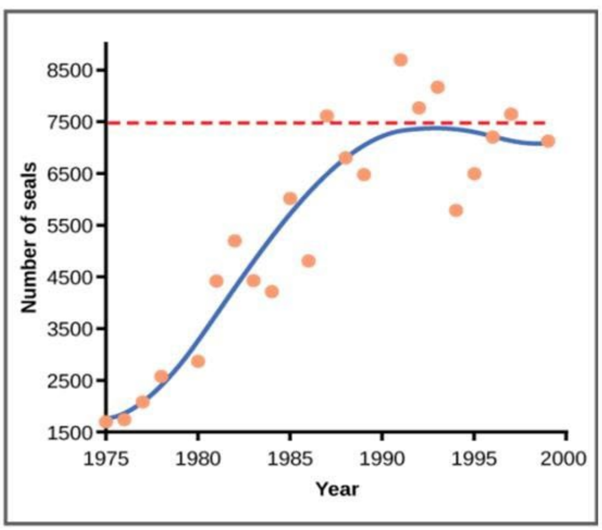


Photo of a common harbor seal by Andreas Trepte - Own work, CC BY-SA 2.5.

**Figure 6.5** Graph showing the number of harbor seals versus time in years (credit: OpenStax. (2020). *Biology 2e*. OpenStax, Rice University).

The curve rises steeply then plateaus around the point that represents the carrying capacity of its habitat. Notice how there is much more scatter in the data than what was exhibited in the yeast example above.

## Factors that Limit Population Growth

Recall previously that we defined density as the number of individuals per unit area. In nature, a population that is introduced to a new environment or is rebounding from a catastrophic decline in numbers may grow exponentially for a while because density is low and resources are not limited. Eventually, one or more environmental factors will limit the population growth rate as the population size approaches the carrying capacity and density increases. Example: imagine that to preserve elk, a population of 20 individuals is introduced to a previously unoccupied island that's 200 $km^2$ in size.

The population density of elk on this island is 0.1 $km^2$ per one elk (or 10 $km^2$ for each individual elk). As this population grows (depending on its per capita rate of increase), the number of individuals increases but the amount of space remains the same so density increases. Suppose that 10 years later, the elk population has grown to 800 individuals, density = 4 elk/ $km^2$ (or 0.25 $km^2$ for everyone). The population growth rate will be limited by various factors in the environment. For example, birth rates may decrease due to limited food or death rate increase due to rapid spread of disease as individuals encounter one another more often. This impact on birth and death rate in turn influences the per capita rate of increase and how the population size changes with changes in the environment. When birth and death rates of a population vary depending on the density of the population, the rates are said to be density-dependent, and the environmental factors that affect birth and death rates are known as **density dependent factors**. Population sizes can also be held in check by factors that are not related to the density of the population and are called **density-independent factors** and influence population size regardless of population density. Conservation biologists want to understand both types because this helps them manage populations and prevent extinction or overpopulation.

The density of a population can enhance or diminish the impact of *density-dependent* factors. Most density-dependent factors are *biological* in nature (biotic), and include such things as predation, inter- and intraspecific competition for food and mates, accumulation of waste, and diseases such as those caused by parasites. Usually, higher population density results in higher death rates and lower birth rates. For example, as a population increases in size food becomes scarcer and some individuals will die from starvation meaning that the death rate from starvation increases as population size increases. Also, as food becomes scarcer, birth rates decrease due to fewer available resources for the mother meaning that the birth rate decreases as population size increases.

For density-dependent factors, there is a feedback loop between population density and the density-dependent factor. Two examples of density-dependent regulation are shown in Figure 6.6. The first one shows results from a study focusing on the giant intestinal roundworm (*Ascaris lumbricoides*), a parasite that infects humans and other mammals. Denser populations of the parasite exhibited lower fecundity (number of eggs per female). One possible explanation for this is that females would be smaller in more dense populations because of limited resources and smaller females produce fewer eggs. The second one is the great tits bird, again showing that as the number of breeding bird pairs increases, the clutch size (number of eggs laid in a single brood by a nesting pair of birds) decreases.

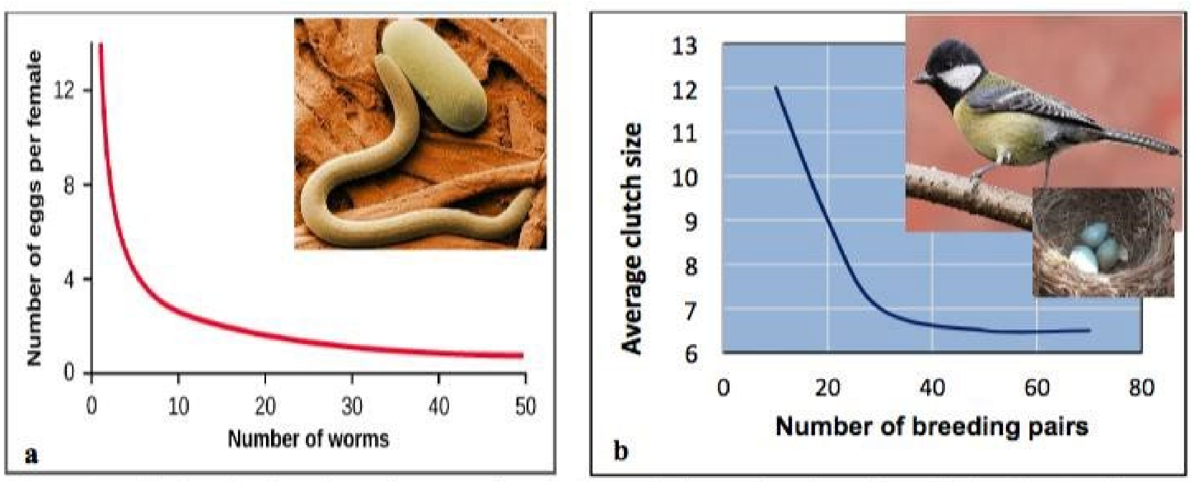


**Figure 6.6** (a) Graph of number of eggs per female (fecundity), as a function of population size. In this population of roundworms, fecundity (number of eggs) decreases with population density. (b) Graph of clutch size (number of eggs per "litter") of the great tits bird as a function of population size (breeding pairs). Again, clutch size decreases as population density increases. (credit: Zehnder, C., Manoylov, K., Mutiti, S., Mutiti, C., VandeVoort, A., & Bennett, D. (2018). *Population Ecology*. In *Environmental Biology* (Chapter 3). Harper College Pressbooks).

***Density-independent*** birth rates and death rates do NOT depend on population size; these factors are independent of, or not influenced by, population density. Many factors influence population size regardless of the population density, including weather extremes, natural disasters (earthquakes, hurricanes, tornadoes, tsunamis, etc.), pollution and other physical/abiotic factors. For example, an individual deer or hundreds of deer may be killed in a forest fire regardless of how many deer there are in the forest. The forest fire is not responding to deer population size. Weather changing from warm summer to cold winter is likely to kill many insects. The change in weather does not depend on whether the population size is 100 mosquitoes or 100,000 mosquitoes, most mosquitoes will die from the cold regardless of the population size and the weather will change irrespective of population density. Looking at the growth curve of such a population would show something like exponential growth followed by a rapid decline rather than leveling off (Figure 6.7).

Weather change acts as a density-independent factor limiting aphid population growth. This insect population undergoes exponential growth in the early spring and then rapidly dies off when the weather turns hot and dry in the summer. In real-life situations, density-dependent and independent factors interact. For example, a devastating earthquake occurred in Haiti in 2010. This earthquake was a natural geologic event that caused a high human death toll from this *density-independent event*. Then there were high densities of people in refugee camps, and the high density caused disease to spread quickly, representing a *density-dependent* death rate.

***Q: Can you think of other examples of density-dependent (biological) and density-independent (abiotic) population limiting factors?***

## Life Tables and Survivorship

Population ecologists use life tables to study species and identify the most vulnerable stages of organisms' lives to develop effective measures for maintaining viable populations. Life tables, track **survivorship**, the chance of an individual in a given population surviving at various ages. Life tables were invented by the insurance industry to predict how long, on average, a person will live. Biologists use a life table as a quick window into the lives of the individuals of a population, showing how long they are likely to live, when they'll reproduce, and how many offspring they'll produce. Life tables are used to construct **survivorship curves**, which are graphs showing the proportion of individuals of a particular age that are now alive in a population. Survivorship (chance of surviving to a particular age) is plotted on the y-axis as a function of age or time on the x-axis. However, if the percentage of maximum lifespan is used on the x-axis instead of actual ages, it is possible to compare survivorship curves for different types of organisms. For example, if an organism has a maximum lifespan of 20 years, 50% of its lifespan is 10 years. If another organism's maximum lifespan is 100 years, 50% if this organism's lifespan is 50 years. It would be challenging to compare these two organisms on the same graph using their absolute ages. However, when presented as a percentage of maximum lifespan, then the two can be plotted on the same graph because 50% means the same thing for both organisms.

All survivorship curves start along with the y-axis intercept with all the individuals in the population (or 100% of the individuals surviving). As the population ages, individuals die, and the curves go down. A survivorship curve never goes up. Survivorship curves reveal a great deal of information about a population, such as whether most offspring die shortly after birth or whether most survive to adulthood and are likely to live long lives. They generally fall into one of three typical shapes, Types I, II and III (Figure 6.7a). Organisms that exhibit **Type I** survivorship curves have the highest probability of surviving every age interval until old age, then the risk of dying increases dramatically. Humans are an example of a species with a Type I survivorship curve. Others include the giant tortoise and most large mammals such as elephants. These organisms have few natural predators and are, therefore, likely to live long lives. They tend to produce only a few offspring at a time and invest significant amounts of time and effort in each offspring, which increases survival.

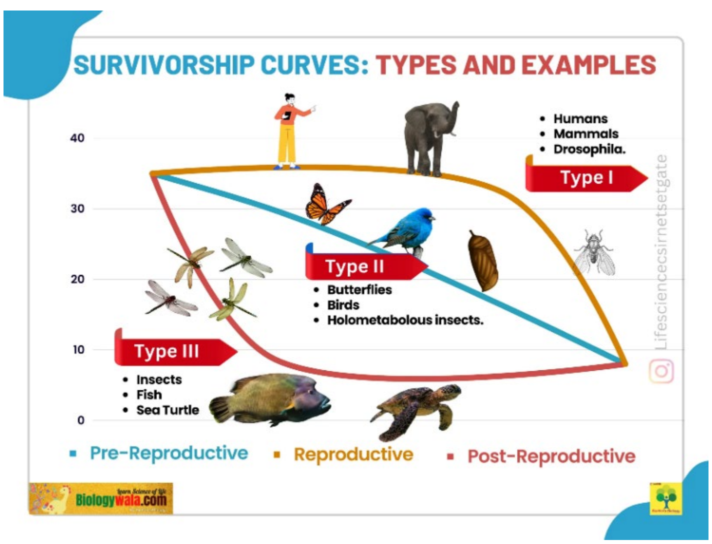


**Figure 6.7 (a)** Survivorship curves (credit: Biologywala. (n.d.). *Survivorship curves: Types and examples*. Retrieved from https://biologywala.com).

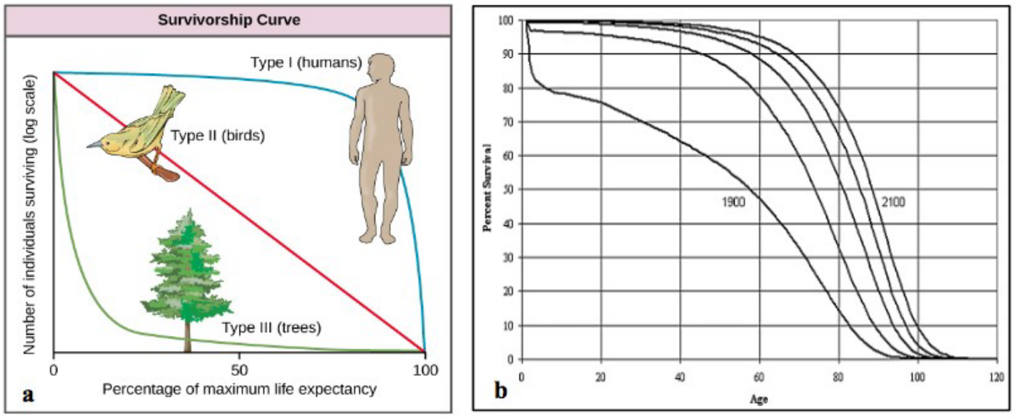


**Figure 6.7 (b)** Survivorship curves show the distribution of individuals in a population according to age. (credit: OpenStax College, Biology, CC BY 4.0).

Humans and most large mammals have a Type I survivorship curve because most death occurs in the older years. Birds have a Type II survivorship curve, as death at any age is equally probable. Trees have a Type III survivorship curve because very few survive in their younger years, but after a certain age, individuals are much more likely to survive.

(**b**) Survivorship curves for the US population for 1900, 1950, 2000, 2050, 2100.

In **t**he **Type III** survivorship curve, most of the deaths occur in the youngest age groups. Juvenile survivorship is very low, and many individuals die young but individuals lucky enough to survive the first few age intervals are likely to live a much longer time.

Most plant species, insect species, frogs as well as marine species such as oysters and fishes have a Type III survivorship curve. A female frog may lay hundreds of eggs in a pond, and these eggs produce hundreds of tadpoles. However, predators eat many of the young tadpoles and competition for food also means that many tadpoles don't survive. But the few tadpoles that do survive and metamorphose into adults then live for a relatively long time (for a frog). The mackerel fish, a female can produce a million eggs and on average only about 2 survive to adulthood. Organisms with this type of survivorship curve tend to produce very large numbers of offspring because most will not survive. They also tend not to provide much parental care, if any.

**Type II** survivorship is intermediate between the others and suggests that such species have an equal chance of dying at any age. Many birds, small mammals such as squirrels, and small reptiles, like lizards, have a Type II survivorship curve. The straight line indicates that the proportion alive in each age interval drops at a steady, regular pace. The likelihood of dying at any age interval is the same.

Most species don't have survivorship curves that are definitively type I, II, or III. They may be anywhere in between. These three, though, represent extremes and help us make predictions about reproductive rates and parental investment without extensive observations of individual behavior. For example, humans in less industrialized countries tend to have higher mortality rates in all age intervals, particularly in the earliest intervals when compared to individuals in industrialized countries. Looking at the population of the United States in 1900 (Figure 6.7b), you can see that mortality was much higher in the earliest intervals and throughout, the population seemed to exhibit a type II survivorship curve, like what might be seen in less industrialized countries or amongst the poorest populations.

## The Human Population

For most of human history, there were fewer than 1 billion people on the planet (Figure 6.8). During the early part of human history, the human population was held in check by diseases, famines, and wars that made life short and uncertain for most people. At the start of the *Agricultural Revolution*, 10,000 B.C., there were only 5-10 million people on Earth - which is about the size of the population of New York City today. During this revolution, human societies transitioned from small nomadic hunter-gatherer societies to larger stationary farming societies, leading to the first dramatic increase in the human population. This increase resulted from the increase in food supply that made it possible to feed more people. Also, there was a need for human labor to run the farms so there was incentive to have many children. People ate better and lived longer resulting in lower death rates while birth rates remained high. This first dramatic increase in population is estimated to have stabilized at around 100 million people, and for many centuries, population increased very slowly.

By the start of the next revolution – the *Industrial Revolution* - in 1800, there were approximately 1 billion people on Earth (Figure 6.8). This revolution was marked with progress in agricultural production, engineering, commerce, information technology, sanitation and health care all of which drove death rates down even further and spurred the next more extreme wave of population growth. Improvements in health care and sanitation spread from developed countries to developing ones like

India and China, enabling people in all countries around the world to live longer than ever before. It, therefore, took all of human history for population to reach 1 billion people in 1804, only about 150 years to reach 3 billion in 1960, and only 12 years to increase from 5 billion in 1987 to 6 billion in 1999 and again another 12 years to increase to 7 billion in 2011. This clearly demonstrates the capacity of the human population to exhibit exponential growth.

### *What is the current human population?*

The reality is that the human population continues to grow every second. So rather than answer this question with an absolute value that quickly becomes outdated, a better option is to provide a population clock that uses an algorithm to keep track of human population growth. These clocks even let you see what the population was at the previous date and project what the population will be at a future date. Two such clocks include one by the US Census Bureau and another by written by Galen Huntington as part of a programing project while at University of California, Berkeley. You will notice some difference in population size estimated by the two population clocks but overall, they are within reasonable amounts of one another. A more important question to ask is, how much more will this population growth continue? It is estimated that the current consumption levels combined with the size of the population are way beyond the Earth's carrying capacity.

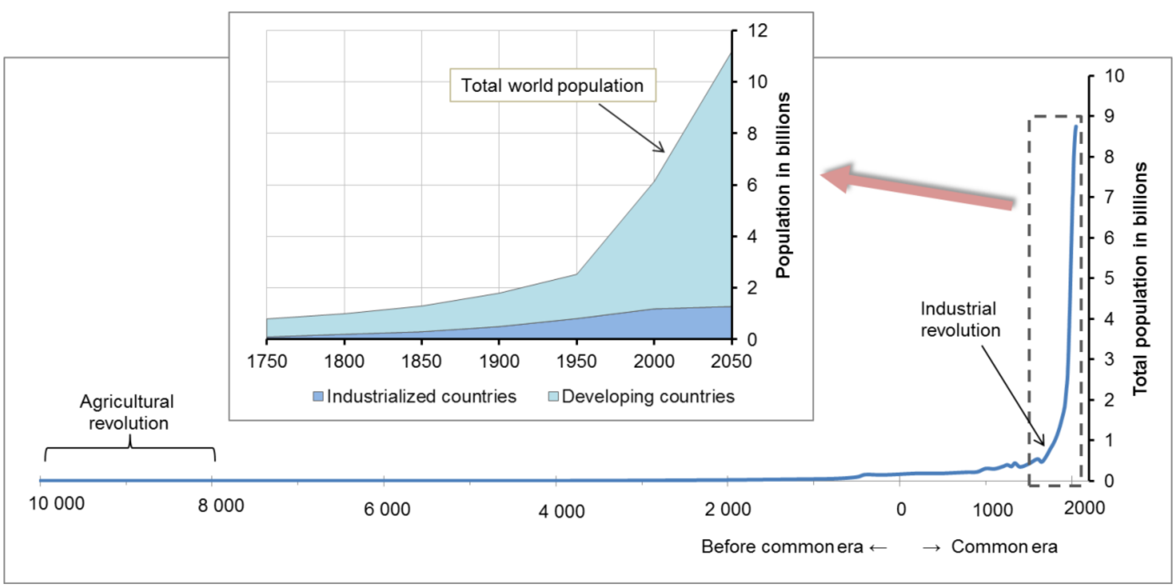


**Figure 6.8** Predicting human population growth (credit: OpenStax College, Biology, CC BY 4.0).

Figure 6.8: Shows the increase in human population size starting from the agricultural revolution and predicted out to 2050. The graph shows that for most of human history; the human population size was low and stable. The inset image shows population growth in the modern era – outer line is the total world population while shaded regions represent population in industrialized countries (bottom) and less-industrialized/developing countries (top). The greatest amount of human population growth will be in less-industrialized countries. Data used to make the graphs were obtained from the United Nations Population Division; future projections are the UN's medium variant.

Dire predictions have been made about the growing world's population leading to a major crisis called the "population explosion." Thomas Malthus (1766-1834) collected evidence showing that populations tended to increase at an exponential rate while food production remained stable or increased slowly. He predicted that human populations would eventually outstrip their food supply leading to starvation, crimes and misery. Karl Marx (1818-1883) presented a different view in which poverty, resource depletion, pollution and other social ills were the cause of population growth and argued that stopping this growth required the elimination of these social ills. These theories about human population growth were developed prior to and did not account for current scientific and technological advances. Food supplies increased faster than population growth since Malthus' time. Progress in agricultural productivity, engineering, information technology, commerce, medicine, sanitation and other achievements of modern life have made it possible to support thousands of times as many people per unit area as was possible 10,000 years ago.

Although humans have increased the carrying capacity of their environment, the technologies used to achieve this transformation have caused unprecedented changes to the environment, altering ecosystems to the point where some may be in danger of collapse. The depletion of the ozone layer, erosion due to acid rain, and damage from global climate change are caused by human activities. The ultimate effect of these changes on our carrying capacity is unknown. As some point out, it is likely that the negative effects of increasing carrying capacity will outweigh the positive ones, the world's carrying capacity for human beings might decrease.

## Demography

**Demography:** The statistical study of human populations, including factors such as **births, deaths, sex ratio, age groups, size, and distribution.** **Demography** applies to the principles of population ecology to the human population. Demographers study how human populations grow, shrink, and change in terms of age and gender compositions using vital statistics about people such as births, deaths, population size, and where people live. Demographers also compare populations in different countries or regions. Currently, there are two disparate demographic worlds.

On one end is an old, rich, and relatively stable world often referred to as "*industrialized*" or "*developed*" world, and includes many European nations, United States, Canada, Japan, and Australia among others. On the other end is young, poor, and rapidly growing world often referred to as "*less-industrialized*", "*less-developed*" or "*developing*" and is made up of most people in Asia, Africa, and Latin America. In between these two extremes are countries such as China, India, Brazil, Mexico, South Africa, Russia, and many others that have not quite attained the developed status but have clearly outpaced the so-called developing countries. These nations are sometimes referred to as "*newly industrialized*" or "*emerging market economies*."

## Age structure diagrams

One of the tools that demographers use to understand and predict future trends in populations is the **age structure diagram**. This diagram shows the distribution by ages of females and males within a certain population in graphic form. Figure 6.9 shows an age structure diagram for the United States' population. In this diagram, the ages are arranged so that age ranges are grouped together, for example: 0 – 4 years, 5 – 9 years, and so on. The population of each group is represented as a bar extending from a central vertical line, with the length of each bar dependent upon the total population for that group. The centerline separates the females from the males. A closer look at **Figure 6.9** shows slightly more boys in the younger age groups than girls; however, the ratio tends to reverse in the upper age groups, when females tend to outnumber males. Many countries have a female majority because of the longer life expectancy for females. Age classes between 0 and 15 years are referred to as *pre-reproductive*, between 15 and 45 years are the *reproductive* age classes and above 45 years are the *post-reproductive* age classes.

An age-structure diagram provides a snapshot of the current population and can present information about the past and give potential clues about future problems. In figure **6.9**, for example, notice the slight bulge among ages 50-54 and 55-59 that represents the so-called "baby boomers." These are individuals who were born during the baby boom that followed the end of the world war when couples were reunited, and new families started. Also notice the slight bulge among the 20-24 and 25-29 age groups; what do you suppose is the explanation for this bulge?

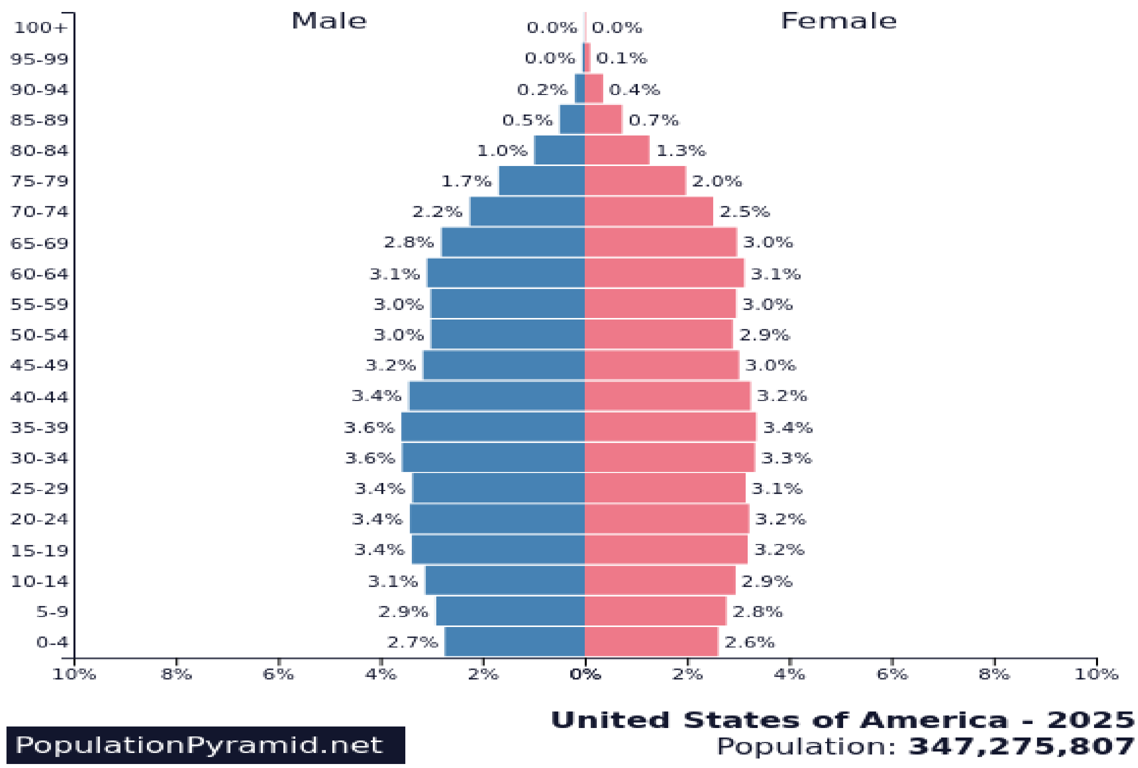


**Figure 6.9** Age Structure diagram for the U.S. in 2025. (credit: PopulationPyramid.net)

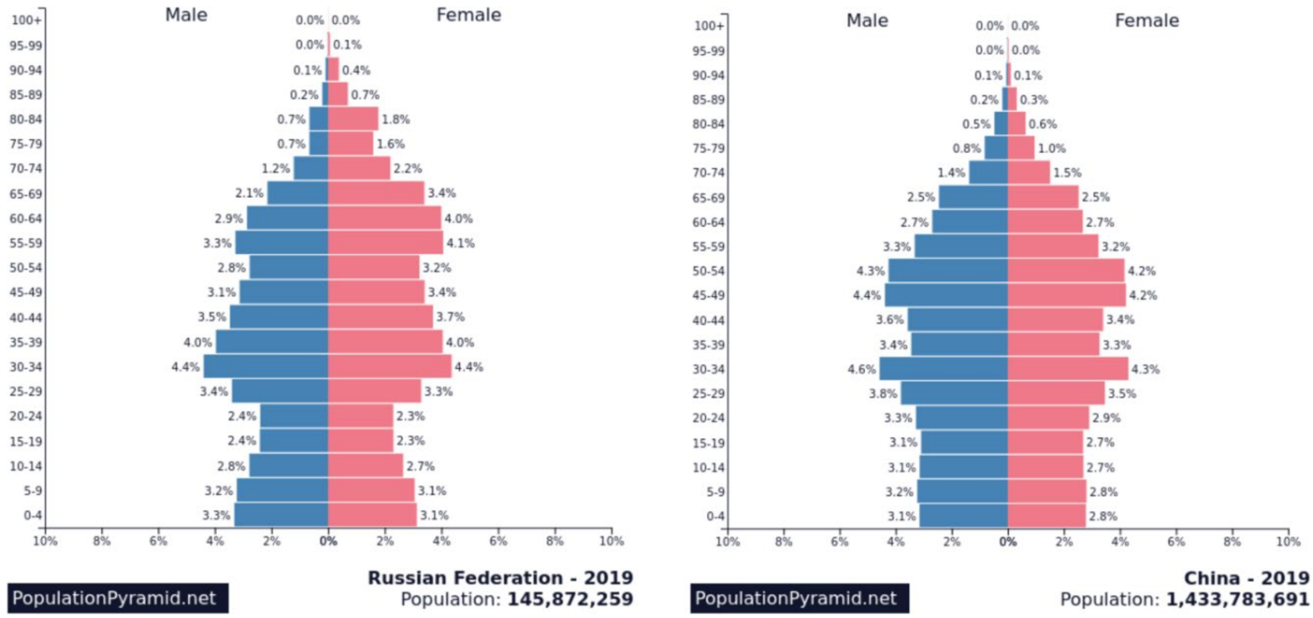


**Figure 6.10** Age structure diagram for Russia and China in 2019. (PopulationPyramid.net).

When interpreting age-structure diagrams, it is important to compare the width of the base to the rest of the population. A country with a stable population, such as the United States (**Figure 6.9**) has nearly the same number of individuals in each age group. Individuals who are born replace those who die so the population remains stable. If the base is very wide compared to the upper parts of the diagram (**Figure 6.11 a**), then this indicates a lot of young people in the population compared to older generations i.e. a high birth rate and a rapidly growing population. An aging population is one with a base that is smaller than the upper parts of the diagram (**Figure 6.11 b**), which implies that more of the population is found in older, post-reproductive age classes than in younger ones. This population is shrinking due to low birth rates and the bulge in the middle represents the age classes for the last high birth rate generation.

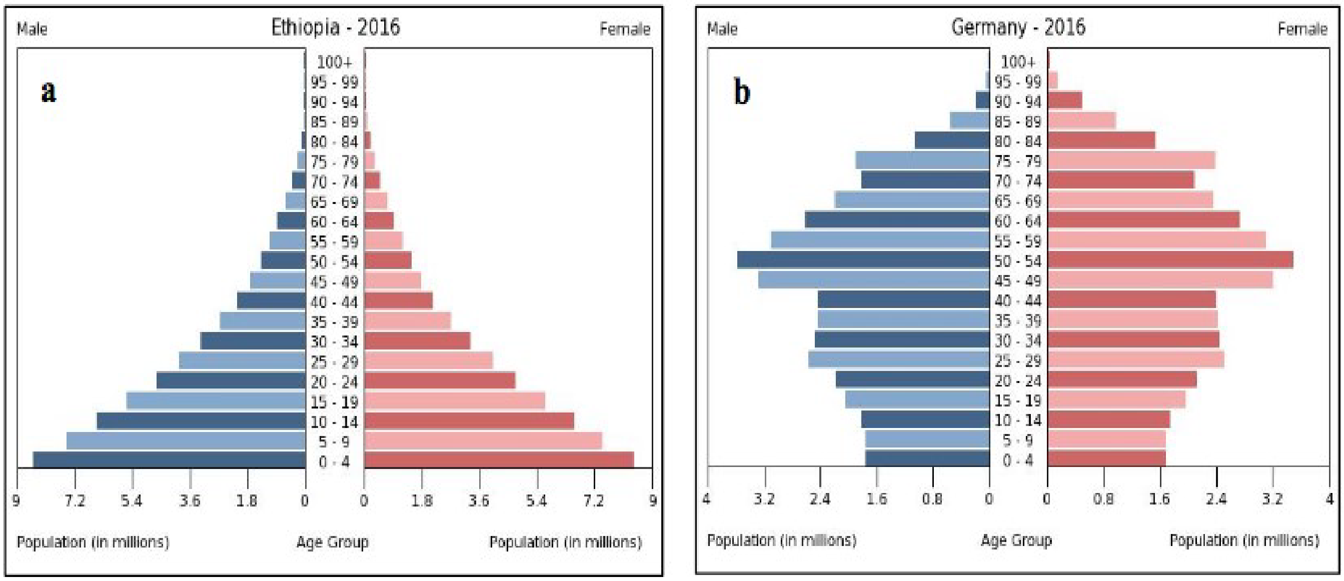


**Figure 6.11**: Age Structure diagram for Ethiopia (a rapidly growing population) and Germany (a declining population) in 2016. (credit: CIA World Factbook).

Countries with rapidly growing and shrinking populations can have a problem with their **dependency ratio**, the number of nonworking individuals compared to working individuals in a population. In rapidly growing populations, each working person supports a high number of children. In shrinking populations, a small number of working people have to support a larger number of retired people with possible dire consequences to the social security system.

## The Demographic Transition Model

The demographic transition model shows the changes in the patterns of birth rates and death rates that typically occur as a country moves through the process of industrialization or development. The demographic transition model was built based on patterns observed in European countries as they were going through industrialization. According to this model, as a country's economy changes from preindustrial to postindustrial, low birth and death rates replace high birth and death rates. This model can be applied to other countries, but not all countries or regions fit the model exactly. And the pace or rate at which a country moves through the demographic transition varies among countries.

In the demographic transition model (Figure 6.12), Stage I is the *preindustrial stage* in which both birth rates and death rates are high. The high death rates are because of disease and potential food scarcity.

A country in Stage I of the demographic transition model does not have good health care; there may not be any hospitals or doctors. Children are not vaccinated against common diseases and many die at a young age. Infant and childhood **mortality rates** (death rates) are very high. A society in Stage I is likely based upon agriculture, and most people grow their own food. Therefore, droughts or floods can lead to widespread food shortages and death from famine. All these factors contribute to the high death rate in Stage I. Partly to compensate for the high death rates, birth rates are also high. High birth rates mean that families are large and each couple, on average, has many children. When death rates are high, having many children means that at least one or two will live to adulthood. In Stage I, children are an important part of the family workforce and are expected to help with growing food and taking care of the family. As you are examining the stages of the demographic transition model, remember that: **Population Growth Rate = Birth Rate – Death Rate.** In Stage I, birth rates are high, but death rates are high as well. Therefore, the population growth rate is low or close to zero (Figure 6.12). For most of human history, all countries were in Stage I but today, no country is classified in Stage I as this model.

As a country develops, medical advances such as access to antibiotics and vaccines are made. Sanitation improvements such as proper waste and sewage disposal, and water treatment for clean drinking water also progress. Food production also increases. Together these changes lead to falling death rates, which mark the beginning of Stage II, the *industrializing/urbanizing stage.* Death rates continue to fall throughout Stage II as conditions improve. This means that people are living longer, and childhood morality drops. However, birth rates are still high in Stage II. There is a time lag between the improving conditions and any subsequent changes in family size, so women are still having many children and now more of these children are living into adulthood. In Stage II, the birth rate is higher than the death rate, so population growth rate is high. This means that population size increases greatly during Stage II of the demographic transition model (Figure 6.12).

A falling birth rate marks the beginning of Stage III – *the mature/industrial stage* - in the demographic transition model. As a country continues to industrialize, many women join the workforce. Additionally, raising children becomes more expensive and children no longer work on the family farm or make large economic contributions to the family. Individuals may have access to birth control and choose to have fewer children. This leads to a drop in birth rates and smaller family sizes. Death rates also continue to drop during Stage III as medicine, sanitation and food security continue to improve. Even though both birth rates and death rates are falling throughout Stage III, birth rates are still higher than death rates. This means that population growth rate is high and that population size continues to increase in Stage III of the demographic transition model.

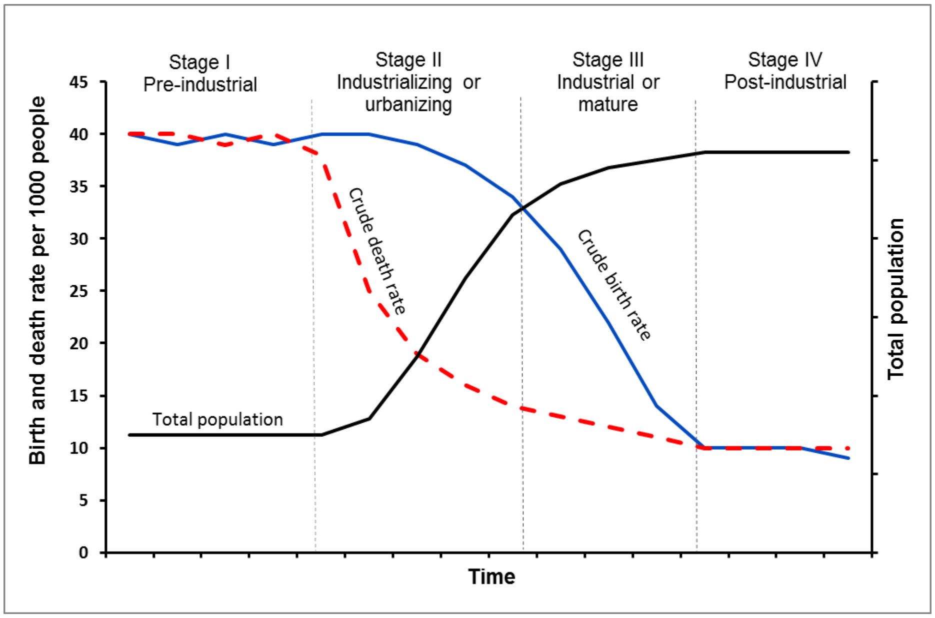


**Figure 6.12** Demographic transition model showing high birth and death rates in Stage I transitioning to low birth and death rates in Stage IV. (credit: OpenStax College, Biology, CC BY 4.0).

In figure 6.12, the population starts off as stable but low in Stage I and transitions to stable but high in Stage IV. Birth rate and death rates drop to low, stable, approximately equal levels in Stage IV – the *postindustrial stage*. Death rates are low because of medical advances, good sanitation, clean drinking water and food security. Most people are therefore dying of old age. Birth rates are low because of access to birth control and many women in the workforce delay marriage and having their first child until they have established their careers. Childhood mortality is low, life expectancy is high, and family size is approximately two children per couple. With low birth rates and low death rates, population growth rate is approximately zero in Stage IV.

## Life expectancy

**Life expectancy** is the average number of years that a person in a particular population is expected to live (average age at death). Life expectancy at birth is the number of years a newborn infant would live if mortality rated at the time of its birth did not change. For example, the life expectancy at birth for someone born in 2016 in Japan is 84.2 years while the life expectancy at birth for someone born in the United States in 2016 is 78.5 years (source: https://www.cia.gov). As a country moves through the demographic transition model, life expectancy increases. Overall, life expectancy has increased in most countries and regions over the past 100 years. The main cause of population growth has not been increased fertility but rather declining death rates due primarily to better food and better sanitation. In 1900, the world average life expectancy was only about 30 years. By 2006, the average age was 64.3 years, attributed to better nutrition, sanitation, and medical care. While overall life expectancy has increased worldwide, there is still a significant change in life expectancy in different regions of the world with a significant discrepancy between rich and poor countries. For example, the life expectancy of an individual born in Lesotho in 2016 is 52.9 years, more than 30 years less than an individual born the same year in Japan.

## Fertility

**Fertility** describes the actual production of offspring. One demographic statistic of fertility is the **crude birth rate**, which is the number of births in a year per thousand people. It is referred to as "crude" because it is not adjusted for important population characteristics such as the number of women of reproductive age. Another statistic is **total fertility rate** (TFR), which is the number of children born to each woman in a population, over the woman's lifespan. The formula for the total fertility rate (TFR) is the sum of all age-specific fertility rates multiplied by five, then divided by 1,000. The TFR is an estimate of the average number of children a woman of childbearing age will have. It assumes that a woman will live to the end of her childbearing years and have the number of live births predicted by the current fertility rates. The TFR is based on age-specific fertility rates from 15–45 years, or five years in age groups.

TFR differs considerably between regions as is clearly demonstrated by figure 6.13**.** However, the forces that determine a region or country's TFR are generally the same, including healthcare, education, economic conditions, culture, and religion. These factors all work together to determine a country's **desired fertility** (the number of children the average couple says they want to have), which in turn influences the TFR. Factors that increase people's desire to have children are known as **pronatalist pressures**.

Countries in the pre-industrial and industrializing stages of the demographic transition (Stage I and II respectively) have higher TFR but this decreases considerably as countries move to the industrialized and post-industrial stages. Prior to industrialization, high infant mortality rate (the number of infants who die in their first year of life per 1000 births) leads couples to have more children to increase the odds that at least some will survive to adulthood. Poverty is strongly correlated with high TFR, as poorer societies tend to show higher population growth rates than wealthier societies.

However, this relationship operates in both directions because rapid population growth tends to worsen poverty. As countries advance through the demographic transition, improved medical care reduces infant mortality rates making it less necessary to have many children. Urbanization removes the need for children to contribute to farm labor, and children are required to go to school, imposing economic costs on their families. Many governments also provide some form of social security, which reduces the need for parents to have many children to support them in their old age.

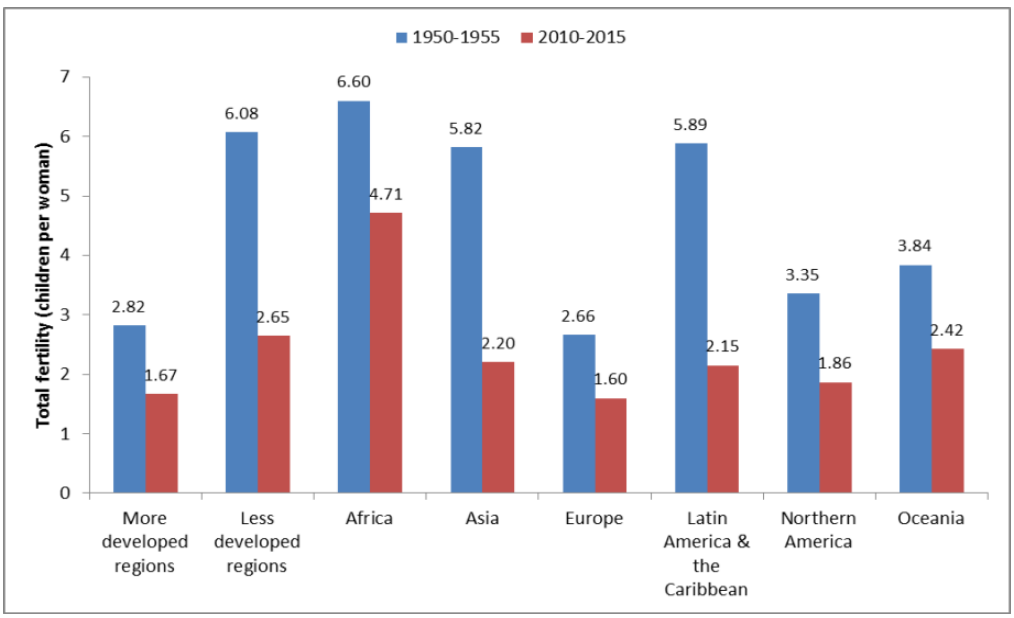


**Figure 6.13** Shows the total fertility of different regions of the world. (credit: OpenStax College, Biology, CC BY 4.0).

The blue bars are the total fertility estimates from 1950-1955. The red bars are the total fertility estimates from 2010-2015. More developed regions include Europe, Northern America (US and Canada), Australia, New Zealand and Japan. Less developed regions comprise all regions of Africa, Asia (except Japan), Latin America and the Caribbean plus Melanesia, Micronesia and Polynesia. Oceania includes Australia, New Zealand, Melanesia, Micronesia and Polynesia. Data are from the United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects, 2015 Revision.

Overall, fertility rates have decreased in most countries and regions over the past 50 years (Figure 6.13). However, there is still a significant amount of variation among different regions of the world, with Africa still showing high TFR. The goal is to achieve **zero population growth**, when the population size is neither increasing nor decreasing. This occurs when the number of people born (birth rate) equals the number of people dying (death rate). Zero population growth is realized when the population reaches the **replacement fertility rate**, meaning that every couple only has enough children to replace themselves. The global replacement fertility rate is currently estimated to be **2.1** children per woman rather than 2 because not all children survive and not all couples have children.

# Chapter Seven: Natural Resources

## Objectives

- Describe natural resource conservation
- Explain HIPPCO
- Describe and explain renewable and nonrenewable energy resources

**Natural resources** are materials or substances found in the environment that are used by humans for various purposes. They are essential for the sustenance of life and the functioning of economies. Natural resources are broadly categorized into renewable and non-renewable resources based on their availability and replenishment rates.

**Biodiversity** is all the different kinds of life you'll find in one area—the variety of animals, plants, fungi, and even microorganisms like bacteria that make up our natural world. Each of these species and organisms works together in ecosystems, like an intricate web, to maintain balance and support life. Biodiversity supports everything in nature that we need to survive food, clean water, medicine, and shelter.

## Renewable Resources

**Solar Energy:** Solar energy is harnessed from the sun's radiation. It is a clean and sustainable source of power used for electricity generation, heating, and various industrial applications. Solar panels and solar thermal systems capture sunlight to produce energy.

**Wind Energy:** Wind energy is generated by harnessing the kinetic energy of the wind through wind turbines. Wind power is an eco-friendly and renewable source of electricity, commonly used in wind farms.

**Hydropower:** Hydropower involves the use of flowing or falling water to generate electricity. Dams and water turbines convert the energy of moving water into electrical power. It is a reliable and widely utilized renewable energy source.

**Biomass:** Biomass refers to organic materials, such as wood, agricultural residues, and organic waste, that can be used for energy production. Biomass can be burned directly for heat or converted into biofuels like ethanol and biodiesel.

**Geothermal Energy:** Geothermal energy is derived from the Earth's internal heat. It involves tapping into underground reservoirs of hot water and steam to generate electricity or for direct heating purposes. Geothermal power plants are common in regions with high geothermal activity.

**Soil**: Soil contains various mineral particles derived from the weathering of rocks. These particles, categorized into sand, silt, and clay, contribute to the soil's texture, structure, and nutrient-holding capacity.

## Non-Renewable Resources

**Fossil Fuels:** Fossil fuels, including coal, oil, and natural gas, are formed from the remains of ancient plants and animals. They are major sources of energy for electricity generation, transportation, and industrial processes. However, their combustion contributes to environmental issues like air pollution and climate change.

**Minerals and Metals:** Various minerals and metals are extracted from the Earth's crust and used for construction, manufacturing, and technological applications. Examples include iron ore, copper, aluminum, and rare earth elements.

**Nuclear Fuels:** Nuclear fuels, such as uranium and thorium, are used in nuclear power plants to generate electricity through nuclear fission. While they provide a significant amount of power, the disposal of nuclear waste and the potential for accidents pose environmental challenges.

**Non-Metallic Minerals:** Non-metallic minerals, such as limestone, gypsum, and salt, are used in construction, agriculture, and various industrial processes. They are essential for producing materials, fertilizers, and chemicals.

**Fossil Water:** Fossil water, also known as non-renewable or ancient groundwater, is stored in underground aquifers for long periods of time. While it is a valuable resource for agriculture and drinking water, its extraction can lead to depletion and environmental consequences.

Balancing the use of natural resources is crucial for sustainable development, considering their finite nature and the environmental impacts associated with their extraction and utilization. Efforts are ongoing to develop technologies and practices that promote responsible resource management and reduce the reliance on non-renewable sources.

## **H**abitat destruction, **I**nvasive species, **P**opulation growth, Pollution, **C**limate change, and **O**verexploitation (**HIPPCO)**

HIPPCO stands for Habitat destruction, Invasive species, Population growth, Pollution, Climate change, and Overexploitation. HIPPCO describes the main factors that cause disruption in biodiversity. Biodiversity is the variety of different species of plants and animals living in a particular area.

## The Salton Sea

The Salton Sea, located in the southern Riverside and northern Imperial counties in Southern California, is California's largest lake (map on the right). Although large seas have cyclically formed and dried over historic time in the basin due to natural flooding from the Colorado River, the current Salton Sea was formed when Colorado River floodwater breached an irrigation canal being constructed in the Imperial Valley in 1905 and flowed into the Salton Sink. The sea has since been maintained by irrigation runoff in the Imperial and Coachella valleys and local rivers. Because the sea is a terminal lake, increasingly concentrated salts have resulted in a salinity that is currently 50 percent greater than that of the ocean.

## Desert Resources

Deserts are areas that receive very little precipitation. People often use the adjectives “hot,” “dry,” and “empty” to describe deserts, but these words do not tell the whole story. Although some deserts are very hot, with daytime temperatures as high as 54°C (130°F), other deserts have cold winters or are cold year-round. And most deserts, far from being empty and lifeless, are home to a variety of plants, animals, and other organisms. People have adapted to life in the desert for thousands of years. Conservation and preservation are vital for the survival of Salten Sea.

**Conservation** involves using the Earth’s resources sustainably, which means they will be available to future generations. Ways in which conservation can be applied include not overfishing, replanting trees when they are logged, and protecting soil in farming areas from erosion.

**Preservation** is the idea of protecting natural areas and trying to keep them as close as possible to their original, unspoiled state. As such, human impacts should be minimal, and resources in preserved areas are not for human use.

One of the foremost examples of preservation is the national park. The governments in nearly 100 countries worldwide have established these parks in wilderness areas where visitors can come and enjoy the scenery and the flora and fauna. The United States is a world leader in national parks, and in fact, the first national park in the world, Yellowstone, was created in the United States in 1872. However, the United States only has 59 national parks, much less than the 685 parks in Australia, the world leader in total parks. In Asia, China boasts the largest number of parks at over 200.

## Desert Ecology and Biodiversity

Deserts are abundant with both flora and fauna. What is so great about deserts such as biomes is their unique biological profile. Species exist in these environments that simply do not appear elsewhere. The Mojave Desert is a case in point; it's one of the harshest environments on the planet with a humidity level that rarely goes higher than 40%, yet it maintains abundant biodiversity throughout the seemingly barren topography. All species have adapted to living in this harsh environment and many are protected because of their geographical limitations and delicate ecological requirements of coping with the high temperatures and dry environment.

Typical botany. include succulents such as cacti which do not have leaves like other species, but spines to protect the fleshy body of chloroplasts adapted to store water, and shallow roots to quickly absorb the little moisture that makes it into the topsoil before evaporating away or soaking through. Similar specialization is also true of fauna which have high water retention, do not have the capability to perspire, and tend to be cold-blooded and small. Larger animals and mammals are rare although this is not always the case.

- Kangaroos, for example, which live in the hot desert climate of Australia are warm-blooded mammals and must find shelter during the hottest part of the day to avoid overheating. They have, however, developed a great defense mechanism against extreme heat in that they lick their bodies, and the saliva cools the blood.
- Camels survive well in deserts because of their high-water retention and survive quite happily in temperatures up to 48$^{o}$ C/120$^{o}$ F.

These are two rare examples of both warm-blooded and larger animals that live in hot deserted environments. But what about cold deserts? They have received less attention than their hotter or semi-arid counterparts. We do understand that as they are in extreme latitudes, that means most cold deserts tend to experience periods (months) of continual dark in the winter and periods of continual sunshine in the summer. This too has an impact on local biodiversity. Like their hotter counterparts, plants must be drought resistant. But succulents do not survive in these environments because of the cold. The most common type of plant in cold deserts are grass, and they form in clumps on rocks and in areas where the little moisture is most abundant. Shrubs occur in some places and the types of plant you might see on scrubland, but this is rare. Trees are also rare with only a handful of species such as the camel thorn acacia in the Gobi and the pistachio tree which grows in the cold deserts of Iran.

**Figure 7.1** Photograph of a Jerboa eating a plant in a desert (credit: Smith, J. (2019).

Animals in cold deserts are warm-blooded and larger than their hot desert counterparts. Typical examples include types of deer and antelope present in most cold deserts, sheep and goats likewise, and in South America llamas and alpacas. As far as carnivores are concerned, this is the realm of the wolf, the snow leopard, and jackals, depending on where in the world the desert is located. Small mammals are much more abundant and cold-blooded reptiles are less abundant. In fact, scorpions appear in just one cold desert - the Iranian Desert.

## Deserts as Climate Indicators

Desert is one biome type that researchers and conservationists do not want to expand all the while ensuring that the deserts we presently have do not disappear. The major reason for this is that desert is of low agricultural quality, low biodiversity, and an extreme environment. Climate change presents a risk of desertification of present marginal landscapes. We know this occurs from paleoenvironmental data. Many of our deserts contain the remnants of ancient lakes, indicated by former water channels and preserved biotic and abiotic materials indicative of previous presence of water. As deserts are the most extreme environments on the planet, they are prone to the most change. Radiation is intense, both in terms of how much deserts receive and how much they reflect into the environment.

The expansion of desert can directly impact global average temperatures further, increasing water evaporation in adjacent areas. Even though the plant and animal species that exist in hot deserts are well-adapted to those environments, we know from studies that such organisms are treading a fine line over environmental tolerance; some are even at their limits, according to the IPCC. Both the Sahara and the Namib are extremely hot deserts and in recent years have experienced some of the hottest temperatures to date. Pakistan and Iran have also experienced record dry spells and high temperatures in the last decade. Even semi-arid desert climates are experiencing an increase in hot and dry spells, becoming more parched and experiencing wildfires in areas where scrub, brush and tree cover is more abundant. California, for example, has always experienced summer wildfires but the season for the fires is getting longer with the increased drought the state is experiencing. Continued drought, lowering precipitation and a dropping of the water table means plants cannot grow as abundantly. This creates a high risk of expanding desertification. The risks are highest in the 50 degrees S-50 degrees N range which is the latitudes within which the hottest and driest desert climates presently are. Evidence demonstrates that the deserts of the Arabian Peninsula alone show increased water vapor feedback, much higher sensitivity, and increased sensitivity in deserts to greenhouse gas emissions. Simply, deserts become hotter and drier during a warming climate with wider implications for the warming climate. That makes this type of biome one of the most useful types for understanding and tracking climate change now and for the future.

## Desert Resources

The desert biome is a rich ecosystem. There are 15 mineral deposit types on our planet and 13 of them are found in deserts. This makes the desert an important place for mineral resources and for the local and global economy. Water leaches through the ground or through evaporation so quickly that mineral deposits are left behind. We discussed the problem with irrigation in Mesopotamia in the archaeology section where increased salt deposits made agriculture more difficult. This leads to the formation of large metal deposits. Typical mineral resources found in desert regions (both hot and cold) include salt and borates, and gypsum. Borates occurred in high density in the Great Basin Desert here in the US. From there, borate was taken to Death Valley to the emerging railroads and all over the country.

This special kind of salt is used to manufacture glass, enamel and other ceramics, and in the pharmaceutical and agrichemical industries. All of it was mined from the dried beds of paleolakes that once existed in the region. It is estimated that the value to the US economy of borates alone has topped $1 billion. The US deserts are also home to copper. Salts have also proven a great resource for the Chilean economy although today its lithium resources have also taken prominence on the world stage as battery development increases for better power storage and production in the new generation of electric cars. No other desert has as much abundant salt as this desert. It is estimated that during the First World War alone, some 3 million metric tons were mined. Like the US deserts, copper is present in Chile.

Australia's deserts are a source of lead and zinc, uranium, gold and silver. As far as non-metal resources are concerned, deserts are also home to clay, beryllium, pumice (where there was past volcanic activity), nitrates and lithium. Some of the most abundant oil deposits are found in desert regions, particularly the Middle East, Central and South America, in the driest places on Earth. These were once marine environments, but the lakes and seas dried up, allowing for the chemical processes that turn organic material into crude oil to create enormous deposits.

# Chapter Eight: Agriculture, Food Production and Environment

## Objectives

- Describe the various farming methods.
- Explain the significance of agriculture to humans.
- Explain impact of conventional agriculture on the environment.
- Discuss the socio-economic concerns of farming.

## Agriculture and the Environment

Agriculture and increasingly aquaculture are essential to supplying our food to sustain the world's population. Farming is also the world's largest industry, employing over one billion people and generating over one trillion dollars' worth of food annually. Moreover, it is the most significant driver of habitat and biodiversity loss around the world.

## Conventional Agriculture

The prevailing agricultural system, variously called "**conventional farming**," "modern agriculture," or "industrial farming," has delivered tremendous gains in productivity and efficiency. Food production worldwide has risen in the past 50 years; the World Bank estimates that between 70 percent and 90 percent of the recent increases in food production are the result of conventional agriculture rather than greater acreage under cultivation. North American consumers have come to expect abundant and inexpensive food.

Conventional farming systems vary from farm to farm and from country to country. However, they share many characteristics such as rapid technological innovation, large capital investments in equipment and technology, large-scale farms, single crops (**monocultures**); uniform high-yield hybrid crops, dependency on agribusiness, mechanization of farm work, and extensive use of pesticides, fertilizers, and herbicides. In the case of livestock, most production comes from systems where animals are highly concentrated and confined.

**Figure 8.1** A Cotton Harvest in a cotton field. (Credit: Kimberly Vardeman, CC BY 4.0.).

Conventional agriculture is dependent on large investments in mechanized equipment powered mostly by fossil fuels. This has made agriculture efficient but has had an impact on the environment. Both positive and negative consequences have come with the bounty associated with industrial farming. Some concerns about conventional agriculture are presented below.

## Ecological Concerns

Agriculture profoundly affects many ecological systems. The negative effects of current practices includes decline in soil productivity due to wind and water erosion of exposed topsoil, soil compaction, loss of soil organic matter, water holding capacity, and biological activity; and **salinization** (increased salinity) of soils in highly irrigated farming areas. Converting land to desert (**desertification)** can be caused by overgrazing livestock and is a growing problem, especially in parts of Africa.

Agricultural practices have been found to contribute to non-point source water pollutants that include salts, fertilizers (nitrates and phosphorus, especially), pesticides, and herbicides. Pesticides from every chemical class have been detected in groundwater and are commonly found in groundwater beneath agricultural areas. They are also widespread in the nation's surface waters. Eutrophication and "dead zones" due to nutrient runoff affect many rivers, lakes, and oceans. Reduced water quality impacts agricultural production, drinking water supplies, and fishery production. Water scarcity (discussed in a previous chapter) in many places is due to overuse of surface and ground water for irrigation with little concern for the natural cycle that maintains stable water availability.

Other environmental ills include over 400 insects and mite pests and more than 70 fungal pathogens that have become resistant to one or more pesticides. Pesticides have also placed stress on pollinators and other beneficial insect species (e.g. honeybees). This, along with habitat loss due to converting wildlands into agricultural fields, has affected entire ecosystems (such as the practice of converting tropical rainforests into grasslands for raising cattle).

Agriculture's link to global climate change is just beginning to be appreciated. Destruction of tropical forests and other native vegetation for agricultural production has a role in elevated levels of carbon dioxide and other greenhouse gases. Recent studies have found that soils may be large reservoirs of carbon. Additionally, the digestive processes of livestock such as cattle are responsible for significant emissions of methane (a potent greenhouse gas), thereby contributing to global climate change.

## Economic and Social Concerns

Economically, the U.S. agricultural sector includes a history of increasingly large federal expenditures. Also observed is a widening disparity among the income of farmers and the escalating concentration of **agribusiness,** industries involved with manufacture, processing, and distribution of farm products, into fewer hands. Market competition is limited, and farmers have little control over prices of their goods, and they continue to receive a smaller portion of consumer dollars spent on agricultural products.

Economic pressures have led to a tremendous loss to the number of farms, particularly small farms, and farmers during the past few decades. More than 155,000 farms were lost from 1987 to 1997. Economically, it is very difficult for potential farmers to enter the business today because of the high cost of doing business. Productive farmland also has been swallowed up by urban and suburban sprawl since 1970, over 30 million acres have been lost to development.

## Impacts on Human Health

Many potential health hazards are tied to farming practices. The general public may be affected by the sub-therapeutic use of antibiotics in animal production and the contamination of food and water by pesticides and nitrates. These are areas of active research to determine the levels of risk. The health of farm workers is also of concern, as their risk of exposure is much higher.

## Philosophical Considerations

Historically, farming played an important role in our development and identity as nations. From strongly agrarian roots, we have evolved into a culture with few farmers. In 2016, less than .75% of Canadians were identified as farmers by the Canadian Census. Can sustainable and equitable food production be established when most Canadian consumers have so little connection to the natural processes that produce their food? What intrinsically Canadian values have changed and will change with the decline of rural life and farmland ownership?

The world population continues to grow. According to recent United Nations population projections, the world population will grow to 9.7 billion in 2050 and 11.2 billion in 2100. The rate of population increase is especially high in many developing countries. In these countries, the population factor, combined with rapid industrialization, poverty, political instability, and large food imports and debt burden, make long-term food security especially urgent.

**Agricultural ecosystems** provide essential habitats for many wild plants and animal species. This is especially the case for traditional farming areas that cultivate diverse species. However, rising demand for food and other agricultural products has seen the large-scale clearing of natural habitats to make room for intensive monocultures. Recent examples include the conversion of lowland rainforests in Indonesia to oil palm plantations, and of large areas of the Amazon rainforest and Brazilian savanna to soybean and cattle farms. This ongoing habitat loss threatens entire ecosystems as well as many species. Expanding palm oil plantations in Indonesia and Malaysia, for example, pose the most significant threats to endangered megafauna, including the Asian elephant, Sumatran rhinoceros, and tigers.

**Aquaculture** is also in direct competition with natural marine and freshwater habitats for space. For example, marine fish farms often need the shelter of bays and estuaries to avoid damage from storms and currents. Also, farmed fish need good water quality, frequent water exchange, and other optimal environmental conditions. However, these locations are also very often ideal for wild fish and other marine life. Some European fish farms have been placed in the migratory routes of wild salmon, while in Asia and Latin America, mangrove forests have been cleared to make space for shrimp farms.

On top of habitat loss due to clearing, unsustainable agricultural practices see 12 million hectares of land lost each year to desertification. **Desertification** is land degradation in arid, semi-arid, and dry subhumid areas resulting from climatic variations and human activities. Desertification is potentially the most threatening ecosystem change, impacting livelihoods of the poor. Persistent reduction of ecosystem services because of desertification links land degradation in drylands to loss of human well-being.

When natural vegetation is cleared, and when farmland is plowed, the exposed topsoil is often blown away by the wind or washed away by rain. Erosion due to soy production, for example, results in Brazil losing 55 million tons of topsoil every year. This leads to reduced soil fertility and degraded land. Other significant crops that cause soil erosion include coffee, cassava, cotton, corn, palm oil, rice, sorghum, tea, tobacco, and wheat. Water resources are also impacted by modern agriculture. Globally, the agricultural sector consumes about 70 percent of the planet's accessible freshwater and many big food producing countries like the US, China, India, Pakistan, Australia, and Spain have reached, or are close to reaching, their renewable water resource limits.
The leading causes of wasteful and unsustainable water use are:

- leaky irrigation systems
- wasteful field application methods
- The cultivation of thirsty crops is not suited to the environment.

Unsustainable water use can harm the environment by changing the water table and depleting groundwater supplies. Studies have also found that excessive irrigation can increase soil salinity and wash pollutants and sediment into rivers – causing damage to freshwater ecosystems and species as well as those further downstream, including coral reefs and coastal fish breeding grounds.

Soil carried off in rain or irrigation water can lead to sedimentation of rivers, lakes and coastal areas. The problem is exacerbated if there is no vegetation left along the banks of rivers and other water courses to hold the soil. Sedimentation causes severe damage to freshwater and marine habitats, as well as the local communities that depend on these habitats. For example, people living in Xingu Indigenous Park in Brazil report declines in fish numbers. This trend is attributed to changes in the courses of waterways resulting from farming-related erosion and the silt deposition this causes. In Central America, plantation soil run-off ends up in the sea, where it affects the Meso-American Reef.

It is not just the eroded soil that is damaging: pesticides and fertilizers carried in rainwater, and irrigation runoff can pollute waterways and harm wildlife. The use of pesticides, fertilizers, and other agrochemicals has increased enormously since the 1950s. For example, the amount of pesticide sprayed on fields has increased 26-fold over the past 50 years. These chemicals do not just stay in the fields they are applied to. Some application methods, such as pesticide spraying by airplane, lead to pollution of adjacent land, rivers or wetlands. Pesticides often do not just kill the target pest. Beneficial insects in and around the fields can be poisoned or killed, as can other animals eating poisoned insects. Pesticides can also kill soil microorganisms. Also, some pesticides are suspected of disrupting the hormone messaging systems of wildlife and people, and many can remain in the environment for generations. Unlike pesticides, fertilizers are not directly toxic. However, their presence in freshwater and marine areas alters the nutrient system, and in consequence the species composition of specific ecosystems. Their most dramatic effect is eutrophication, resulting in an explosive growth of algae due to excess nutrients. This depletes the water of dissolved oxygen, which in turn can kill fish and other aquatic life.

Food production is one of the primary causes of biodiversity loss through habitat degradation, overexploitation of species such as overfishing, pollution, and soil loss. Even though its environmental impacts are immense, the current food system is expected to expand rapidly to keep up with projected increases in population, wealth, and animal-protein consumption.

## Sustainable Agriculture Movement

A growing movement has emerged during the past two decades to question the role of the agricultural establishment in promoting practices that contribute to these problems. Advocates argue that not only does sustainable agriculture address many environmental and social concerns, but it offers innovative and economically viable opportunities for growers, laborers, consumers, policymakers and many others in the entire food system. The "food system" extends far beyond the farm and involves the interaction of individuals and institutions with contrasting and often competing goals including farmers, researchers, input suppliers, farmworkers, unions, farm advisors, processors, retailers, consumers, and policymakers. Relationships among these actors shift over time as new technologies spawn economic, social, and political changes.

Regarding food and agricultural policies, new federal, state, and local government policies are needed to simultaneously promote environmental health, economic profitability, and social and economic equity. For example, commodity and price support programs could be restructured to allow farmers to realize the full benefits of the productivity gains made possible through alternative practices. Tax and credit policies could be modified to encourage a diverse and decentralized system of family farms rather than corporate concentration and absentee ownership. Government and land-grant university research policies could be modified to emphasize the development of sustainable alternatives. Marketing orders and cosmetic standards could be amended to encourage reduced pesticide use.

Conversion of agricultural land to urban uses is a particular concern, as rapid growth and escalating land values threaten farming on prime soils. At the same time, the proximity of newly developed residential areas to farms is increasing the public demand for environmentally safe farming practices. Comprehensive new policies to protect prime soils and regulate development are needed, particularly in California's Central Valley. By helping farmers to adopt practices that reduce chemical use and conserve scarce resources, sustainable agriculture research and education can play a crucial role in building public support for agricultural land preservation. Educating land use planners and decision-makers about sustainable agriculture is an urgent priority.

Rural communities are often among the poorest locations in the nation. The reasons for the decline are complex, but changes in farm structure have played a significant role. Sustainable agriculture presents an opportunity to rethink the importance of family farms and rural communities. Economic development policies are needed that encourage more diversified agricultural production on family farms as a foundation for healthy economies in rural communities. In combination with other strategies, sustainable agriculture practices and policies can help foster community institutions that meet employment, educational, health, cultural and spiritual needs. Consumers can play a critical role in creating a sustainable food system. Through their purchases, they send strong messages to producers, retailers, and others in the system about what they think is essential. Food cost and nutritional quality have always influenced consumer choices. The challenge now is to find strategies that broaden consumer perspectives, so that environmental quality, resource use, and social equity issues are also considered in shopping decisions.

## Pests and Pesticides

**Pests** are organisms that occur where they are not wanted or that cause damage to crop or humans or other animals. Thus, the term "pest" is a highly subjective term. A **pesticide** is a term for any substance intended for preventing, destroying, repelling, or mitigating any pest. Though often misunderstood to refer only to insecticides, the term pesticide also applies to herbicides, fungicides, and various other substances used to control pests. Most pesticides create some risk of harm, pesticides can cause harm to humans, animals, and/or the environment because they are designed to kill or otherwise adversely affect living things. At the same time, pesticides are useful to human society because they can kill potential disease-causing organisms and control insects, weeds, worms, and fungi. The cotton boll weevil is considered a major pest because of the damage it does to cotton plants.

**Figure 8.2** Cotton boll weevil (credit: Jimmy Smith,  CC BY-NC-ND 4.0)

## Pest Control is a Common Tool

The management of pests is an essential part of agriculture, public health, and maintenance of power lines and roads. Chemical pest management has helped to reduce losses in agriculture and to limit human exposure to disease vectors, such as mosquitoes, saving many lives. Chemical pesticides can be effective, fast acting, adaptable to all crops and situations. When first applied, pesticides can result in impressive production gains of crops. However, despite these initial gains, excessive use of pesticides can be ecologically unsound, leading to the destruction of natural enemies, the increase of pesticide resistance, and outbreaks of secondary pests.

These consequences have often resulted in higher production costs as well as environmental and human health costs, side-effects which have been unevenly distributed. Even though the lion's share of chemical pesticides is applied in developed countries, 99 percent of all pesticide poisoning cases occur in developing countries where regulatory, health and education systems are weakest. Many farmers in developing countries overuse pesticides and do not take proper safety precautions because they do not understand the risks and fear smaller harvests. Some countries seldom have strong regulatory systems for dangerous chemicals. Prolonged exposure to pesticides has been associated with several chronic and acute health effects like non-Hodgkin's lymphoma, leukemia, as well as cardiopulmonary disorders, neurological and hematological symptoms, and skin diseases.

## Pesticide Effect on Human Health; a Case of Potato Production in Ecuador

The International Potato Center (CIP) conducted an interdisciplinary and inter-institutional research intervention project dealing with pesticide impacts on agricultural production, human health, and the environment in Carchi, Ecuador. They use tremendous amounts of pesticides for the control of the Andean potato weevil and the late blight fungus.

The study found that the health problems caused by pesticides are severe and are affecting a high percentage of the rural population. Despite the existence of technology and policy solutions, government policies continue to promote the use of pesticides. The study conclusions concurred with those by the pesticide industry, "that any company that could not ensure the safe use of highly toxic pesticides should remove them from the market and that it is almost impossible to achieve safe use of highly toxic pesticides among small farmers in developing countries."

## Persistent organic pollutants (POPs)

**Persistent organic pollutants** (POPs) are a group of organic chemicals, such as DDT, that have been widely used as pesticides or industrial chemicals and pose risks to human health and ecosystems. POPs have been produced and released into the environment by human activity. They have the following three characteristics:

**Persistent**: POPs are chemicals that last a long time in the environment. Some may resist breakdown for years and even decades while others could potentially break down into other toxic substances.

**Bioaccumulative substances**: Bioaccumulative substances are chemicals that tend to build up in the tissues of living organisms over time. POPs can accumulate in animals and humans, usually in fatty tissues and largely from the food they consume. As these compounds move up the food chain, they concentrate on levels that could be thousands of times higher than acceptable limits.

**Toxic**: POPs can cause a wide range of health effects in humans, wildlife, and fish. They have been linked to effects on the nervous system, reproductive and developmental problems, suppression of the immune system, cancer, and endocrine disruption. The deliberate production and use of most POPs has been banned around the world, with some exceptions made for human health considerations (e.g., DDT for malaria control) and/or in very specific cases where alternative chemicals have not been identified. However, the unintended production and/or the current use of some POPs continue to be an issue of global concern. Even though most POPs have not been manufactured or used for decades, they continue to be present in the environment and thus potentially harmful. The same properties that originally made them so effective, particularly their stability, make them difficult to eradicate from the environment.

## Persistent Organic Pollutants (POPs) and Health

The relationship between exposure to environmental contaminants such as POPs and human health is complex. There is mounting evidence that these persistent, bioaccumulative and toxic chemicals (PBTs) cause long-term harm to human health and the environment. Drawing a direct link, however, between exposure to these chemicals and health effects is complicated, particularly since humans are exposed daily to many different environmental contaminants through the air they breathe, the water they drink, and the food they eat. Numerous studies link POPs with several adverse effects in humans. These include effects on the nervous system, problems related to reproduction and development, cancer, and genetic impacts. Moreover, there is mounting public concern over the environmental contaminants that mimic hormones in the human body (**endocrine disruptors**).

As with humans, animals are exposed to POPs in the environment through air, water and food. POPs can remain in sediments for years, where bottom-dwelling creatures consume them and who are then eaten by larger fish. Because tissue concentrations can increase or biomagnify at each level of the food chain, top predators (like largemouth bass or walleye) may have a million times greater concentrations of POPs than the water itself. The animals most exposed to PBT contaminants are those higher up the food web such as marine mammals including whales, seals, polar bears, and birds of prey in addition to fish species such as tuna, swordfish and bass (figure 8.3). Once POPs are released into the environment, they may be transported within a specific region and across international boundaries transferring among air, water, and land.

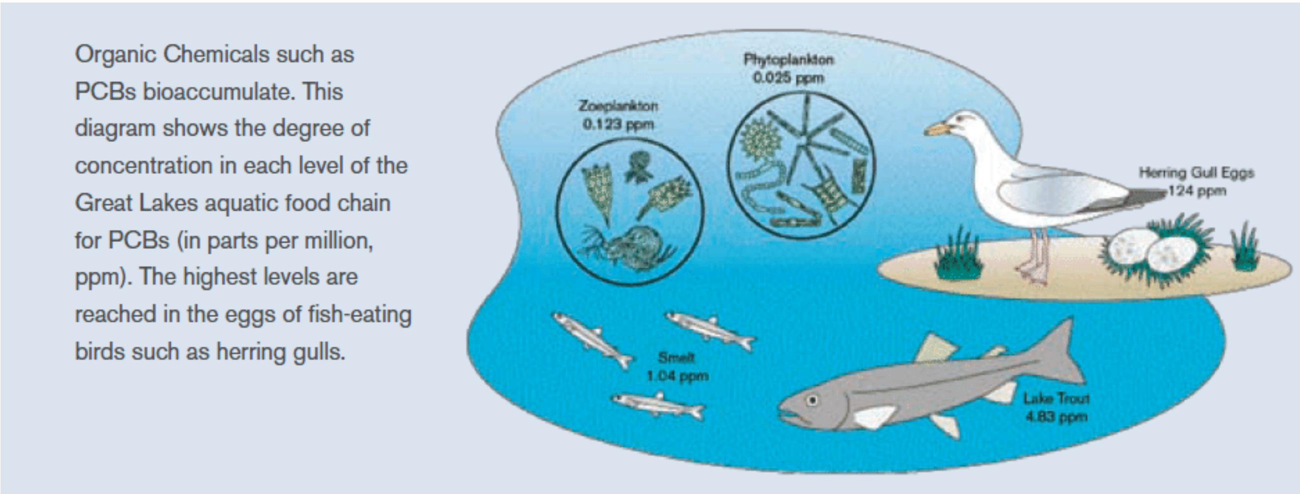


**Figure 8.3** Bioaccumulation and biomagnification. (Credit: U.S. EPA. Great Lakes.)

## Grasshopper Effect involving Persistent Organic Pollutants (POPs)

While generally banned or restricted, POPs make their way into and throughout the environment daily through a cycle of long-range air transport and deposition called the "**grasshopper effect.**" The "grasshopper" processes, illustrated in Figure 8.4, begin with the release of POPs into the environment. When POPs enter the atmosphere, they can be carried with wind currents, sometimes for long distances.

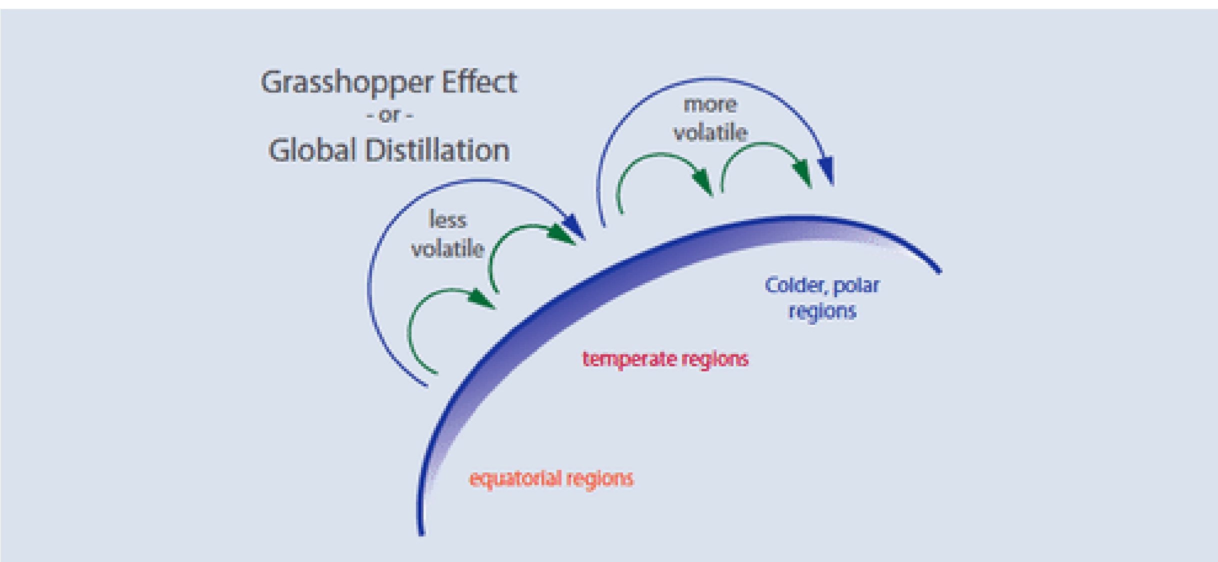


**Figure 8.4** How POPs move throughout the environment. Source: Environment Canada. (credit: The Science and Environment Bulletin. May/June 1998.)

Through atmospheric processes, they are deposited onto land or into water ecosystems where they accumulate and potentially cause damage. From these ecosystems, they evaporate, again entering the atmosphere, typically traveling from warmer temperatures toward cooler regions. They condense out of the atmosphere whenever the temperature drops, eventually reaching highest concentrations in circumpolar countries. Through these processes, POPs can move thousands of kilometers from their original source of release in a cycle that may last decades.

## Integrated Pest Management

**Integrated Pest Management** (IPM) refers to a mix of farmer-driven, ecologically based pest control practices that seek to reduce reliance on synthetic chemical pesticides. IPM is a Combination of Common-Sense Practices. It involves (a) managing pests (keeping them below economically damaging levels) rather than seeking to eradicate them; (b) relying, to the extent possible, on non-chemical measures to keep pest populations low; and (c) selecting and applying pesticides, when they have to be used, in a way that minimizes adverse effects on beneficial organisms, humans, and the environment. It is commonly understood that applying an IPM approach does not necessarily mean eliminating pesticide use, although this is often the case because pesticides are often over-used for a variety of reasons.

The IPM approach regards pesticides as mainly short-term corrective measures when more ecologically based control measures are not working adequately (sometimes referred to as using pesticides as the "last resort"). In those cases when pesticides are used, they should be selected and applied in such a manner as to minimize the amount of disruption that they cause to the environment, such as using products that are non-persistent and applying them in the most targeted way possible.

## Biological Control

**Biological control** (biocontrol) is the use of one biological species to reduce populations of a different species. There has been a substantial increase in commercialization of biocontrol products, such as beneficial insects, cultivated predators and natural or non-toxic pest control products. Biocontrol is being mainstreamed to major agricultural commodities, such as cotton, corn and most commonly vegetable crops. Biocontrol is also slowly emerging in vector control in public health and in areas that for a long time mainly focused on chemical vector control in mosquito/malaria, and black fly/onchocerciasis, control programs. Successful and commercialized examples of biocontrol include ladybugs to depress aphid populations, parasitic wasps to reduce moth populations, use of the bacterium *Bacillus thuringenensis* to kill mosquito and moth larvae, and introduction of fungi, such as Trichoderma, to suppress fungal-caused plant diseases, leaf beetle (*Galerucella calmariensis*) to suppress purple loosestrife, a noxious weed. In all these cases, the idea is not to destroy the pathogen or pest, but rather to reduce the damage below economically significant values.

**Figure 8.5** Leaf beetle damage on plant leaves. (credit: Jimmy Smith).

Young larvae of the leaf-beetle feed in and on the developing buds of plants, often destroying them. This may stunt plant growth and delay or prevent flowering. Adults and older larvae feed on leaves and cause severe defoliation. Leaf-beetles can be used to as a biocontrol for invasive plants such as purple loosestrife.

## Intercropping Promotes Plant Interactions

**Intercropping** means growing two or more crops in close proximity to each other during part or all their life cycles to promote soil improvement, biodiversity, and pest management. Incorporating intercropping principles into an agricultural operation increases diversity and interaction between plants, arthropods, mammals, birds and microorganisms resulting in a more stable crop-ecosystem and a more efficient use of space, water, sunlight, and nutrients (Figure 8.6). This collaborative type of crop management mimics nature and is subject to fewer pest outbreaks, improved nutrient cycling and crop nutrient uptake, and increased water infiltration and moisture retention. Soil quality, water quality and wildlife habitat all benefit.

**Figure 8.6** Intercropping (Credit: Stock Photo Libraries/Alamy).
Intercropping alyssum (the flowering plants shown center left) with organic romaine lettuce for aphid control.

## Organic Farming Practices Reduce Unnecessary Input Use

In modern agricultural practices, heavy machinery is used to prepare the seedbed for planting, to control weeds, and to harvest the crops. The use of heavy equipment has many advantages in saving time and labor but can cause compaction of soil and disruption of the natural soil organisms. The problem with soil compaction is that increased soil density limits root penetration depth and may inhibit proper plant growth. Alternative practices generally encourage **minimal tillage** or **no tillage methods**. With proper planning, this can simultaneously limit compaction, protect soil organisms, reduce costs (if performed correctly), promote water infiltration, and help to prevent topsoil erosion (figure 8.7).

**Figure 8.7** Soybean field with crop residue in a no-till farming system, which is an example of conservation tillage (credit: USDA Natural Resources Conservation Service. (n.d.). *Crop residue management guide: Corn & soybeans*).

Farmers should consider no-till farming as the most important tool to prevent loss of soil moisture. Tillage of fields does help to break up clods that were previously compacted, so best practices may vary at sites with different soil textures and composition. Another aspect of soil tillage is that it may lead to more rapid decomposition of organic matter due to greater soil aeration. Over large areas of farmland, this has the unintended consequence of releasing more carbon and nitrous oxides (greenhouse gases) into the atmosphere, thereby contributing to global warming effects. In no-till farming, carbon can become sequestered into the soil. Thus, no-till farming may be advantageous to sustainability issues on the local scale and the global scale. No-till systems of conservation farming have proved a major success in Latin America and are being used in South Asia and Africa.

## Crop Rotation

Crop rotations are planned sequences of crops over time on the same field. Rotating crops provide productivity benefits by improving soil nutrient levels and breaking crop pest cycles. Farmers may also choose to rotate crops to reduce their production risk through diversification or to manage scarce resources, such as labor, during planting and harvesting timing. This strategy reduces the pesticide costs by naturally breaking the cycle of weeds, insects and diseases. Also, grass and legumes in rotation protect water quality by preventing excess nutrients or chemicals from entering water supplies.

## Aeroponics, Aquaponics, Hydroponics

### *Soilless Cultivation*

Soilless cultivation has become an increasingly effective method to precisely control the indoor environment. There are three soilless growing technologies now used across the industry: hydroponics, aquaponics, and aeroponics. Hydroponics grows plants suspended in water, aeroponics grows plants suspended in air, and aquaponics is a unique combination of hydroponics and fish farming in an integrated system.

### *What is Aeroponics?*

Aeroponics is a method of growing plants without soil, where roots are suspended in the air and misted with a nutrient-rich solution

### *What is Hydroponics?*

Hydroponics literally means 'water working' and is the soil-less growing of plants. In hydroponics, plants grow their roots in a soil alternative (called a growing medium) such as rockwool or hydroton.

Then a nutrient solution (in liquid form) is added to the water which is used for watering the plants. Various nutrient formulas have been designed specifically for hydroponics and have the proper ratios of nitrogen, phosphorous, and potassium (N-P-K) along with other trace elements plants need to encourage optimal plant growth. This solution is added to the water that is later absorbed by plants supplying the dissolved nutrients.

## *What is Aquaponics?*

Aquaponics are different than both hydroponics and aeroponics. It is achieved through a combination of aquaculture (raising fish) and hydroponics (the soil-less growing of plants). Adding fish into the equation creates a natural ecosystem in which fish, plants, and bacteria thrive off one another. Instead of needing a nutrient solution mixed with chemicals, the waste from fish and the living bacteria in an aquaponics system provide all of the nutrients the plants need. Likewise, the fish together with the bacteria create a cleaner, non-toxic environment for the fish to live in.

## *Advantages of Hydroponics*

Hydroponics and aeroponics have an advantage in that they are a bit quicker to start. In some cases, setting up these systems can also be simpler. When fish are left out of the equation, there are less variables to measure and monitor for water quality. Fish can die off quickly in an aquaponics system if the water quality (temp, oxygen, nitrogen levels) isn't right for them. This could be a good reason to start with hydroponics if you're new to all these growing techniques. (We recommend starting with a hydroponics kit if it's your first time so you have everything you need to get started, this link will take you to one made by Agrowponics). One more advantage for hydroponics is that an aquaponics system must be cultivated in the beginning and it takes at least a month or so to introduce fish into the water. This process involves letting a bacteria colony build in the system that can regulate the water and covert fish waste to keep it from being too toxic for the fish.

### *Advantages of Aquaponics*

Besides growing and harvesting fish for protein, one of the biggest advantages of aquaponics over other methods is that it is a necessarily natural and organic process. Hydroponics requires growing in a man-made environment and adding man-made nutrient solutions, whereas in aquaponics you are creating a natural ecosystem relying on bacteria to convert fish waste into a complete plant food. Because of the way this natural process works, aquaponics is scientifically proven to achieve better growth, lower disease rates, and less system maintenance.

## Why Do These Farming Methods Matter?

The beautiful thing about all these methods is that there are open possibilities for growing healthy, high-quality produce in a way that's both fun and efficient. Because these methods do not use soil, they can be set up and used indoors in places that have cold, harsh climates like Alaska. These water-working methods can also be used in places that have poor, sandy soil like areas in southern Florida. In urban areas, vertical farming techniques using equipment like growing towers, we save space and make growing large quantities of crops possible on rooftops and small abandoned lots.

# Chapter Nine: Water Resource, Pollution, and Conservation

## Objectives

- Describe the various sources of water.
- Describe various sources of water pollution.
- Explain water conservation and the various approaches and activities for environmental conservation

## Water Resource

The **water cycle** (or hydrologic cycle) shows the movement of water through different reservoirs, which include oceans, atmosphere, glaciers, groundwater, lakes, rivers, and biosphere. Solar energy and gravity drive the motion of water in the water cycle. Simply put, the water cycle involves water moving from oceans, rivers, and lakes to the atmosphere by evaporation, forming clouds. From clouds, it falls as precipitation (rain and snow) on both water and land. The land water can either return to the ocean by surface runoff, rivers, glaciers, and subsurface groundwater flow or return to the atmosphere by evaporation or **transpiration** (loss of water by plants to the atmosphere).

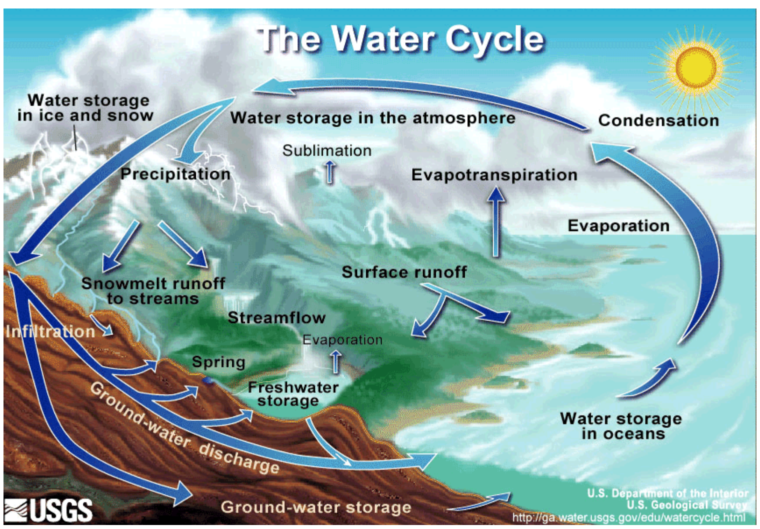


**Figure 9.1** The Water Cycle (Source: United States Geological Survey)

Arrows in Figure 9.1 depict movement of water to different reservoirs located above, at, and below Earth's surface.

An important part of the water cycle is how water varies in salinity, which is the abundance of dissolved ions in water. The saltwater in the oceans is highly saline, with about 35,000 mg of dissolved ions per liter of seawater. **Evaporation** (where water changes from liquid to gas at ambient temperatures) is a distillation process that produces nearly pure water with almost no dissolved ions. As water vaporizes, it leaves the dissolved ions in the original liquid phase. Eventually, **condensation** (where water changes from gas to liquid) forms clouds and sometimes precipitation (rain and snow). After rainwater falls onto land, it dissolves minerals in rock and soil, which increases its salinity. Most lakes, rivers, and near-surface groundwater have a relatively low salinity and are called freshwater. The next several sections discuss important parts of the water cycle relative to freshwater resources.

## Primary Fresh Water Resources: Precipitation

Precipitation levels are unevenly distributed around the globe, affecting freshwater availability (figure 9.2). More precipitation falls near the equator, whereas less precipitation tends to fall near 30 degrees north and south latitude, where the world's largest deserts are located. These rainfall and climate patterns are related to global wind circulation cells. The intense sunlight at the equator heats air, causing it to rise and cool, which decreases the ability of the air mass to hold water vapor and results in frequent rainstorms. Around 30 degrees north and south latitude, descending air conditions produce warmer air, which increases its ability to hold water vapor and results in dry conditions. Both the dry air conditions and the warm temperatures of these latitude belts favor evaporation. Global precipitation and climate patterns are also affected by the size of continents, major ocean currents, and mountains.

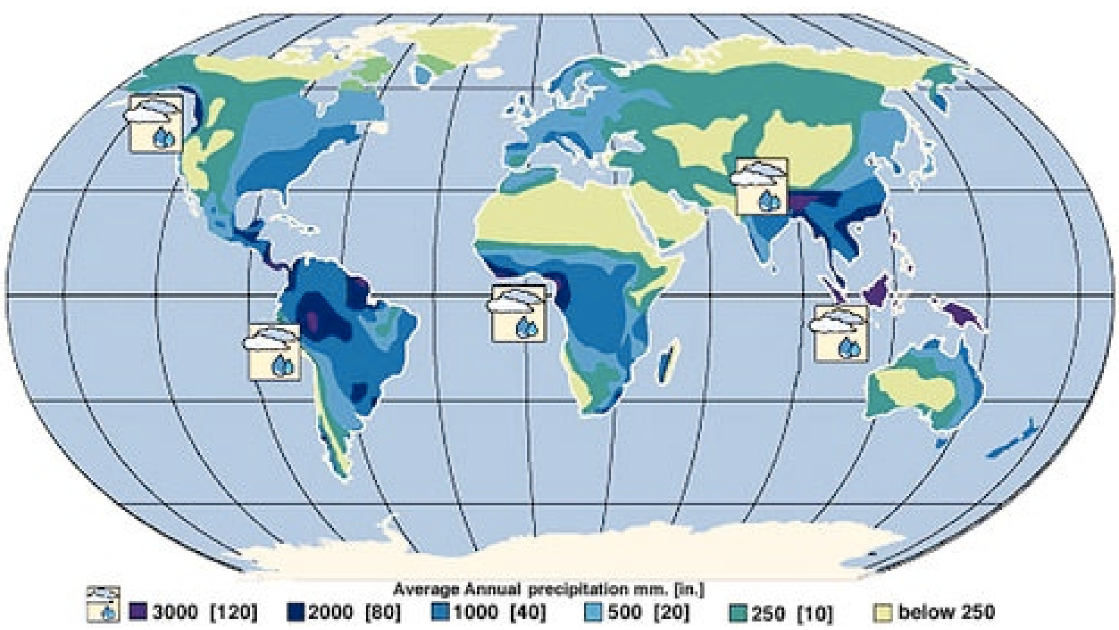


**Figure 9.2** World Rainfall Map. (credit: OpenStax College, Biology, CC BY 4.0).

The false-color map above shows the amount of rain that falls around the world. Areas of high rainfall include Central and South America, western Africa, and Southeast Asia. Since these areas receive so much rainfall, they are where most of the world's rainforests grow. Areas with very little rainfall usually turn into deserts. The desert areas include North Africa, the Middle East, western North America, and Central Asia. Source: United States Geological Survey Earth Forum, Houston Museum Natural Science

## Surface Water Resources: Rivers, Lakes, and Glaciers

Flowing water from rain and melted snow on land enters river channels by surface runoff (Figure 9.3). The relative contributions of surface runoff vs. groundwater seepage to river discharge depend on precipitation patterns, vegetation, topography, land use, and soil characteristics. Soon after a heavy rainstorm, river discharge increases due to surface runoff. The steady, normal flow of river water is mainly from groundwater that discharges into the river. Gravity pulls river water downhill toward the ocean. Along the way, the moving water of a river can erode soil particles and dissolve minerals. Groundwater also contributes a large amount of the dissolved minerals in river water. The geographic area drained by a river and its tributaries is called a **drainage basin** or **watershed**. The Mississippi River drainage basin includes approximately 40% of the U.S., a measure that includes the smaller drainage basins, such as the Ohio River and Missouri River, that help to comprise it. Rivers are an important water resource for the irrigation of cropland and drinking water for many cities around the world. Rivers that have had international disputes over water supply include the Colorado (Mexico, southwest U.S.), Nile (Egypt, Ethiopia, Sudan), Euphrates (Iraq, Syria, Turkey), Ganges (Bangladesh, India), and Jordan (Israel, Jordan, Syria).

**Figure 9.3** Surface Runoff (Source: James M. Pease at Wikimedia Commons).

Surface runoff is part of the overland flow in the water cycle. Groundwater seepage can be seen in Box Canyon in Idaho, where approximately 10 cubic meters per second of seepage emanates from its vertical headwall.

**River discharge** describes the volume of water moving through a river channel over time (Figure 9.4).

**Figure 9.4** River Discharge, Colorado River, U.S. (Source: Gonzo fan2007 at Wikimedia Commons).

Rivers are part of the overland flow in the water cycle and an important surface water resource. In addition to rivers, lakes can also be an excellent source of freshwater for human use. They usually receive water from surface runoff and groundwater discharge. They tend to be short-lived on a geological timescale because they are constantly filling in with sediment supplied by rivers. Lakes form in a variety of ways including glaciation, recent tectonic uplift (e.g., Lake Tanganyika, Africa), and volcanic eruptions (e.g., Crater Lake, Oregon). People also create artificial lakes (**reservoirs**) by damming rivers. Large climate changes can result in major changes in a lake's size. As Earth was coming out of the last Ice Age about 15,000 years ago, the climate in the western U.S. changed from cool and moist to warm and arid, which caused more than 100 large lakes to disappear. The Great Salt Lake in Utah is a remnant of a much larger lake called Lake Bonneville.

Although **glaciers** represent the largest reservoir of fresh water, they generally are not used as a water source because they are located too far from most people. Melting glaciers do provide a natural source of river water and groundwater. During the last Ice age, there was as much as 50% more water in glaciers than there is today, which caused the sea level to be about 100 m lower. Over the past century, sea levels have been rising in part due to melting glaciers. If Earth's climate continues to warm, the melting glaciers will cause an additional rise in sea level. Mountain Glacier in Argentina Glaciers are the largest reservoir of fresh water, but they are not used much as a water resource directly by society because of their distance from most people.

## Groundwater Resources

Although most people in the world use surface water, groundwater is a much larger reservoir of usable fresh water, containing more than 30 times more water than rivers and lakes combined. Groundwater is a particularly important resource in arid climates, where surface water may be scarce. In addition, groundwater is the primary water source for rural homeowners, providing 98% of that water demand in the U.S. **Groundwater** is water located in small spaces, called **pore space**, between mineral grains and fractures in subsurface earth materials (rock or sediment). Most groundwater originates from rain or snowmelt, which infiltrates the ground and moves downward until it reaches the **saturated zone** (where groundwater fills pore spaces in earth materials).

Other sources of groundwater include seepage from surface water (lakes, rivers, reservoirs, and swamps), surface water deliberately pumped into the ground, irrigation, and underground wastewater treatment systems (septic tanks). **Recharge areas** are locations where surface water infiltrates the ground rather than running into rivers or evaporating. Wetlands, for example, are excellent recharge areas.

## What is an aquifer?

An aquifer is an underground layer of permeable or "leaky" rock. The mixture of sediment and rock in these layers contains many holes of different sizes that can store a massive amount of water. A large area of sub-surface, porous rock that holds water is an aquifer. These groundwater storage systems feed water to the landscape, providing essential support to several ecosystems and many species of wildlife.

The **Ogallala Aquife**r is a prime example of an aquifer that has been used extensively to support natural and working landscapes in the region. The Ogallala Aquifer that lies beneath Nebraska is part of a larger system known as the High Plains Aquifer, which underlies about 174,000 square miles across Nebraska, Kansas, Oklahoma, and Texas, as well as parts of Wyoming, Colorado, and New Mexico. Aquifers like the Ogallala are located close to the surface and provide a source of fresh water for human needs such as drinking, bathing, irrigation, and industrial activities. Aquifers are commonly drilled, and wells are installed, to provide water for agriculture and personal use.

## Water Use in the U.S. and World

People need water, oftentimes large quantities, to produce the food, energy, and mineral resources they use. Consider, for example, these approximate water requirements for some things people in the developed world use every day: one tomato = 11.4 liters; one kilowatt-hour of electricity from a thermoelectric power plant = 79.5 liters; one loaf of bread = 568 liters; one pound of beef = 6056.6 liters; and one ton of steel = 238,480.9 liters. Human beings require only about 3.8 liters per day to survive, but a typical Canadian uses approximately 466 liters per day, which includes cooking, washing dishes and clothes, flushing the toilet, bathing, as well as commercial and industrial uses provided by public utilities. The **water demand** of an area is a function of the population and other uses of water.

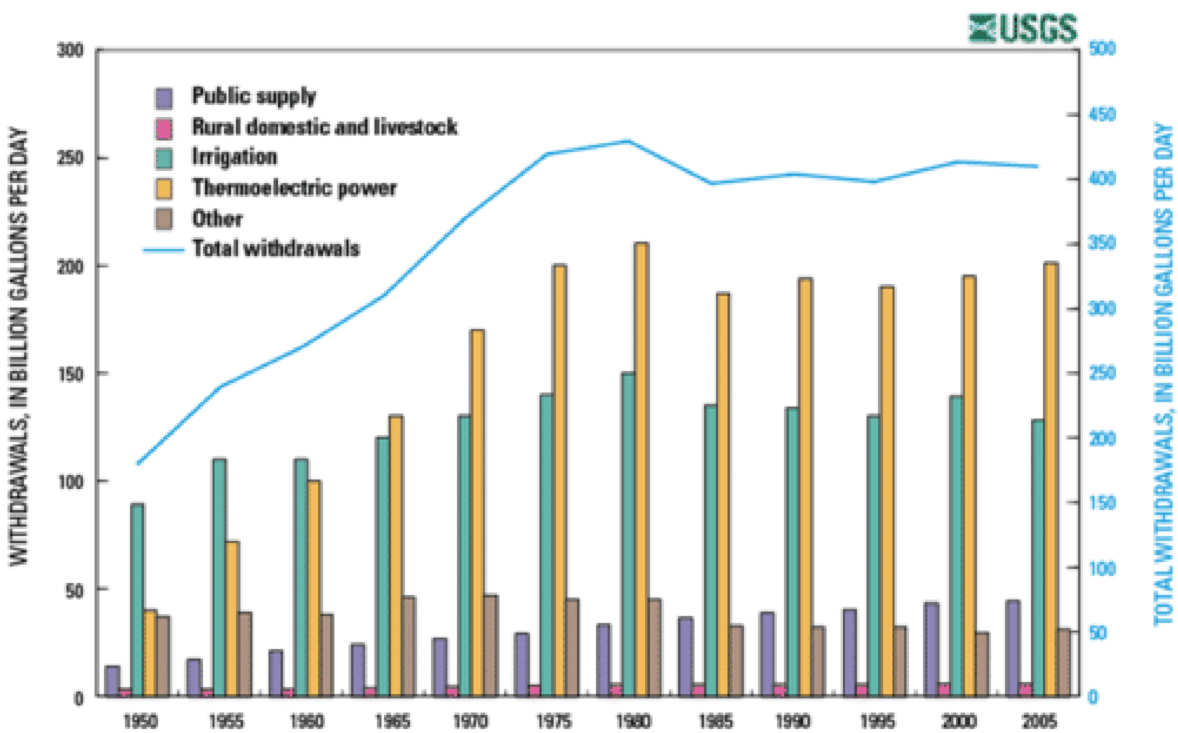


**Figure 9.5** Underground water withdrawals (Source: United States Geological Survey).

Trends in Total Water Withdrawals by Water-use Category, 1950-2005 Trends in total water withdrawals in the U.S. from 1950 to 2005 by water use category, including bars for thermoelectric power, irrigation, public water supply, and rural domestic and livestock.

The thin blue line represents total water withdrawals using vertical scale on right.

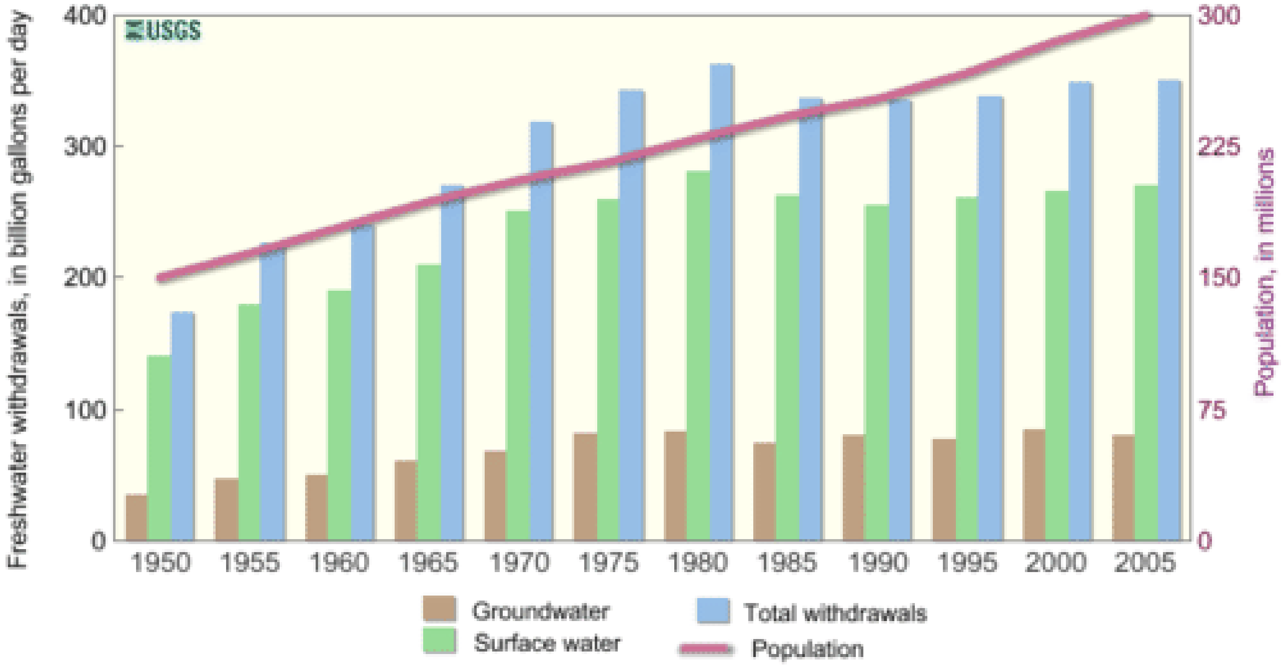


**Figure 9.6** Trends in Source of Fresh Water Withdrawals in the U.S. from 1950 to 2005. (Source: United States Geological Survey).

Trends in source of freshwater withdrawals in the U.S. from 1950 to 2005, including bars for surface water, groundwater, and total water. Red line gives U.S. population using vertical scale on right. Global total water use is steadily increasing at a rate greater than world population growth (figure 9.7). During the 20th century, the global population tripled, and water demand grew by a factor of six. The increase in global water demand beyond the rate of population growth is due to improved standard of living without an offset by water conservation. Increased production of goods and energy entails a large increase in water demand. The major global water uses are irrigation (68%), public supply (21%), and industry (11%).

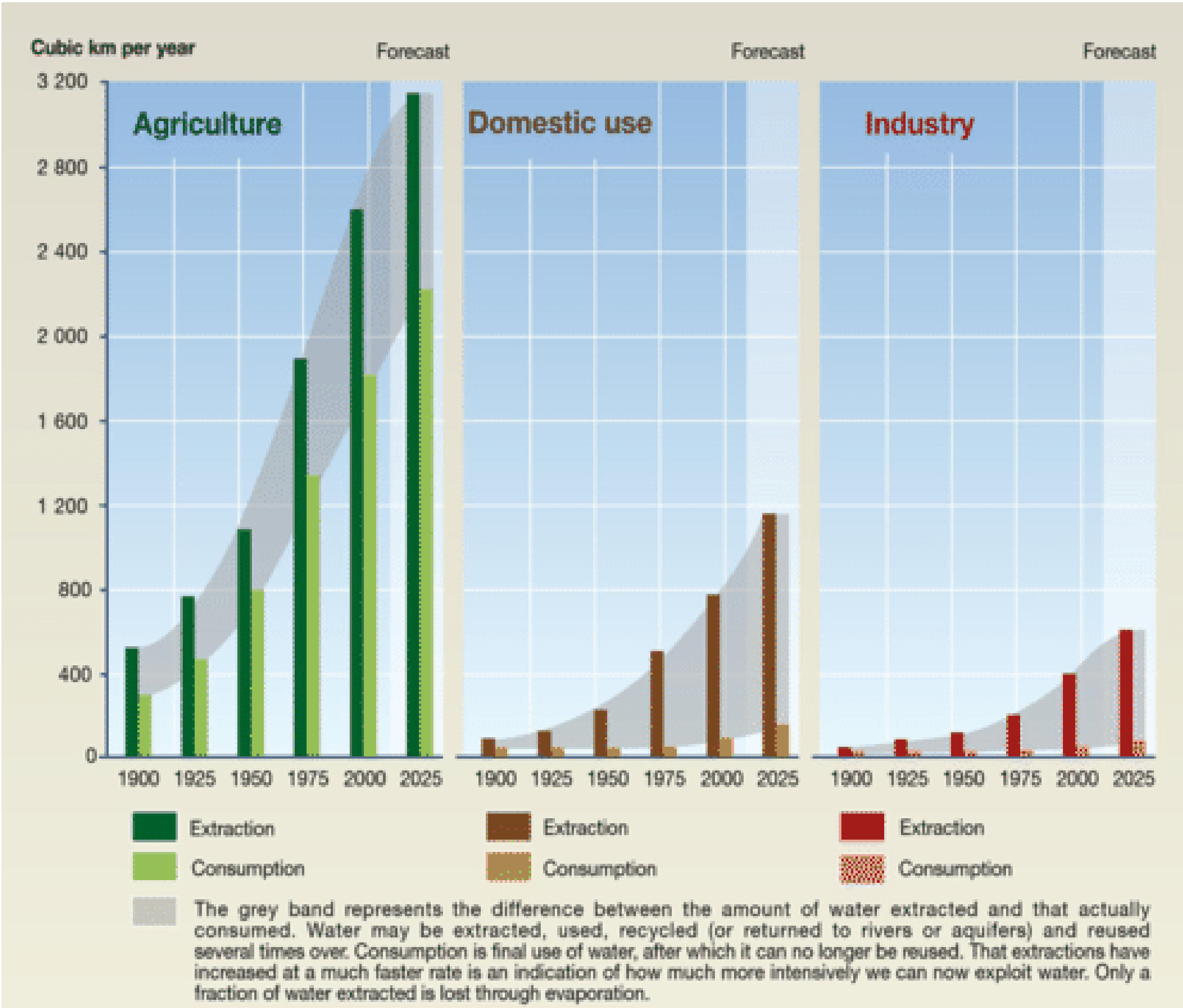


**Figure 9.7** Trends in world water use from 1900 to 2000 and projected to 2025. (credit: Igor A. Shiklomanow).

For each water major use category, including trends for agriculture, domestic use, and industry. Darker colored bar represents total water extracted for that use category and lighter colored bar represents water consumed (i.e., water that is not quickly returned to surface water or groundwater system) for that category.

## Water Supply Problems: Resource Depletion

As groundwater is pumped from water wells, there usually is a localized drop in the water table around the well called a cone of depression. When there are many wells that have been pumping water for a long time, the regional water table can drop significantly. This is called **groundwater mining**, which can force the drilling of deeper, more expensive wells that commonly encounter more saline groundwater. Rivers, lakes, and artificial lakes (reservoirs) can also be depleted due to overuse. Some large rivers, such as the Colorado in the U.S. and Yellow in China, run dry in some years. The case history of the Aral Sea discussed later in this chapter involves depletion of a lake. Finally, glaciers are being depleted due to accelerated melting associated with global warming over the past century.

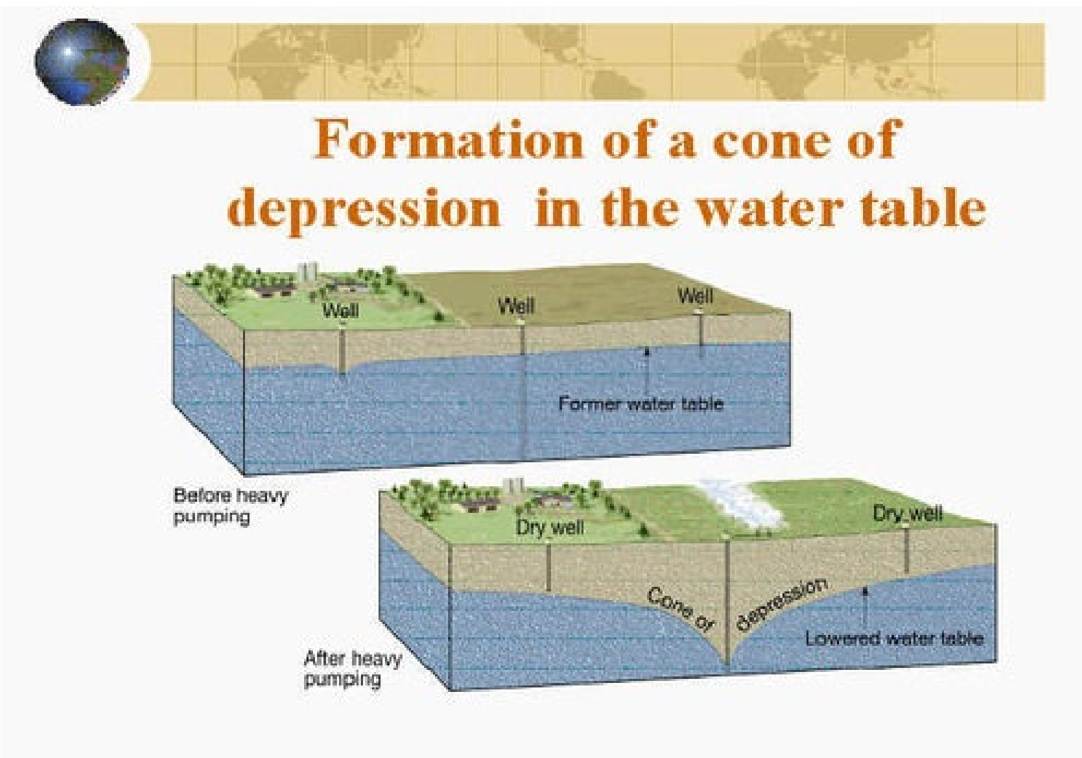


**Figure 9.8** Formation of a Cone of Depression around a Pumping Water Well. (Source: Fayette County Groundwater Conservation District, TX).

Another water resource problem associated with groundwater mining is saltwater intrusion, where the over pumping of freshwater aquifers near ocean coastlines causes saltwater to enter freshwater zones. The drop of the water table around a **cone of depression** in an unconfined aquifer can change the direction of regional groundwater flow, which could send pollution nearby toward the pumping well instead of away from it. Finally, problems of **subsidence** (gradual sinking of the land surface over a large area) and **sinkholes** (rapid sinking of the land surface over a small area) can develop due to a drop in the water table.

## Water Supply Crisis

The **water crisis** refers to a global situation where people in many areas lack access to sufficient water, clean water, or both. This section describes the global situation involving water shortages, also called **water stress**. In general, water stress is greatest in areas with very low precipitation (major deserts), large population density (e.g., India), or both. Future global warming could worsen the water crisis by shifting precipitation patterns away from humid areas and by melting mountain glaciers that recharge rivers downstream. Melting glaciers will also contribute to rising sea levels, which will worsen saltwater intrusion in aquifers near ocean coastlines.

**Water stress** is defined as having a high percentage of water withdrawal compared to total available water in the area.

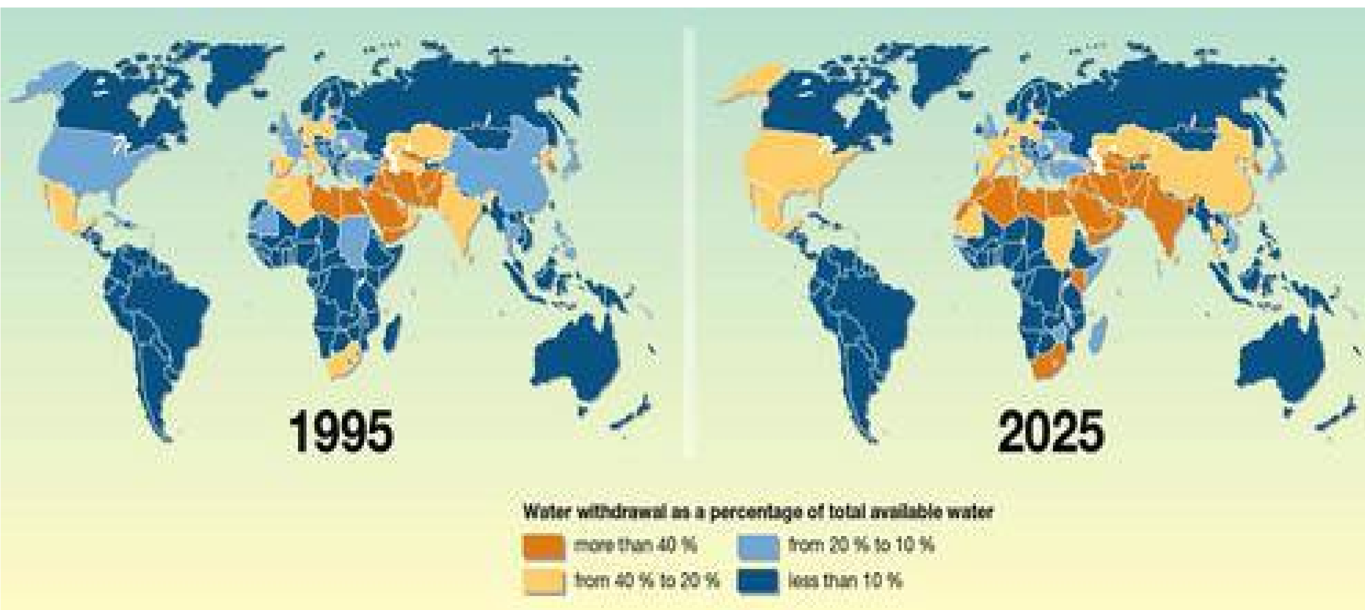


**Figure 9.9** Countries facing water stress in 1995 and projected in 2025 (Credit: Philippe Rekacewicz). According to a 2006 report by the United Nations Development Program, 700 million people (11% of the world's population) lived with water stress. Most of them live in the Middle East and North Africa. By 2025, the report projects that more than 3 billion people (about 40% of the world's population) will

live in water-stressed areas, with the large increase coming mainly from China and India. The water crisis will also impact food production and our ability to feed the ever-growing population. We can expect future global tension and even conflict associated with water shortages and pollution. Historic and future areas of water conflict include the Middle East (Euphrates and Tigris River conflict among Turkey, Syria, and Iraq; Jordan River conflict among Israel, Lebanon, Jordan, and the Palestinian territories), Africa (Nile River conflict among Egypt, Ethiopia, and Sudan), Central Asia (Aral Sea conflict among Kazakhstan, Uzbekistan, Turkmenistan, Tajikistan, and Kyrgyzstan), and south Asia (Ganges River conflict between India and Pakistan).

## Sustainable Solutions to the Water Supply Crisis?

The current and future water crisis described above requires multiple approaches to extending our fresh water supply and moving towards sustainability. Some of the long-standing traditional approaches include dams and aqueducts.

**Reservoirs** that form behind dams in rivers can collect water during wet times and store it for use during dry spells. They also can be used for urban water supplies. Other benefits of dams and reservoirs are hydroelectricity, flood control, and recreation. Some of the drawbacks are evaporative loss of water in arid climates, downstream river channel erosion, and impact on the ecosystem including a change from a river to lake habitat and interference with migration and spawning of fish.

**Aqueducts** can move water from where it is plentiful to where it is needed. Aqueducts can be controversial and politically difficult especially if the water transfer distances are large. One drawback is the water diversion can cause drought in the area from where the water is drawn. For example, Owens Lake and Mono Lake in central California began to disappear after their river flow was diverted to the Los Angeles aqueduct. Owens Lake remains almost completely dry, but Mono Lake has recovered more significantly due to legal intervention.

**Figure 9.10** Hoover Dam, Nevada, U.S. Hoover Dam, Nevada, U.S. (credit: U.S. Bureau of Reclamation. (n.d.). *Hoover Dam on the Colorado River*).

The **Hoover Dam** is a major concrete arch-gravity dam located on the border between Nevada and Arizona in the United States. It is a well-known landmark and hydroelectric power facility. Behind the dam is Lake Mead, the largest reservoir in U.S. White band in figure 8.10 reflects the lowered water levels in the reservoir due to drought conditions from 2000 – 2010.

**Figure 9.11** The California Aqueduct California Aqueduct in southern California, U.S. (credit: California Department of Water Resources. (n.d.). *California Aqueduct*).

One method that can increase the amount of fresh water on Earth is **desalination**, which involves removing dissolved salt from seawater or saline groundwater. There are several ways to desalinate seawater including boiling, filtration, and electrodialysis. All these procedures are moderately to very expensive and require considerable energy input, making the water produced much more expensive than fresh water from conventional sources. In addition, the process creates highly saline wastewater, which must be disposed of and creates significant environmental impact. Desalination is most common in the Middle East, where energy from oil is abundant but water is scarce.

**Conservation** means using less water and using it more efficiently. Around the home, conservation can involve both engineered features, such as high-efficiency clothes washers and low-flow showers and toilets, as well as behavioral decisions, such as growing native vegetation that requires little irrigation in desert climates, turning off the water while you brush your teeth, and fixing leaky faucets.

**Rainwater harvesting** involves catching and storing rainwater for reuse before it reaches the ground. Another important technique is **efficient irrigation,** which is extremely important because irrigation accounts for a much larger water demand than public water supply. Water conservation strategies in agriculture include growing crops in areas where the natural rainfall can support them, more efficient irrigation systems such as drip systems that minimize losses due to evaporation, no-till farming that reduces evaporative losses by covering the soil and reusing treated wastewater from sewage treatment plants. Recycled wastewater has also been used to recharge aquifers.

## Water Pollution

**Water pollution** is the contamination of water by an excess amount of a substance that can cause harm to human beings and/or the ecosystem. The level of water pollution depends on the abundance of the pollutant, the ecological impact of the pollutant, and the use of the water. Pollutants are derived from biological, chemical, or physical processes.

Any natural water contains dissolved chemicals, some of which are important human nutrients while others can be harmful to human health. The concentration of a water pollutant is commonly given in very small units such as parts per million (**ppm**) or even parts per billion (**ppb**). An arsenic concentration of 1 ppm means 1 part of arsenic per million parts of water. This is equivalent to one drop of arsenic in 50 liters of water. To give you a different perspective on appreciating small concentration units, converting 1 ppm to length units is 1 cm (0.4 in) in 10 km (6 miles) and converting 1 ppm to time units is 30 seconds in a year. **Total dissolved solids** (TDS) represent the total amount of dissolved material in water. Average TDS values for rainwater, river water, and seawater are about 4 ppm, 120 ppm, and 35,000 ppm, respectively.

Although natural processes such as volcanic eruptions or evaporation sometimes can cause water pollution, most pollution is derived from human, land-based activities (figure 9.12).

**Figure 9.12** Water Pollution. Obvious water pollution in the form of floating debris; invisible water pollutants sometimes can be much more harmful than visible ones. (Source: PBS NewsHour. (2015, February 12). In world's poorest slums, landfills and polluted rivers become a child's playground [Photo essay]. Reuters. https://www.pbs.org/newshour/world/in-worlds-poorest-slums-landfills-and-polluted-rivers-become-a-childs-playground)

Water pollutants can move through different water reservoirs, as the water carrying them progresses through stages of the water cycle (figure 9.13). **Water residence time** (the average time that a water molecule spends in a water reservoir) is very important to pollution problems because it affects pollution potential. Water in rivers has a relatively short residence time, so pollution usually is there only briefly. Of course, pollution in rivers may simply move to another reservoir, such as the ocean, where it can cause further problems. Groundwater is typically characterized by slow flow and longer residence time, which can make groundwater pollution particularly problematic. Finally, **pollution residence time** can be much greater than the **water residence time** because a pollutant may be held up for a long time within the ecosystem or absorbed onto sediment.

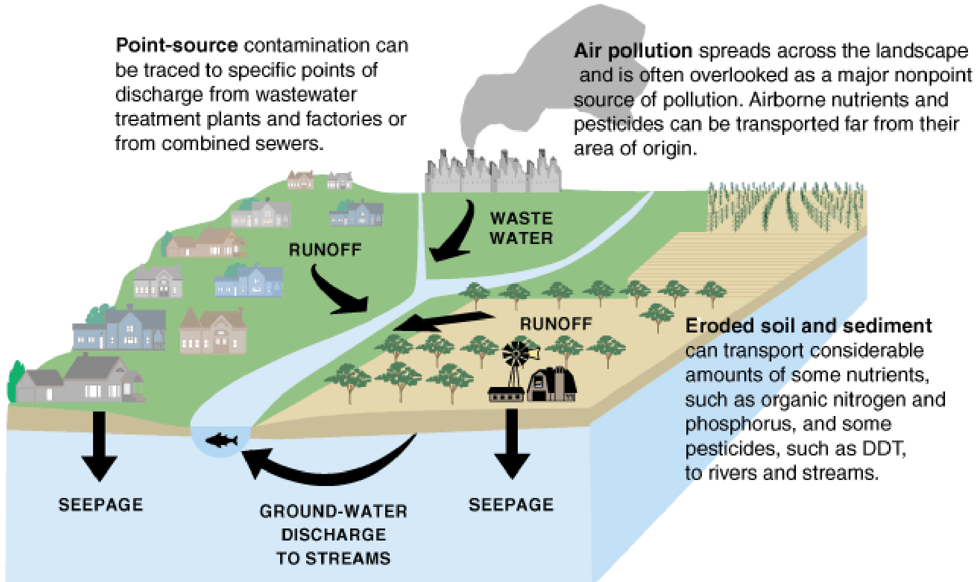


**Figure 9.13** Sources of Water Contamination. (Credit: U.S. Geological Survey).

Figure 9.13 shows sources of water pollutants and movement of pollutants into different water reservoirs of the water cycle. Pollutants enter water supplies from **point sources**, which are readily identifiable and relatively small locations, or **nonpoint sources**, which are large and more diffuse areas. Point sources of pollution include animal factory farms (figure 9.14) that raise a large number and high density of livestock such as cows, pigs, and chickens. Also included are pipes from factories or sewage treatment plants. Combined sewer systems that have a single set of underground pipes to collect both sewage and storm water runoff from streets for wastewater treatment can be major point sources of pollutants as well. During heavy rain, storm water runoff may exceed sewer capacity, causing it to back up and spill untreated sewage directly into surface waters.

**Figure 9.14** Hogs' feedlot, an example of a concentrated feeding operations (credit: Jeff Vanuga, USDA NRCS Photo Gallery).

Large animal farms are often referred to as **concentrated feeding operations (CFOs).** These farms are considered potential sources of pollution because untreated animal waste may enter nearby waterbodies as untreated sewage.

**Nonpoint sources of pollution** include agricultural fields, cities, and abandoned mines. Rainfall runs over the land and through the ground, picking up pollutants such as herbicides, pesticides, and fertilizers from agricultural fields and lawns; oil, antifreeze, animal waste, and road salt from urban areas; and acid and toxic elements from abandoned mines. Then, this pollution is carried into surface water bodies and groundwater. Nonpoint source pollution, which is the leading cause of water pollution in North America, is usually much more difficult and expensive to control than point source pollution because of its low concentration, multiple sources, and much greater volume of water.

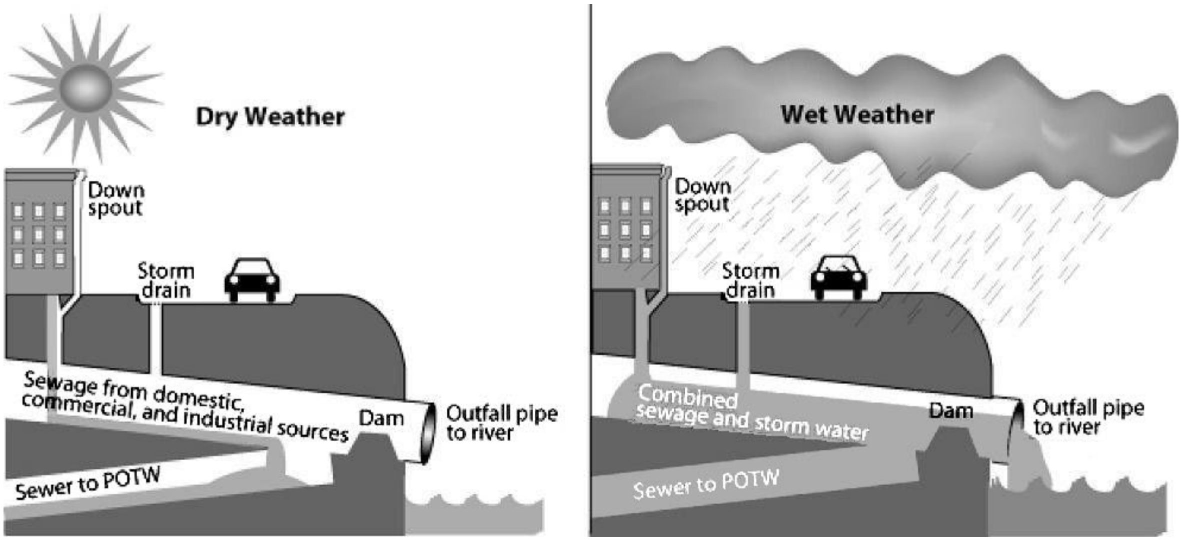


**Figure 9.15** Combined sewer system. (credit: U.S. Environmental Protection Agency at Wikimedia Commons).

A combined sewer system is a possible major "**point source water pollution"** during heavy rain due to overflow of untreated sewage. During dry weather (and small storms), all flows are handled by the publicly owned treatment works (POTW). During large storms, the relief structure allows some of the combined stormwater and sewage to be discharged untreated to an adjacent water body.

## Types of Water Pollutants

**Oxygen-demanding waste** is an extremely important pollutant to ecosystems. Most surface water in contact with the atmosphere has a small amount of dissolved oxygen, which is needed by aquatic organisms for cellular respiration. Bacteria decompose dead organic matter and remove dissolved oxygen ($O_2$) according to the following reaction:

$$\text{organic matter} + O_2 \rightarrow CO_2 + H_2O$$

Too much decaying organic matter in water is a pollutant because it removes oxygen from water, which can kill fish, shellfish, and aquatic insects. The amount of oxygen used by **aerobic** (in the presence of oxygen) bacterial decomposition of organic matter is called **biochemical oxygen demand** (BOD). The major source of dead organic matter in many natural waters is sewage; grass and leaves are smaller sources. An unpolluted water body with respect to BOD is a turbulent river that flows through a natural forest. Turbulence continually brings water in contact with the atmosphere where the $O_2$ content is restored. The dissolved oxygen content in such a river, ranges from **10 to 14 ppm $O_2$**, BOD is low, and clean-water fish such as trout can survive. A polluted water body with respect to oxygen is a stagnant deep lake in an urban setting with a combined sewer system. This system favors a high input of dead organic carbon from sewage overflows and limited chance for water circulation and contact with the atmosphere. In such a lake, the dissolved $O_2$ content is ≤5 ppm $O_2$, BOD is high, and low $O_2$-tolerant fish, such as carp and catfish dominate. Excessive plant nutrients, particularly nitrogen (N) and phosphorous (P), are pollutants closely related to oxygen-demanding waste. Aquatic plants require about 15 nutrients for growth, most of which are plentiful in water. N and P are called limiting nutrients, however, because they usually are present in water at low concentrations and therefore restrict the total amount of plant growth.

This explains why N and P are major ingredients in most fertilizers. High concentrations of N and P from human sources (mostly agricultural and urban runoff including fertilizer, sewage, and phosphorus-based detergent) can cause cultural eutrophication, which leads to the rapid growth of aquatic producers, particularly algae. Thick mats of floating algae or rooted plants lead to a form of water pollution that damages the ecosystem by clogging fish gills and blocking sunlight. A small percentage of algal species produce toxins that can kill animals, including humans. Exponential growths of these algae are called **harmful algal blooms**. When the prolific algal layer dies, it becomes oxygen-demanding waste, which can create very low $O_2$ in water (< 2 ppm $O_2$), a condition called hypoxia, which becomes a **dead zone** because it causes death to organisms that are unable to leave that environment.

An estimated 50% of lakes in North America, Europe, and Asia are negatively impacted by cultural eutrophication. In addition, the size and number of marine hypoxic zones have grown dramatically over the past 50 years including a very large dead zone located offshore Louisiana in the Gulf of Mexico. Cultural eutrophication and hypoxia are difficult to combat, because they are caused primarily by nonpoint source pollution, which is difficult to regulate, and N and P, which are difficult to remove from wastewater.

**Pathogens** are disease-causing microorganisms, e.g., viruses, bacteria, parasitic worms, and protozoa, which cause a variety of intestinal diseases such as dysentery, typhoid fever, and cholera. Pathogens are the major cause of the water pollution crisis discussed at the beginning of this section. Unfortunately, nearly a billion people around the world are exposed to waterborne pathogen pollution daily and around

1.5 million children mainly in underdeveloped countries die every year of waterborne diseases from pathogens. Pathogens enter water primarily from human and animal fecal waste due to inadequate sewage treatment. In many underdeveloped countries, sewage is discharged into local waters either untreated or after only rudimentary treatment. In developed countries untreated sewage discharge can occur from overflows of combined sewer systems, poorly managed livestock factory farms, and leaky or broken sewage collection systems. Water with pathogens can be remediated by adding chlorine or ozone layer, by boiling, or by treating the sewage in the first place.

**Oil spills** are another kind of organic pollution. Oil spills can result from supertanker accidents such as the Exxon Valdez in 1989, which spilled 10 million gallons of oil into the rich ecosystem of coastal Alaska and killed massive numbers of animals. The largest marine oil spill was the Deepwater Horizon disaster, which began with a natural gas explosion (Figure 6) at an oil well 65 km offshore of Louisiana and flowed for 3 months in 2010, releasing an estimated 200 million gallons of oil. The worst oil spill ever occurred during the Persian Gulf war of 1991, when Iraq deliberately dumped approximately 200 million gallons of oil in offshore Kuwait and set more than 700 oil well fires that released enormous clouds of smoke and acid rain for over nine months.

During an oil spill on water, oil floats to the surface because it is less dense than water, and the lightest hydrocarbons evaporate, decreasing the size of the spill but polluting the air. Then, bacteria begin to decompose the remaining oil, in a process that can take many years. After several months only about 15% of the original volume may remain, but it is in thick asphalt lumps, a form that is particularly harmful to birds, fish, and shellfish. Cleanup operations can include skimmer ships that vacuum oil from the water surface (effective only for small spills), controlled burning (works only in early stages before the light, ignitable part evaporates but also pollutes the air), **dispersants** (detergents that break up oil to accelerate its decomposition, but some dispersants may be toxic to the ecosystem),
and bioremediation (adding microorganisms that specialize in quickly decomposing oil, but this can disrupt the natural ecosystem).

**Figure 9.16** Deepwater Horizon Explosion (Credit: United States Coast Guard via Wikimedia Commons).

In figure 9.16, boats are seen fighting the fire from an explosion at the deepwater horizon drilling rig in Gulf of Mexico offshore Louisiana on April 20, 2010. Toxic chemicals involve many different kinds and sources, primarily from industry and mining. General kinds of toxic chemicals include hazardous chemicals and persistent organic pollutants that include DDT (pesticide), dioxin (herbicide by-product), and polychlorinated biphenyls (**PCBs**), which were used as a liquid insulator in electric transformers).

Persistent organic pollutants (**POPs**) are long-lived in the environment, biomagnify through the food chain, and can be toxic. Another category of toxic chemicals includes radioactive materials such as cesium, iodine, uranium, and radon gas, which can result in long-term exposure to radioactivity if it gets into the body. The final group of toxic chemicals are heavy metals such as lead, mercury, arsenic, cadmium, and chromium, which can accumulate through the food chain. Heavy metals are commonly produced by industry and at metallic ore mines. Arsenic and mercury are discussed in more detail below. Arsenic (As) has been famous as an agent of death for many centuries. Only recently have scientists recognized that health problems can be caused by drinking small arsenic concentrations in water over a long time. It enters the water supply naturally from weathering of arsenic-rich minerals and from human activities such as coal burning and smelting of metallic ore.

The worst case of arsenic poisoning occurred in the densely populated impoverished country of Bangladesh, which had experienced hundreds of thousands of deaths from diarrhea and cholera each year from drinking surface water contaminated with pathogens due to improper sewage treatment. In the 1970s the United Nations provided aid for millions of shallow water wells, which resulted in a dramatic drop in pathogenic diseases. Unfortunately, many of the wells produced water naturally rich in arsenic. Tragically, there are an estimated 77 million people (about half of the population) who inadvertently may have been exposed to toxic levels of arsenic in Bangladesh as a result. The World Health Organization has called it the largest mass poisoning of a population in history.

Mercury (Hg) is used in a variety of electrical products, such as dry cell batteries, fluorescent light bulbs, and switches, as well as in the manufacture of paint, paper, vinyl chloride, and fungicides. Mercury acts on the central nervous system and can cause loss of sight, feeling, and hearing as well as nervousness, shakiness, and death. Like arsenic, mercury enters the water supply naturally from the weathering of mercury-rich minerals and from human activities such as coal burning and metal processing. A famous mercury poisoning case in Minamata, Japan involved methylmercury-rich industrial discharge that caused high Hg levels in fish. People in the local fishing villages ate fish up to three times per day for over 30 years, which resulted in over 2,000 deaths. During that time the company responsible and national government did little to mitigate, help alleviate or even acknowledge the problem.

**Hard water** contains abundant calcium and magnesium, which reduces its ability to develop soapsuds and enhances scale (calcium and magnesium carbonate minerals) formation on hot water equipment. Water softeners remove calcium and magnesium, which allows the water to lather easily and resist scale formation. Hard water develops naturally from the dissolution of calcium and magnesium carbonate minerals in soil; it is a health threat to humans.

**Groundwater pollution** can occur from underground sources and all of the pollution sources that contaminate surface waters. Common sources of groundwater pollution are leaking underground storage tanks for fuel, septic tanks, agricultural activity, landfills, and fossil fuel extraction. Common groundwater pollutants include nitrate, pesticides, volatile organic compounds, and petroleum products. Another troublesome feature of groundwater pollution is that small amounts of certain pollutants, e.g., petroleum products and organic solvents, can contaminate large areas. In Denver, Colorado 80 liters of several organic solvents contaminated 4.5 trillion liters of groundwater and produced a 5 km long contaminant plume. A major threat to groundwater quality is from underground fuel storage tanks. Fuel tanks commonly are stored underground at gas stations to reduce explosion hazards. Before 1988 in the U.S. these storage tanks could be made of metal, which can corrode, leak, and quickly contaminate local groundwater. Now, leak detectors are required, and the metal storage tanks are supposed to be protected from corrosion or replaced with fiberglass tanks. Currently there are around 600,000 underground fuel storage tanks in the U.S. and over 30% still do not comply with EPA regulations regarding either release prevention or leak detection.

## Water Treatment

Resolution of the global water pollution crisis requires multiple approaches to improve the quality of our fresh water and move towards sustainability. The deadliest form of water pollution, pathogenic microorganisms that cause waterborne diseases, kills almost 2 million people in underdeveloped countries every year. The best strategy for addressing this problem is proper sewage (wastewater) treatment. Untreated sewage is not only a major cause of pathogenic diseases, but also a major source of other pollutants, including oxygen-demanding waste, nutrients (N and P, particularly), and toxic heavy metals. Wastewater treatment is done at a sewage treatment plant in urban areas and through a septic tank system in rural areas.

The main purpose of **sewage (wastewater) treatment** is to remove organic matter (oxygen-demanding waste) and kill bacteria. Special methods also can be used to remove nutrients and other pollutants. The numerous steps at a conventional sewage treatment plant include **pretreatment** (screening and removal of sand and gravel), **primary treatment** (settling or floatation to remove organic solids, fat, and grease), **secondary treatment** (aerobic bacterial decomposition of organic solids), **tertiary treatment** (bacterial decomposition of nutrients and filtration), **disinfection** (treatment with chlorine, ozone, ultraviolet light, or bleach to kill most microbes), and either **discharge** to surface waters (usually a local river) or reuse in irrigation, habitat preservation, and artificial groundwater recharge.

The concentrated organic solid produced during primary and secondary treatment is called **sludge**, which is treated in a variety of ways including landfill disposal, incineration, use as fertilizer, and anaerobic bacterial decomposition, which is done in the absence of oxygen. Anaerobic decomposition of sludge produces methane gas, which can be used as an energy source. To reduce water pollution problems, separate sewer systems (where street runoff goes to rivers and only wastewater goes to a wastewater treatment plant) are much better than combined sewer systems, which can overflow and release untreated sewage into surface waters during heavy rain. Some cities such as Chicago in Illinois have constructed large underground caverns and use abandoned rock quarries to hold storm sewer overflow. After the rain stops, the stored water goes to the sewage treatment plant for processing.

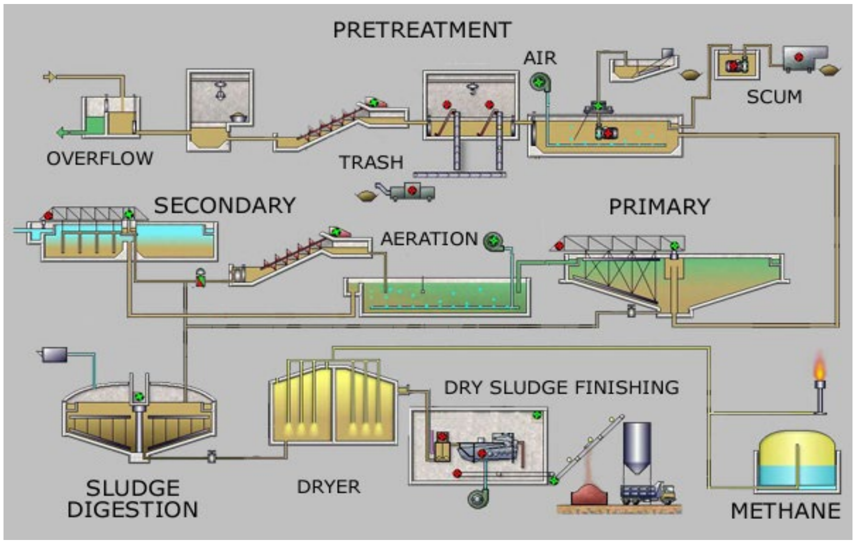


**Figure 9.17** Steps at a Sewage Treatment Plant. (Source: U.S. Environmental Protection Agency. (2004). Typical wastewater treatment plant flow diagram (Primer for municipal wastewater treatment systems (EPA 832-R-04-001).

The numerous processing steps at a conventional sewage treatment plant include pretreatment (screening and removal of sand and gravel), primary treatment (settling or floatation to remove organic solids, fat, and grease), secondary treatment (aerobic bacterial decomposition of organic solids), tertiary treatment (bacterial decomposition of nutrients and filtration), disinfection (treatment with chlorine, ozone, ultraviolet light, or bleach), and either discharge to surface waters (usually a local river) or reuse for some other purpose, such as irrigation, habitat preservation, and artificial groundwater recharge.

A **septic tank system** is an individual sewage treatment system for homes in typically rural settings. The basic components of a septic tank system (figure 9.18) include a sewer line from the house, a septic tank (a large container where sludge settles to the bottom and microorganisms decompose the organic solids anaerobically), and the drain field (network of perforated pipes where the clarified water seeps into the soil and is further purified by bacteria). Water pollution problems occur if the septic tank malfunctions, which usually occurs when a system is established in the wrong type of soil or maintained poorly.

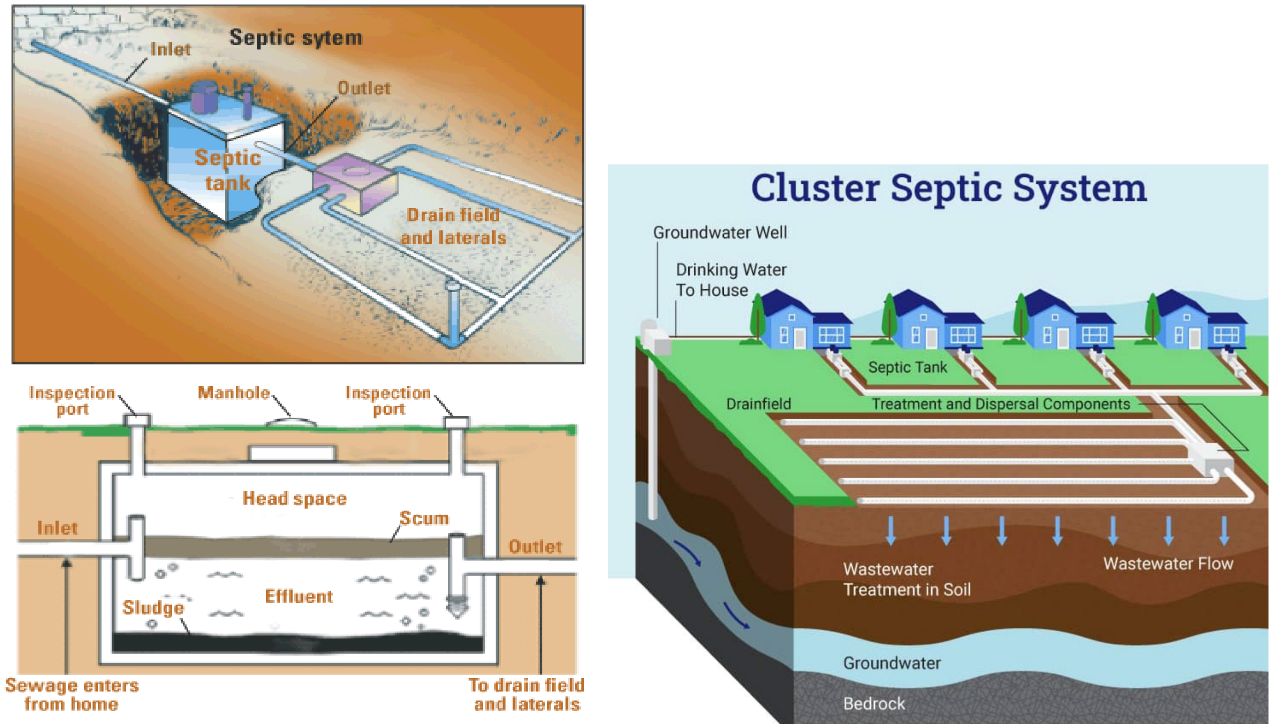


**Figure 9.18** Septic tank system for Sewage Treatment (Source: United States Geological Survey).

For many developing countries, financial aid is necessary to build adequate sewage treatment facilities. The World Health Organization estimates an estimated cost savings of between $3 and $34 for every $1 invested in clean water delivery and sanitation. The cost savings are from health care savings, gains in work and school productivity, and prevented deaths. Simple and inexpensive techniques for treating water at home include chlorination, filters, and solar disinfection. Another alternative is to use constructed wetlands technology (marshes built to treat contaminated water), which is simpler and cheaper than a conventional sewage treatment plant.

Bottled water is not a sustainable solution to the water crisis. Bottled water is not necessarily any safer than the U.S. public water supply, it costs on average about 700 times more than U.S. tap water, and every year it uses approximately 200 billion plastic and glass bottles that have a relatively low rate of recycling. Compared to tap water, it uses much more energy, mainly in bottle manufacturing and long-distance transportation. Additionally, some bottled water has been found to contain microplastics, an inadvertent pollution of the bottled water itself during the bottling process. If you don’t like the taste of your tap water, then please use a water filter instead of bottled water!

## Clean Water Act

During the early 1900s, rapid industrialization in North America resulted in widespread water pollution due to free discharge of waste into surface waters. The Cuyahoga River in northeast Ohio caught fire numerous times, including a famous fire in 1969 that caught national attention. In 1972 the US Congress passed one of the most important environmental laws in North American history, the Federal Water Pollution Control Act, which is more commonly called the **Clean Water Act**.

The purpose of the Clean Water Act and later amendments is to maintain and restore water quality, or in simple terms to make water swimmable and fishable. It became illegal to dump pollution into surface water unless there was formal permission. U.S. water quality improved significantly as a result. More progress is needed because currently the EPA considers over 40,000 U.S. water bodies as impaired, most commonly due to pathogens, metals, plant nutrients, and oxygen depletion. Another concern is protecting groundwater quality, which is not yet addressed sufficiently by US federal law.
In Canada, a patchwork of legislation is responsible for protecting water, including the Canadian Environmental Protection Act, as well as provincial water legislation like the Water Sustainability Act (WSA) in British Columbia.

## Eutrophication

Eutrophication is the process in which a water body becomes overly enriched with nutrients, leading to plentiful growth of simple plant life. Eutrophication may be defined as the inorganic nutrient enrichment of natural waters, leading to an increased production of algae and macrophytes. The excessive growth (or bloom) of algae and plankton in a water body are indicators of this process. Eutrophication is considered to be a serious environmental concern since it often results in the deterioration of water quality and the depletion of dissolved oxygen in water bodies. Eutrophic waters can eventually become “dead zones” that are incapable of supporting life.

Many lakes are naturally eutrophic, and, in some cases, there is progressive eutrophication as the lake matures. The term Eutrophication is more widely known in relation to human activities where the artificial introduction of plant nutrients has led to community changes and a deterioration of water quality in many freshwater systems. This aspect has become increasingly important with increases in human population and more extensive development of agriculture and eutrophication now ranks with other major anthropogenic effects such as deforestation, global warming depletion of the ozone layer and large scale environmental disturbance in relation to its potentially harmful effect on natural ecosystems (Figure 9.19).

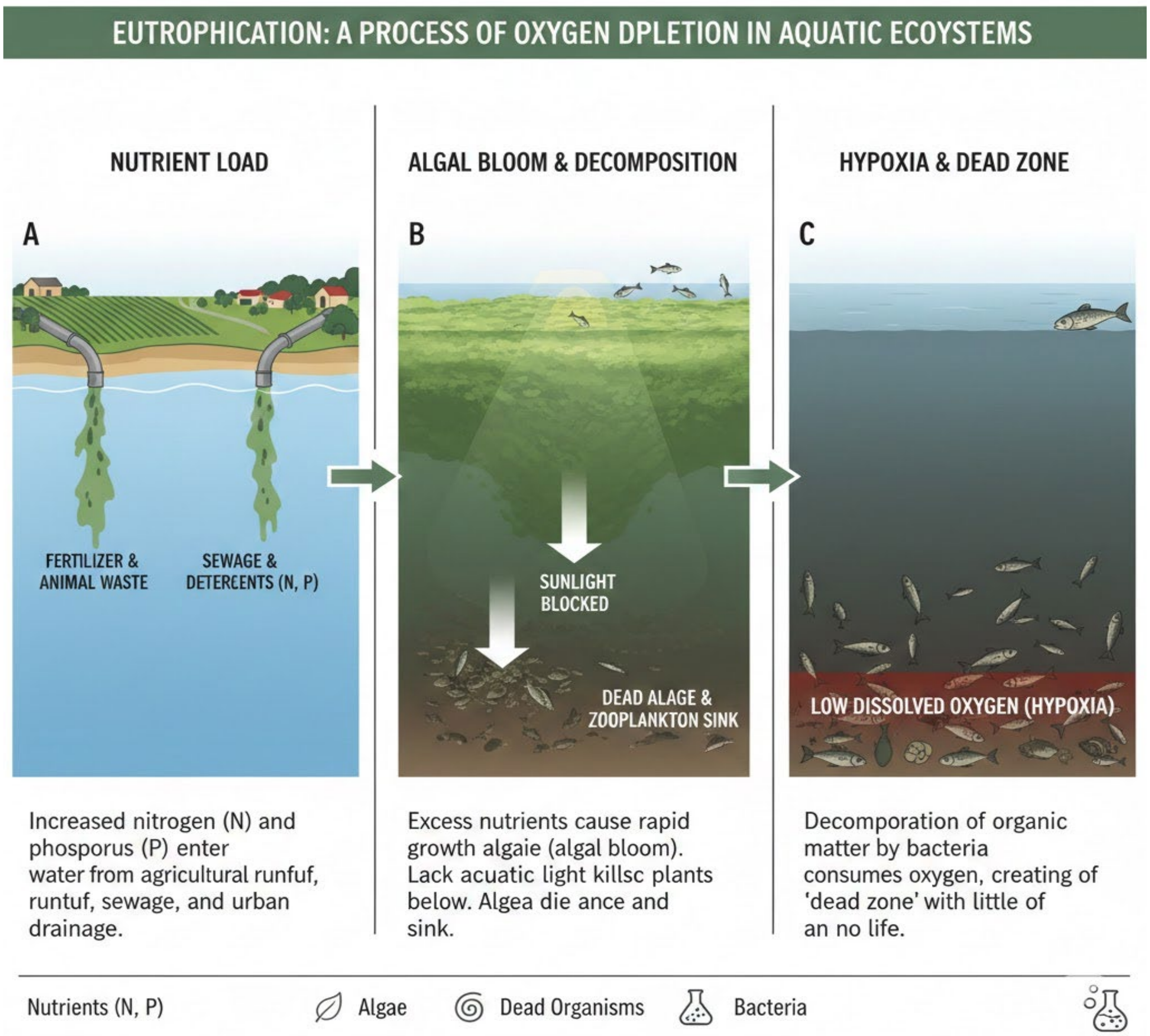


**Figure 9.19** Algal Bloom Eutrophication Leading to Hypoxia (Source: Gemini AI)

The figure 9:19 illustrates nutrient pollution and water-quality issues as a result of eutrophication. It provides a sneak peak of a pond surface completely covered by a dense, bright green layer of algal bloom (most likely cyanobacteria, commonly known as blue-green algae). This type of harmful algal bloom (HAB) is typically caused by eutrophication from excess nutrients, especially nitrogen and phosphorus from agricultural runoff, sewage, or industrial discharges. Aquatic ecosystems are home to several plant and animal life forms – both simple and complex. The process of eutrophication destroys the balance in these ecosystems by favoring the growth of simple plant life. This greatly decreases the biodiversity of the ecosystem by killing off several desirable species.

## Causes of Eutrophication

The availability of nutrients such as nitrogen and phosphorus limits the growth of plant life in an ecosystem. When water bodies are overly enriched with these nutrients, the growth of algae, plankton, and other simple plant life is favored over the growth of more complex plant life.

## How do Water Bodies Become Overly Enriched?

Phosphorus is considered one of the primary limiting factors for the growth of plant life in freshwater ecosystems. Several sources also claim that the availability of nitrogen is an important limiting factor for the growth of algae.

Phosphates tend to stick to the soil and are transported along with it. Therefore, soil erosion is a major contributor to the phosphorus enrichment of water bodies. Some other phosphorus-rich sources that enrich water bodies with nutrients include:

- Fertilizers
- Untreated sewage
- Detergents containing phosphorus
- Industrial discharge of waste.

Among these sources, the primary contributors to eutrophication include agriculture and industrial waste.

## What Happens to the Huge Biomass of Algae in Eutrophic Waters?

The excessive growth of algae in eutrophic waters is accompanied by the generation of a large biomass of dead algae. These dead algae sink to the bottom of the water body where they are broken down by bacteria, which consume oxygen in the process.

The diagram in Figure 9.20 illustrates the process of eutrophication, including key elements such as water bodies, nutrient inputs (e.g., from fertilizers), runoff, algae blooms, and resulting environmental impacts like oxygen depletion and fish suffocation. This visual aid shows the consequences of nutrient enrichment in aquatic ecosystems. The overconsumption of oxygen leads to hypoxic conditions (conditions in which the availability of oxygen is low) in the water. The hypoxic conditions at the lower levels of the water body lead to the suffocation and eventual death of larger life forms such as fish.

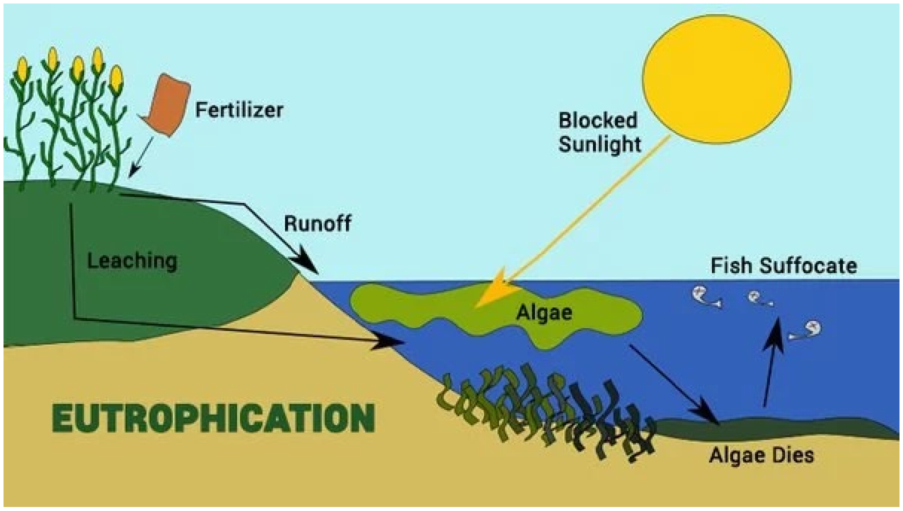


**Figure 9.20**. Process of Eutrophication. This is an illustration of the process and consequences of eutrophication in lakes and ponds. It shows how excess nitrogen and phosphorus from runoff trigger explosive phytoplankton and algal growth, leading to algal blooms, light blockage, seagrass die-off, oxygen depletion, decay, and ultimately the loss of aquatic life, habitat, and oxygen production. (Credit: Grok AI).

## Classification of Eutrophication

The process of eutrophication can be categorized into two types based on its root cause. Both these types are explained in this subsection.

## Anthropogenic Eutrophication

Anthropogenic eutrophication is caused by human activity, Agricultural farms, golf courses, lawns, etc. are supplied with nutrients by humans in the form of fertilizers. These fertilizers are washed away by rain and eventually find their way into water bodies such as lakes and rivers. When introduced to an aqueous ecosystem, the fertilizers supply plentiful nutrients to algae and plankton, resulting in the eutrophication of the water body.

Overpopulation places a huge demand on industrial and agricultural expansion, which in turn leads to deforestation. When this occurs, the soil erodes more easily, resulting in increased soil deposits in water bodies. If the soil is rich in phosphorus, it can lead to eutrophication and severely damage the ecosystem in and around the water body. When sewage pipes and industrial waste are directed to water bodies, the nutrients present in the sewage and other wastes increase the rate at which eutrophication occurs.

## Natural Eutrophication

Natural eutrophication refers to the excessive enrichment of water bodies via natural events. For example, the nutrients from the land can be washed away in a flood and deposited into a lake or a river. These water bodies become overly enriched with nutrients, enabling the excessive growth of algae and other simple plant life. The process of natural eutrophication is much slower when compared to the process of anthropogenic eutrophication. This process is also somewhat dependent on the temperature of the environment. It may even be complemented by the temperature changes brought on by global warming.

## Effects of Eutrophication

Primarily, the adverse effects of eutrophication on aquatic bodies include a decrease in biodiversity, increase in toxicity of the water body, and change in species dominance. Some other important effects of this process are listed below.

- **Phytoplanktons** grow much faster in such situations. These phytoplankton species are toxic and are inedible.
- Gelatinous zooplankton blooms fast in these waters.
- Increased biomass of epiphytic and benthic algae can be observed in eutrophic waters.
- Significant changes arise in the species composition of macrophytes and biomass.
- The water loses its transparency and develops a bad smell and color. The treatment of this water becomes difficult.
- Depletion of dissolved oxygen in the water body.
- Frequent fish kill incidents occur and many desirable fish species are removed from the water body.
- The populations of shellfish and harvestable fish are lowered.
- The aesthetic value of the water body diminishes significantly.

**Figure 9.21** Eutrophication of Water Bodies. (credit: Energy Education).

Figure 9.21 provides an image detailing the change in the quality of water in eutrophic water bodies. **Eutrophic water bodies** are highly productive, having been enriched with excess nutrients, especially phosphorus and nitrogen, which leads to rapid algal growth, often called blooms

## Ecological Effects of Eutrophication

Natural standing waters range from ultra oligotrophic to eutrophic with progressive increase in productivity and related parameters. In addition to such general changes, eutrophication also affects the vertical structure of lakes with further implications for the biology of freshwater organisms. The transition from eutrophic to hypertrophic status is usually the result of human activities and ultimately affects the whole ecological balance of the freshwater system.

## Decrease in Biodiversity

When an aquatic ecosystem is enriched with nutrients by either natural or artificial means, the conditions become extremely beneficial to primary producers. Commonly, algae and other similar species utilize these nutrients and a huge increase in their population (algal bloom) is observed. These algal blooms hinder the flow of sunlight to the bottom of the aquatic body and also cause wide swings in the dissolved oxygen levels in the water.

When the dissolved oxygen in the water reduces to an amount below the hypoxic level, many marine animals suffocate and die. This reduces the effective biodiversity of the water body.

### Increase in Water Toxicity

A few algae are toxic to many plants and animals. When these algae bloom in eutrophic waters, they release neurotoxins and hepatotoxins. These toxins can also move up the food chain. via shellfish or other marine animals and lead to the death of many animals.

Toxic algal blooms can also be harmful to humans and are the root cause of many cases of neurotoxic, paralytic, and diarrhetic shellfish poisoning.

## Invasion of New Species

A limiting nutrient corresponding to a water body can be made abundant by the eutrophication process, leading to a shift in the species composition of the aquatic body and the ecosystem surrounding it. If a nitrogen deficient water body is suddenly enriched with it, many other competitive species might relocate to the water body and outcompete the original inhabitants of the ecosystem. One such example of a new species invading eutrophic conditions is the common carp, which has adapted to these conditions.

# Chapter Ten: Hazardous Solid Waste

## Learning Outcomes

After studying this chapter, you should be able to:

- Understand the environmental concerns with the growing quantities and improper management of waste being generated
- Recognize various environmental regulations governing the management of solid and hazardous waste
- Recognize integrated waste management strategies

## Managing Growing Waste Generation

An enormous quantity of waste is generated and disposed of annually. Alarmingly, this quantity continues to increase on an annual basis. Industries generate and dispose over 7.6 billion tons of industrial solid waste each year, and it is estimated that over 40 million tons of this waste is hazardous. Nuclear waste as well as medical wastes are also increasing in quantity every year. Developed nations generate more waste than developing nations due to higher rates of consumption. Not surprisingly, the United States generates more waste per capita than any other country. High waste per capita rates are also very common throughout Europe and developed nations in Asia and Oceania. In the United States, about 243 million tons (243 trillion kg) of MSW is generated per year, which is equal to about 4.3 pounds (1.95 kg) of waste per person per day. Nearly 34 percent of MSW is recovered and recycled or composted, approximately 12 percent is burned at a combustion facility, and the remaining 54 percent is disposed of in landfills. Waste stream percentages also vary widely by region. As an example, San Francisco, California captures and recycles nearly 75 percent of its waste material, whereas Houston, Texas recycles less than three percent.

With respect to waste mitigation options, landfilling is quickly evolving into a less desirable or feasible option. Landfill capacity in the United States has been declining primarily due to (a) older existing landfills that are increasingly reaching their authorized capacity, (b) the promulgation of stricter environmental regulations has made the permitting and siting of new landfills increasingly difficult, (c) public opposition (e.g. "Not In My Backyard" or NIMBYism) delays or, in many cases, prevents the approval of new landfills or expansion of existing facilities.

## Effects of Improper Waste Disposal and Unauthorized Releases

Prior to the passage of environmental regulations, waste was disposed improperly without due consideration of potential effects on public health and the environment. This practice has led to numerous contaminated sites where soil and groundwater have been contaminated and pose risk to the public safety. Of more than 36,000 environmentally impacted candidate sites, there are more than 1,400 sites listed under the Superfund program National Priority List (NPL) which requires immediate cleanup resulting from acute, imminent threats to environmental and human health. The USEPA identified about 2,500 additional contaminated sites that eventually require remediation. The United States Department of Defense maintains 19,000 sites, many of which have been extensively contaminated from a variety of uses and disposal practices. Further, approximately 400,000 underground storage tanks have been confirmed or are suspected to be leaking, contaminating underlying soils and groundwater. Over $10 billion (more than $25 billion in current dollars) were specifically allocated by CERCLA and subsequent amendments to mitigate impacted sites. However, USEPA has estimated that the value of environmental remediation exceeds $100 billion. Alarmingly, if past expenditures on NPL sites are extrapolated across remaining and proposed NPL sites, this total may be significantly higher – well into the trillions of dollars.

It is estimated that more than 4,700 facilities in the United States currently treat, store or dispose of hazardous wastes. Of these, about 3,700 facilities that house approximately 64,000 solid waste management units (SWMUs) may require corrective action. Accidental spillage of hazardous wastes and nuclear materials due to anthropogenic operations or natural disasters has also caused enormous environmental damage as evidenced by the events such as the facility failure in Chernobyl, Ukraine (formerly USSR) in 1986, the effects of Hurricane Katrina that devastated New Orleans, Louisiana in 2005, and the 2011 Tōhoku earthquake and tsunami in Fukushima, Japan.

## Adverse Impacts on Public Health

A wide variety of chemicals are present within waste materials, many of which pose a significant environmental concern. Though the **leachate** generated from the waste may contain toxic chemicals, the concentrations and variety of toxic chemicals are quite small compared to hazardous waste sites. For example, explosives and radioactive waste are primarily located at Department of Energy (DOE) sites because many of these facilities have been historically used for weapons research, fabrication, testing, and training. Organic contaminants are largely found at oil refineries, or petroleum storage sites, and inorganic and pesticide contamination usually is the result of a variety of industrial activities as well as agricultural activities. Yet, soil and groundwater contamination are not the only direct adverse effects of improper waste management activities – recent studies have also shown that greenhouse gas emissions from the wastes are significant, exacerbating global climate change.

A wide range of toxic chemicals, with an equally wide distribution of respective concentrations, is found in waste streams. These compounds may be present in concentrations that alone may pose a threat to human health or may have a synergistic/cumulative effect due to the presence of other compounds. Exposure to hazardous waste has been linked to many types of cancer, chronic illnesses, and abnormal reproductive outcomes such as birth defects, low birth weights, and spontaneous abortions. Many studies have been performed on major toxic chemicals found at hazardous waste sites incorporating epidemiological or animal tests to determine their toxic effects.

As an example, the effects of radioactive materials are classified as **somatic** or **genetic**.
The **somatic** effects may be immediate or occur over a long period of time. Immediate effects from large radiation doses often produce nausea and vomiting, and may be followed by severe blood changes, hemorrhage, infection, and death. Delayed effects include leukemia, and many types of cancer including bone, lung, and breast cancer. **Genetic** effects have been observed in which gene mutations or chromosome abnormalities result in measurable harmful effects, such as decreases in life expectancy, increased susceptibility to sickness or disease, infertility, or even death during embryonic stages of life. Because of these studies, occupational dosage limits have been recommended by the National Council on Radiation Protection. Similar studies have been completed for a wide range of potentially hazardous materials. These studies have, in turn, been used to determine safe exposure levels for numerous exposure scenarios, including those that consider occupational safety and remediation standards for a variety of land use scenarios, including residential, commercial, and industrial land uses.

## Impacts on the Environment

The chemicals found in wastes not only pose a threat to human health, but they also have profound effects on entire eco-systems. Contaminants may change the chemistry of waters and destroy aquatic life and underwater eco-systems that are depended upon by more complex species. Contaminants may also enter the food chain through plants or microbiological organisms, and higher, more evolved organisms bioaccumulate the waste through subsequent ingestion. As the contaminants move farther up the food chain, the continued bioaccumulation results in increased contaminant mass and concentration. In many cases, toxic concentrations are reached, resulting in increased mortality of one or more species.

As the populations of these species decrease, the natural inter-species balance is affected. With decreased numbers of predators or food sources, other species may be drastically affected, leading to a chain reaction that can affect a wide range of flora and fauna within a specific eco-system. As the eco-system continues to deviate from equilibrium, disastrous consequences may occur. Examples include the near extinction of the bald eagle due to persistent ingestion of DDT-impacted fish, and the depletion of oysters, crabs, and fish in Chesapeake Bay due to excessive quantities of fertilizers, toxic chemicals, farm manure wastes, and power plant emissions.

The long-recognized hierarchy of management of wastes, in order of preference, consists of prevention, minimization, recycling and **reuse**, **biological treatment**, incineration, and landfill disposal (see Figure 10.1).

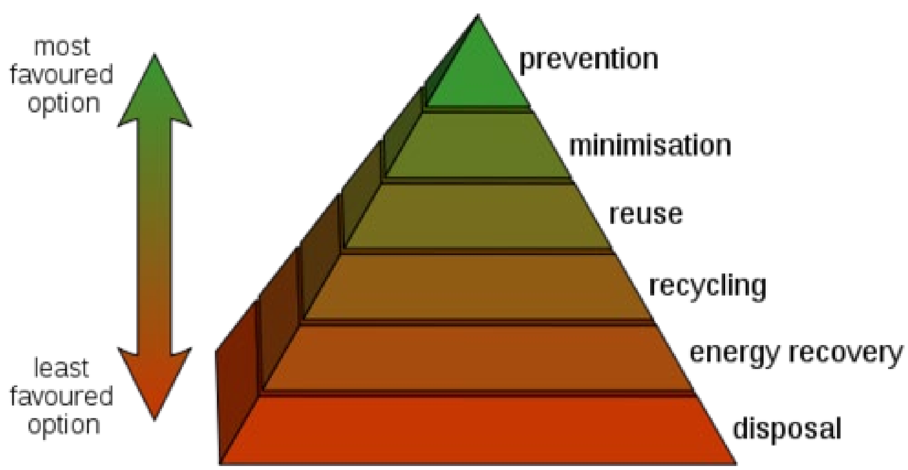


**Figure 10.1** Hierarchy of Waste Management. (Source: Drstuey via Wikimedia Commons)
Figure 10.1 shows the hierarchy of management of wastes in order or preference, starting with prevention as the most favorable to disposal as the least favorable option.

## Waste Prevention

The ideal waste management alternative is to prevent waste generation in the first place. Hence, **waste prevention** is a basic goal of all waste management strategies. Numerous technologies can be employed throughout the manufacturing, use, or post-use portions of product life cycles to eliminate waste and, in turn, reduce or **prevent pollution**. Some representative strategies include environmentally conscious manufacturing methods that incorporate less hazardous or harmful materials, the use of modern leakage detection systems for material storage, innovative chemical neutralization techniques to reduce reactivity, or water saving technologies that reduce the need for freshwater inputs.

## Waste Minimization

In many cases, waste cannot be eliminated from a variety of processes. However, numerous strategies can be implemented to reduce or minimize waste generation. **Waste minimization**, or source reduction, refers to the collective strategies of design and fabrication of products or services that minimize the amount of generated waste and/or reduce the toxicity of the resultant waste. Often these efforts come about from identified trends or specific products that may be causing problems in the waste stream and the subsequent steps taken to halt these problems. In industry, waste can be reduced by reusing materials, using less hazardous substitute materials, or by modifying components of design and processing. Many benefits can be realized by waste minimization or source reduction, including reduced use of natural resources and the reduction of toxicity of wastes.

Waste minimization strategies are extremely common in manufacturing applications; the savings of material use preserves resources but also saves significant manufacturing related costs. Advancements in streamlined packaging reduce material use, increased distribution efficiency reduces fuel consumption and resulting air emissions. Further, engineered building materials can often be designed with specific favorable properties that, when accounted for in overall structural design, can greatly reduce the overall mass and weight of material needed for a given structure. This reduces the need for excess material and reduces the waste associated with component fabrication.

The dry-cleaning industry provides an excellent example of product substitution to reduce toxic waste generation. For decades, dry cleaners used tetrachloroethylene, or "**perc**" as a dry-cleaning solvent. Although effective, tetrachloroethylene is a relatively toxic compound. Additionally, it is easily introduced into the environment, where it is highly recalcitrant due to its physical properties. Further, when its degradation occurs, the intermediate daughter products generated are more toxic to human health and the environment.

Because of its toxicity and impact on the environment, the dry-cleaning industry has adopted new practices and increasingly utilizes less toxic replacement products, including petroleum-based compounds. Further, new emerging technologies are incorporating carbon dioxide and other relatively harmless compounds. While these substitutes products have in many cases been mandated by government regulation, they have also been adopted in response to consumer demands and other market-based forces.

## Recycling and Reuse

Recycling refers to recovery of useful materials such as glass, paper, plastics, wood, and metals from the waste stream so they may be incorporated into the fabrication of new products. With greater incorporation of recycled materials, the required use of raw materials for identical applications is reduced. Recycling reduces the need for natural resource exploitation for raw materials, but it also allows waste materials to be recovered and utilized as valuable resource materials. Recycling waste directly conserves natural resources, reduces energy consumption and emissions generated by extraction of virgin materials and their subsequent manufacture into finished products, reduces overall energy consumption and greenhouse gas emissions that contribute to global climate change, and reduces the incineration or landfilling of the materials that have been recycled. Moreover, recycling creates several economic benefits, including the potential to create job markets and drive growth.

Common recycled materials include paper, plastics, glass, aluminum, steel, and wood. Additionally, many construction materials can be reused, including concrete, asphalt materials, masonry, and reinforcing steel. "Green" plant-based wastes are often recovered and immediately reused for mulch or fertilizer applications. Many industries also recover various by-products and/or refine and "re-generate" solvents for reuse. Examples include copper and nickel recovery from metal finishing processes; the recovery of oils, fats, and plasticizers by solvent extraction from filter media such as activated carbon and clays; and acid recovery by spray roasting, ion exchange, or crystallization. Further, a range of used food-based oils are being recovered and utilized in "biodiesel" applications.

Numerous examples of successful recycling and reuse efforts are encountered every day. In some cases, the recycled materials are used as input materials and are heavily processed into end products. Common examples include the use of scrap paper for new paper manufacturing, or the processing of old aluminum cans into new aluminum products. In other cases, reclaimed materials undergo little or no processing prior to their re-use. Some common examples include the use of tree waste as wood chips, or the use of brick and other fixtures into new structural construction. In any case, the success of recycling depends on effective collection and processing of recyclables, markets for reuse (e.g. manufacturing and/or applications that utilize recycled materials), and public acceptance and promotion of recycled products and applications utilizing recycled materials.

## Biological Treatment

Landfill disposal of wastes containing significant organic fractions is increasingly discouraged in many countries, including the United States. Such disposal practices are even prohibited in several European countries. Since landfilling does not provide an attractive management option, other techniques have been identified. One option is to treat waste so that biodegradable materials are degraded and the remaining inorganic waste fraction (known as residuals) can be subsequently disposed of or used for a beneficial purpose.

Biodegradation of waste can be accomplished by using aerobic composting, anaerobic digestion, or mechanical biological treatment (MBT) methods. If the organic fraction can be separated from inorganic material, aerobic composting or anaerobic digestion can be used to degrade the waste and convert it into usable **compost**. For example, organic wastes such as food waste, yard waste, and animal manure that consist of naturally degrading bacteria can be converted under controlled conditions into compost, which can then be utilized as natural fertilizer. Aerobic composting is accomplished by placing selected proportions of organic waste into piles, rows or vessels, either in open conditions or within closed buildings fitted with gas collection and treatment systems. During the process, bulking agents such as wood chips are added to the waste material to enhance the aerobic degradation of organic materials. Finally, the material is allowed to stabilize and mature during a curing process where pathogens are concurrently destroyed. The end-products of the composting process include carbon dioxide, water, and the usable compost material.

Compost material may be used in a variety of applications. In addition to its use as a soil amendment for plant cultivation, compost can be used remediate soils, groundwater, and stormwater. Composting can be labor-intensive, and the quality of the compost is heavily dependent on proper control of the composting process. Inadequate control of the operating conditions can result in compost that is unsuitable for beneficial applications. Nevertheless, composting is becoming increasingly popular; composting diverted 82 million tons of waste material away from the landfill waste stream in 2009, increased from 15 million tons in 1980. This diversion also prevented the release of approximately 178 million metric tons of carbon dioxide in 2009, an amount equivalent to the yearly carbon dioxide emissions of 33 million automobiles.

In some cases, aerobic processes are not feasible. As an alternative, anaerobic processes may be utilized. Anaerobic digestion consists of degrading mixed or sorted organic waste in vessels under anaerobic conditions. The anaerobic degradation process produces a combination of methane and carbon dioxide (biogas) and residuals (biosolids). Biogas can be used for heating and electricity production, while residuals can be used as fertilizers and soil amendments. Anaerobic digestion is a preferred degradation for wet wastes as compared to the preference of composting for dry wastes. The advantage of anaerobic digestion is biogas collection; this collection and subsequent beneficial utilization makes it a preferred alternative to landfill disposal of wastes. Also, waste is degraded faster through anaerobic digestion as compared to landfill disposal.

Another waste treatment alternative, mechanical biological treatment (MBT), is not common in the United States. However, this alternative is widely used in Europe. During implementation of this method, waste material is subjected to a combination of mechanical and biological operations that reduce volume through the degradation of organic fractions in the waste. Mechanical operations such as sorting, shredding, and crushing prepare the waste for subsequent biological treatment, consisting of either aerobic composting or anaerobic digestion. Following the biological processes, the reduced waste mass may be subjected to incineration.

## Incineration

Waste degradation not only produces useful solid end-products (such as compost), but degradation by-products can also be used as a beneficial energy source. As discussed above, anaerobic digestion of waste can generate biogas, which can be captured and incorporated into electricity generation. Alternatively, waste can be directly incinerated to produce energy. Incineration consists of waste combustion at very high temperatures to produce electrical energy. The byproduct of incineration is ash, which requires proper characterization prior to disposal, or in some cases, beneficial re-use. It is widely used in developed countries due to landfill space limitations. It is estimated that about 130 million tons of waste are annually combusted in more than 600 plants in 35 countries. Further, incineration is often used to effectively mitigate hazardous waste such as chlorinated hydrocarbons, oils, solvents, medical wastes, and pesticides.

**Table 10.1** Pros and Cons of Incinerators

| **Pros of Incinerators** | **Cons of Incinerators** |
|---|---|
| The incinerated waste is turned into energy. | The fly ash (airborne particles) has high levels of toxic chemicals, including dioxin, cadmium and lead. |
| The volume of waste is reduced. | The initial construction costs are high. |

Despite the advantages, incineration is often viewed negatively because of high initial construction costs, and emissions of ash, which is toxic (see Table 10.1). Currently, many 'next generation" systems are being researched and developed, and the USEPA is developing new regulations to carefully monitor incinerator air emissions under the Clean Air Act.

## Landfill Disposal

Despite advances in reuse and recycling, landfill disposal remains the primary waste disposal method in the United States. As previously mentioned, the rate of MSW generation continues to increase, but overall landfill capacity is decreasing. New regulations concerning proper waste disposal and the use of innovative liner systems to minimize the potential of groundwater contamination from leachate infiltration and migration have resulted in a substantial increase in the costs of landfill disposal. Also, public opposition to landfills continues to grow, partially inspired by memories of historic uncontrolled dumping practices, the resulting undesirable side effects of uncontrolled vectors, contaminated groundwater, unmitigated odors, and subsequent diminished property values.

Landfills can be designed and permitted to accept hazardous waste in accordance with RCRA Subtitle C regulations, or they may be designed and permitted to accept municipal solid waste in accordance with RCRA Subtitle D regulations. Regardless of their waste designation, landfills are engineered structures consisting of bottom and side liner systems, leachate collection and removal systems, final cover systems, gas collection and removal systems, and groundwater monitoring systems. An extensive permitting process is required for sitting, designing and operating landfills. Post-closure monitoring of landfills is also typically required for at least 30 years. Because of their design, waste within landfills is degraded anaerobically. During degradation, biogas is produced and collected. The collection systems prevent uncontrolled subsurface gas migration and reduce the potential for an explosive condition. The captured gas is often used in cogeneration facilities for heating or electricity generation. Further, upon closure, many landfills undergo "land recycling" and redeveloped as golf courses, recreational parks, and other beneficial uses.

Wastes commonly exist in dry conditions within landfills, and as a result, the rate of waste degradation is commonly very slow. These slow degradation rates are coupled with slow rates of degradation-induced settlement, which can in turn complicate or reduce the potential for beneficial land re-use at the surface. Recently, the concept of bioreactor landfills has emerged, which involves recirculation of leachate and/or injection of selected liquids to increase the moisture in the waste, which in turn induces rapid degradation. The increased rates of degradation increase the rate of biogas production, which increases the potential of beneficial energy production from biogas capture and utilization.

## Regulatory Framework in the United States

During the 20th century, especially following World War II, the United States experienced unprecedented economic growth. Much of the growth was fueled by rapid and increasingly complex industrialization. With advances in manufacturing and chemical applications also came increases in volume, and in many cases the toxicity of generated wastes. Furthermore, few if any controls or regulations were in place with respect to the handling of toxic materials or the disposal of waste products. Continued industrial activity led to several high-profile examples of detrimental consequences to the environment resulting from these uncontrolled activities. Finally, several forms of intervention, both in the form of government regulation and citizen action, occurred in the early 1970s.

Ultimately, several regulations were promulgated on the state and federal levels to ensure the safety of public health and the environment. With respect to waste materials, the Resource Conservation and Recovery Act (RCRA), enacted by the United States Congress, first in 1976 and then amended in 1984, provides a comprehensive framework for the proper management of hazardous and non-hazardous solid wastes in the United States. RCRA stipulates broad and general legal objectives while mandating the United States Environmental Protection Agency (USEPA) to develop specific regulations to implement and enforce the law. States and local governments can either adopt the federal regulations, or they may develop and enforce more stringent regulations than those specified in RCRA. Similar regulations have been developed or are being developed worldwide to manage waste in a similar manner in other countries.

The broad goals of RCRA include: (1) the protection of public health and the environment from the hazards of waste disposal; (2) the conservation of energy and natural resources; (3) the reduction or elimination of waste; and (4) the assurance that wastes are managed in an environmentally-sound manner (e.g. the remediation of waste which may have spilled, leaked, or been improperly disposed). It should be noted here that the RCRA focuses only on active and future facilities and does not address abandoned or historical sites. These types of environmentally impacted sites are managed under a different regulatory framework, known as the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, or more commonly known as "Superfund."

## Solid Waste Regulations

RCRA defines solid waste as any garbage or refuse, sludge from a wastewater treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semi-solid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities. In general, solid waste can be categorized as either **non-hazardous waste** or **hazardous waste**.

Non-hazardous solid waste can be trash or garbage generated from residential households, offices and other sources. Generally, these materials are classified as **municipal solid waste** (MSW)**.** Alternatively, non-hazardous materials that result from the production of goods and products by various industries (e.g. coal combustion residues, mining waste, cement kiln dust), are collectively known as industrial solid waste. Because they are classified as non-hazardous material, many components of municipal solid waste and industrial waste have potential for recycling and re-use. Significant efforts are underway by both government agencies and industry to advance these objectives.

Hazardous waste, generated by many industries and businesses (e.g. dry cleaners and auto repair shops), is constituted of materials that are dangerous or potentially harmful to human health and the environment. Waste is classified as hazardous if it exhibits at least one of these four characteristics:

- **Ignitability**, which refers to the creation of fires under certain conditions; including materials that are spontaneously combustible or those that have a flash point less than 140 $^0$F.
- **Corrosivity**, which refers to capability to corrode metal containers, including materials with a pH less than or equal to 2 or greater than or equal to 12.5.
- **Reactivity**, which refers to materials susceptible to unstable conditions such as explosions, toxic fumes, gases, or vapors when heated, compressed, or mixed with water under normal conditions.
- **Toxicity**, which refers to substances that can induce harmful or fatal effects when ingested or absorbed or inhaled.

## Radioactive Waste Regulations

Although non-hazardous waste and hazardous waste are regulated by RCRA, nuclear or radioactive waste is regulated in accordance with the Atomic Energy Act of 1954 by the Nuclear Regulatory Commission (NRC) in the United States.

Radioactive waste is characterized according to four categories: (1) **High-level waste** (HLW), (2) **Transuranic waste** (TRU), (3) **Low-level waste** (LLW), and (4) **Mill tailings**. Various radioactive wastes decay at different rates, but health and environmental dangers due to radiation may persist for hundreds or thousands of years.

High-level waste is typically liquid or solid waste that results from government defense related activities or from nuclear power plants and spent fuel assemblies. These wastes are extremely dangerous due to their heavy concentrations of radio nuclides, and humans must not come into contact with them.

**Transuranic waste** mainly results from the reprocessing of spent nuclear fuels and from the fabrication of nuclear weapons for defense projects. They are characterized by moderately penetrating radiation and a decay time of approximately twenty years until safe radionuclide levels are achieved. Following the passage of a reprocessing ban in 1977, most of this waste generation ended. Even though the ban was lifted in 1981, Transuranic waste continues to be rare because reprocessing of nuclear fuel is expensive. Further, because the extracted plutonium may be used to manufacture nuclear weapons, political and social pressures minimize these activities.

Low level waste includes much of the remainder of radioactive waste materials. They constitute over 80 percent of the volume of all nuclear waste, but only about two percent of total radioactivity. Sources of Low-level wastes include all the previously cited sources of High-level waste and Transuranic waste, plus wastes generated by hospitals, industrial plants, universities, and commercial laboratories. Low level waste is much less dangerous than High-level waste, and NRC regulations allow some very low-level wastes to be released to the environment. Low level waste may also be stored or buried until the isotopes decay to levels low enough such that it may be disposed of as non-hazardous waste. Low level wastes disposal is managed at the state level, but requirements for operation and disposal are established by the USEPA and NRC. The Occupational Health and Safety Administration (OSHA) is the agency in charge of setting standards for workers that are exposed to radioactive materials.

## International Regulatory Framework

### *The 1992 Basel Convention*

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal first came into force in 1992. The Convention puts an onus on exporting countries to ensure that hazardous waste is managed in an environmentally sound manner in the country of import.
The Basel Convention places obligations on countries that are party to the Convention. 151 Countries have ratified the Basel Convention as of December 2002. These have obligations to:

- Minimize generation of hazardous waste.
- Ensure adequate disposal facilities are available.
- Control and reduce international movements of hazardous waste.
- Ensure environmentally sound management of wastes; and
- Prevent and punish illegal traffic.

### *The 1995 Waigani Convention*

The Basel Convention establishes a global control system for hazardous waste being shipped from one country to another. States which are Parties to the Convention must not trade in hazardous wastes with non-Parties but an exception to this is provided for in Article 11 of the Convention, whereby Parties may enter into agreements or arrangements either with other Parties or with non-Parties.

**Electronic waste**, commonly known as **e-waste**, refers to discarded electronic products such as televisions, computers and computer peripherals (e.g. monitors, keyboards, disk drives, and printers), telephones and cellular phones, audio and video equipment, video cameras, fax and copy machines, video game consoles, and others. Various regulatory and voluntary programs have been instituted to promote reuse, recycling and safe disposal of bulk e-waste. Reuse and refurbishing have been promoted to reduce raw material use energy consumption, and water consumption associated with the manufacture of new products.

Recycling and recovery of elements such as lead, copper, gold, silver and platinum can yield valuable resources which otherwise may cause pollution if improperly released into the environment. The recycling and recovery operations must be conducted with extreme care, as the exposure of e-waste components can result in adverse health impacts on the workers performing these operations. For economic reasons, recycled e-waste is often exported to other countries for recovery operations. However, lax regulatory environments in many of these countries can lead to unsafe practices or improper disposal of bulk residual e-waste, which in turn can adversely affect vulnerable populations.

In the United States, there are no specific federal laws dealing with e-waste, but many states have recently developed e-waste regulations that promote environmentally sound management. For example, the State of California passed the Electronic Waste Recycling Act in 2003 to foster recycling, reuse, and environmentally sound disposal of residual bulk e-waste. Yet, despite recent regulations and advances in reuse, recycling and proper disposal practices, additional sustainable strategies to manage e-waste are urgently needed.

One sustainable strategy used to manage e-waste is extended producer responsibility (EPR), also known as product stewardship. This concept holds manufacturers liable for the entire life-cycle costs associated with the electronic products, including disposal costs, and encourages the use of environmental-friendly manufacturing processes and products. Manufacturers can pursue EPR in multiple ways, including reuse/refurbishing, buy-back, recycling, and energy production or beneficial reuse applications. Life-cycle assessment and life-cycle cost methodologies may be used to compare the environmental impacts of these different waste management options. Incentives or financial support are also provided by some government and/or regulatory agencies to promote EPR. The use of non-toxic and easily recyclable materials in product fabrication is a major component of any EPR strategy. A growing number of companies (e.g. Dell, Sony, HP) are embracing EPR with various initiatives towards achieving sustainable e-waste management.

EPR is a preferred strategy because the manufacturer bears financial and legal responsibility for their products; hence, they have an incentive to incorporate green design and manufacturing practices that incorporate easily recyclable and less toxic material components while producing electronics with longer product lives. One obvious disadvantage of EPR is the higher manufacturing cost, which leads to an increase in the cost of electronics to consumers.

There is no specific federal law requiring EPR for electronics, but the United States Environmental Protection Agency (USEPA) undertook several initiatives to promote EPR to achieve the following goals: (1) foster environmentally conscious design and manufacturing, (2) increase purchasing and use of more environmentally sustainable electronics, and (3) increase safe, environmentally sound reuse and recycling of used electronics. To achieve these goals, USEPA has been engaged in various activities, including the promotion of environmental considerations in product design, the development of evaluation tools for environmental attributes of electronic products, the encouragement of recycling (or *e*-cycling), and the support of programs to reduce e-waste, among others. More than 20 states in the United States and various organizations worldwide have already developed laws and/or policies requiring EPR in some form when dealing with electronic products. For instance, the New York State Wireless Recycling Act emphasizes that authorized retailers and service providers should be compelled to participate in take-back programs, thus allowing increased recycling and reuse of e-waste. Similarly, Maine is the first U.S. state to adopt a household e-waste law with EPR.

In Illinois, Electronic Products Recycling & Reuse Act requires the electronic manufacturers to participate in the management of discarded and unwanted electronic products from residences. The

Illinois EPA has also compiled locations where the residents can give away their discarded electronic products at no charge. Furthermore, USEPA compiled a list of local programs and manufacturers/retailers that can help consumers to properly donate or recycle e-waste. Overall, the growing quantities and environmental hazards associated with electronic waste are of major concern to waste management professionals worldwide. Current management strategies, including recycling and refurbishing, have not been successful. As a result, EPR regulations are rapidly evolving throughout the world to promote sustainable management of e-waste. However, neither a consistent framework nor assessment tools to evaluate EPR have been fully developed.

# Chapter Eleven: Air Pollution, Climate Change, and Ozone Depletion

## Learning Outcomes

After studying this chapter, you should be able to:

- Identify sources of air pollution
- List the common air pollutants
- Explain how the greenhouse effect causes the atmosphere to retain heat
- Explain how we know that humans are responsible for recent climate change
- List some effects of climate change
- Identify some climate change policies and adaptation measures

Air pollution occurs in many forms but can generally be thought of as gaseous and particulate contaminants that are present in the earth's atmosphere. Chemicals discharged into the air that have a direct impact on the environment are called **primary pollutants**. These primary pollutants sometimes react with other chemicals in the air to produce **secondary pollutants**. Air pollution is typically separated into two categories: **outdoor** air pollution and **indoor** air pollution. Outdoor air pollution involves exposures that take place outside of the built environment. Examples include fine particles produced by the burning of coal, noxious gases such as sulfur dioxide, nitrogen oxides and carbon monoxide, ground-level ozone and tobacco smoke. Indoor air pollution involves exposures to particulates, carbon oxides, and other pollutants carried by indoor air or dust. Examples include gases, household products and chemicals, building materials (asbestos, formaldehyde, lead, etc.) outdoor indoor allergens (cockroach and mouse dropping, etc.), tobacco smoke, mold and pollen.

## Sources of Air Pollution

**Stationery and Area Sources.** A stationary source of air pollution refers to an emission source that does not move, also known as a point source. Stationary sources include factories, power plants, dry cleaners and degreasing operations. The term area source is used to describe many small sources of air pollution located together whose individual emissions may be below thresholds of concern, but whose collective emissions can be significant. Residential wood burners are a good example of a small source, but when combined with many other small sources, they can contribute to local and regional air pollution levels. Area sources can also be thought of as non-point sources, such as construction of housing developments, dry lake beds, and landfills.

**Mobile Sources.** A mobile source of air pollution refers to a source that can move under its own power. In general, mobile sources imply "on-road" transportation, which includes vehicles such as cars, sport utility vehicles, and buses. In addition, there is also a "non-road" or "off-road" category that includes gas-powered lawn tools and mowers, farm and construction equipment, recreational vehicles, boats, planes, and trains.

**Agricultural Sources.** Agricultural operations, those that raise animals and grow crops, can generate emissions of gases and particulate matter. For example, animals confined to a barn or restricted area (rather than field grazing), produce large amounts of manure. Manure emits various gases, particularly ammonia, into the air. This ammonia can be emitted from animal houses, manure storage areas, or from the land after the manure is applied. In crop production, the misapplication of fertilizers, herbicides, and pesticides can potentially result in aerial drift of these materials and harm may be caused.

**Natural Sources.** Although industrialization and the use of motor vehicles are overwhelmingly the most significant contributors to air pollution, there are important natural sources of "pollution" as well. Wildland fires, dust storms, and volcanic activity also contribute gases and particulates to our atmosphere. Unlike the sources of air pollution, natural "air pollution" is not caused by people or their activities. An erupting volcano emits particulate matter and gases; forest and prairie fires can emit large quantities of "pollutants"; plants and trees naturally emit VOCs which are oxidized and form aerosols that can cause a natural blue haze; and dust storms can create large amounts of particulate matter. Wild animals in their natural habitat are also considered natural sources of "pollution."

## Six Common Air Pollutants

The commonly found air pollutants (also known as **criteria pollutants**) are *particle pollution* (often referred to as particulate matter), *ground-level ozone*, *carbon monoxide, sulfur oxides*, *nitrogen oxides*, and *lead*. These pollutants can harm health and the environment, and cause property damage. Of the six pollutants, particle pollution and ground-level ozone are the most widespread health threats. The U.S. EPA calls these pollutants "criteria" air pollutants because it regulates them by developing human health-based and/or environmentally based criteria (science-based guidelines) for setting permissible levels. The set of limits based on human health is called **primary standards**. Another set of limits intended to prevent environmental and property damage is called **secondary standards**.

Ground level or "bad" **ozone** is not emitted directly into the air but is created by chemical reactions between oxides of nitrogen (NOx) and volatile organic compounds (VOC) in the presence of sunlight. Emissions from industrial facilities and electric utilities, motor vehicle exhaust, gasoline vapors, and chemical solvents are some of the major sources of NOx and VOC. Breathing ozone can trigger a variety of health problems, particularly for children, the elderly, and people of all ages who have lung diseases such as asthma. Ground level ozone can also have harmful effects on sensitive vegetation and ecosystems.

**Particulate matter**, also known as particle pollution or PM, is a complex mixture of extremely small particles and liquid droplets. Particle pollution is made up of several components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles. The size of particles is directly linked to their potential for causing health problems. EPA is concerned about particles that are 10 micrometers in diameter or smaller because those are the particles that generally pass through the throat and nose and enter the lungs. Once inhaled, these particles can affect the heart and lungs and cause serious health effects.

**Carbon monoxide** (CO) is a colorless, odorless gas emitted from combustion processes. Nationally and, particularly in urban areas, most CO emissions to ambient air come from mobile sources. CO can cause harmful health effects by reducing oxygen delivery to the body's organs (like the heart and brain) and tissues. At extremely high levels, CO can cause death.

**Nitrogen dioxide** ($NO_2$) is one of a group of highly reactive gases known as "oxides of nitrogen," or nitrogen oxides (NOx). Other nitrogen oxides include nitrous acid and nitric acid. EPA's National Ambient Air Quality Standard uses $NO_2$ as the indicator for the larger group of nitrogen oxides. NO2 forms quickly from emissions from cars, trucks and buses, power plants, and off-road equipment. In addition to contributing to the formation of ground-level ozone, and fine particle pollution, NO2 is linked with several adverse effects on the respiratory system.

**Sulfur dioxide** ($SO_2$) is one of a group of highly reactive gasses known as "oxides of sulfur." The largest sources of $SO_2$ emissions are from fossil fuel combustion at power plants (73%) and other industrial facilities (20%). Smaller sources of $SO_2$ emissions include industrial processes such as extracting metal from ore, and the burning of high sulfur containing fuels by locomotives, large ships, and non-road equipment. $SO_2$ is linked with several adverse effects on the respiratory system.

**Lead** is a metal found naturally in the environment as well as in manufactured products. The major sources of lead emissions have historically been from fuels in on-road motor vehicles (such as cars and trucks) and industrial sources. As a result of regulatory efforts in the U.S. to remove lead from on-road motor vehicle gasoline, emissions of lead from the transportation sector dramatically declined by 95 percent between 1980 and 1999, and levels of lead in the air decreased by 94 percent between 1980 and 1999. Today, the highest levels of lead in air are usually found near lead smelters. The major sources of lead emissions to the air today are ore and metals processing and piston-engine aircraft operating on leaded aviation gasoline.

## Indoor Air Pollution (Major concerns in developed countries)

Most people spend approximately 90 percent of their time indoors. However, the indoor air we breathe in homes and other buildings can be more polluted than outdoor air and can increase the risk of illness. There are many sources of indoor air pollution in homes. They include biological contaminants such as bacteria, molds and pollen, burning of fuels and environmental tobacco smoke, building materials and furnishings, household products, central heating and cooling systems, and outdoor sources. Outdoor air pollution can enter buildings and become a source of indoor air pollution.

*Sick building syndrome* is a term used to describe situations in which building occupants have health symptoms that are associated only with spending time in that building. Causes of sick building syndrome are believed to include inadequate ventilation, indoor air pollution, and biological contaminants. Usually, indoor air quality problems only cause discomfort. Most people feel better as soon as they remove the source of the pollution. Making sure that your building is well-ventilated and getting rid of pollutants can improve the quality of your indoor air.

| **Secondhand Smoke (Environmental Tobacco Smoke)** |
|---|
| Secondhand smoke is the combination of smoke that comes from a cigarette and smoke breathed out by a smoker. When a non-smoker is around someone smoking, they breathe in secondhand smoke.<br>Secondhand smoke is dangerous to anyone who breathes it in. There is no safe amount of secondhand smoke. It contains over 7,000 harmful chemicals, at least 250 of which are known to damage human health. It can also stay in the air for several hours after somebody smokes. Even breathing secondhand smoke for a short amount of time can hurt your body.<br>Over time, secondhand smoke can cause serious health issues in non-smokers. The only way to fully protect non-smokers from the dangers of secondhand smoke is to not allow smoking indoors. Separating smokers from nonsmokers (like "no smoking" sections in restaurants) cleaning the air, and airing out buildings does not completely get rid of secondhand smoke.<br>Source: Smokefree.gov |

The ozone depletion process begins when CFCs and other ozone-depleting substances (ODS) are emitted into the atmosphere. Winds efficiently mix the troposphere and evenly distribute the gases. CFCs are extremely stable, and they do not dissolve in rain. After a period of several years, ODS molecules reach the stratosphere, about 10 kilometers above the Earth's surface. Strong UV light breaks apart the ODS molecule. CFCs, HCFCs, carbon tetrachloride, methyl chloroform, and other gases release chlorine atoms, and halons and methyl bromide release bromine atoms. It is these atoms that destroy ozone, not the intact ODS molecules. It is estimated that one chlorine atom can destroy over 100,000 ozone molecules before it is removed from the stratosphere.

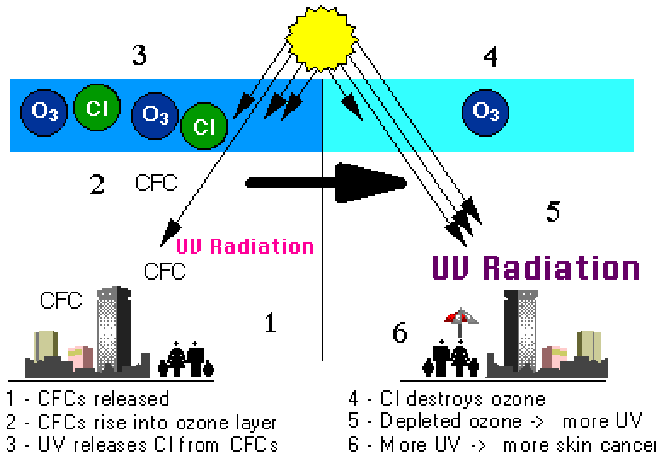


**Figure 11.1** Ozone, greenhouse gases, and ultraviolet light. (credit: U.S. Environmental Protection Agency. (n.d.). Effect of ozone depletion on UV radiation reaching Earth's surface).

Figure 11.1 is a classic educational diagram illustrating the role of the ozone layer in protecting Earth from harmful ultraviolet (UV) radiation.

- Left side: Intact ozone layer ($O_3$ molecules) absorbs most incoming UV radiation, allowing only a small amount to reach the surface.
- Right side: Depleted or destroyed ozone layer (the "ozone hole") lets significantly more UV radiation reach the ground, increasing risks to human health, ecosystems, and materials.

Ozone is constantly produced and destroyed in a natural cycle, as shown in the above picture, courtesy of NASA GSFC. However, the overall amount of ozone is essentially stable. Similarly, while ozone production and destruction are balanced, ozone levels remain stable. This was the situation until the past several decades. Large increases in stratospheric chlorine and bromine, however, have upset that balance. In effect, they have added a siphon downstream, removing ozone faster than natural ozone creation reactions can keep up. Therefore, ozone levels fall. Since ozone filters out harmful UVB radiation, less ozone means higher UVB levels at the surface. The more the depletion, the larger the increase in incoming UVB. UVB has been linked to skin cancer, cataracts, damage to materials like plastics, and harm to certain crops and marine organisms. Although some UVB reaches the surface even without ozone depletion, its harmful effects will increase because of this problem.

## Policies to Reduce Ozone Destruction

One success story in reducing pollutants that harm the atmosphere concerns ozone-destroying chemicals. In 1973, scientists calculated that CFCs could reach the stratosphere and break apart. This would release chlorine atoms, which would then destroy ozone. Based only on their calculations, the United States and most Scandinavian countries banned CFCs in spray cans in 1978. More confirmation that CFCs break down ozone layers was needed before more was done to reduce production of ozone-destroying chemicals. In 1985, members of the British Antarctic Survey reported that a 50% reduction in the ozone layer had been found over Antarctica in the previous three springs.

Two years after the British Antarctic Survey report, the "Montreal Protocol on Substances that Deplete the Ozone Layer" was ratified by nations all over the world.
The **Montreal Protocol** controls the production and consumption of 96 chemicals that damage the ozone layer. Hazardous substances are phased out first by developed nations and one decade later by developing nations. More hazardous substances are phased out more quickly. CFCs have been mostly phased out since 1995, although were used in developing nations until 2010. Some of the less hazardous substances will not be phased out until 2030. Protocol also requires that wealthier nations donate money to develop technologies that will replace these chemicals.

Since CFCs take many years to reach the stratosphere and can survive there a long time before they break down, the ozone hole will probably continue to grow for some time before it begins to shrink. The ozone layer will reach the same levels it had before 1980 around 2068 and 1950 levels in one or two centuries. Reductions in stratospheric ozone levels will lead to higher levels of UVB reaching the Earth's surface. The sun's output of UVB does not change; rather, less ozone means less protection, and hence more UVB reaches the Earth.

## Health and Environmental Effects of Ozone Layer Depletion

*The Connection Between Ozone Layer Depletion and UVB Radiation*

Reductions in stratospheric ozone levels will lead to higher levels of UVB reaching the Earth's surface. The sun's output of UVB does not change; rather, less ozone means less protection, and hence more UVB reaches the Earth. Studies have shown that in the Antarctic, the amount of UVB measured at the surface can double during the annual ozone hole.

### *Effects on Human Health*

Laboratory and epidemiological studies demonstrate that UVB causes nonmelanoma skin cancer and plays a major role in malignant melanoma development. In addition, UVB has been linked to cataracts, a clouding of the eye's lens. All sunlight contains some UVB, even with normal stratospheric ozone levels. It is always important to protect your skin and eyes from the sun. Ozone layer depletion increases the amount of UVB and the risk of health effects.

### *Effects on Plants*

Physiological and developmental processes of plants are affected by UVB radiation, even by the amount of UVB in present-day sunlight. Despite mechanisms to reduce or repair these effects and a limited ability to adapt to increased levels of UVB, plant growth can be directly affected by UVB radiation.

### *Effects on Marine Ecosystems*

Phytoplankton form the foundation of aquatic food webs. Phytoplankton productivity is limited to the euphotic zone, the upper layer of the water column in which there is sufficient sunlight to support net productivity. The position of the organisms in the euphotic zone is influenced by the action of wind and waves. In addition, many phytoplankton are capable of active movements that enhance their productivity and, therefore, their survival. Exposure to solar UVB radiation has been shown to affect both orientation mechanisms and motility in phytoplankton, resulting in reduced survival rates for these organisms.

## Effects on Biogeochemical Cycles

Increases in solar UV radiation could affect terrestrial and aquatic biogeochemical cycles, thus altering both sources and sinks of greenhouse and chemically important trace gases e.g., carbon dioxide ($CO_2$), carbon monoxide (CO), carbonyl sulfide (COS) and possibly other gases, including ozone. These potential changes would contribute to biosphere-atmosphere feedback that attenuates or reinforces the atmospheric buildup of these gases.

## Acid Rain

Acid rain is a term referring to a mixture of wet and dry deposition (deposited material) from the atmosphere containing higher than normal amounts of nitric and sulfuric acids. The precursors, or chemical forerunners, of acid rain formation result from both natural sources, such as volcanoes and decaying vegetation, and man-made sources, primarily emissions of sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_x$) resulting from fossil fuel combustion.

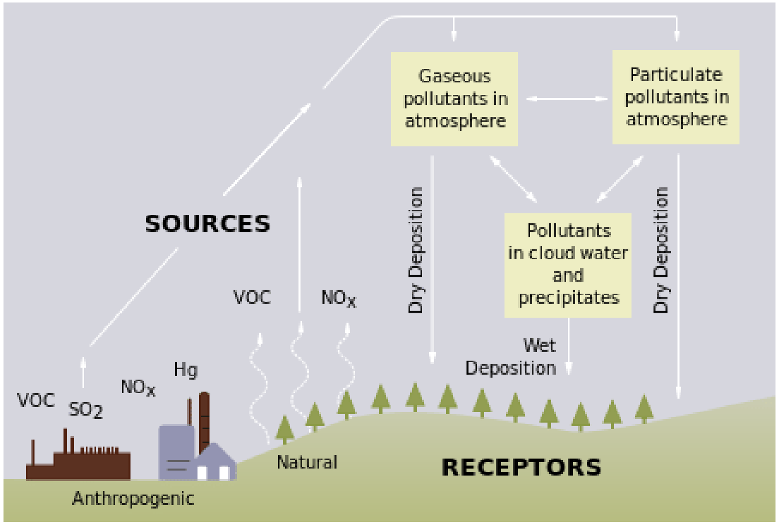


**Figure 11.2** Acid rain formation. (credit: NASA)

Acid rain occurs when these gases react in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds. The result is a mild solution of sulfuric acid and nitric acid. When sulfur dioxide and nitrogen oxides are released from power plants and other sources, prevailing winds blow these compounds across state and national borders, sometimes over hundreds of miles.

## Measuring Acid Rain

Acid rain is measured using a scale called "pH." The lower a substance's pH, the more acidic it is. Pure water has a pH of 7.0. However, normal rain is slightly acidic because carbon dioxide ($CO_2$) dissolves into it forming weak carbonic acid, giving the resulting mixture a pH of approximately 5.6 at typical atmospheric concentrations of $CO_2$. As of 2000, the most acidic rain falling in the U.S. has a pH of about 4.3.

## Effects of Acid Rain

Acid rain causes **acidification** of lakes and streams and contributes to the damage of trees at high elevations (for example, red spruce trees above 2,000 feet) and many sensitive forest soils. In addition, acid rain accelerates the decay of building materials and paints, including irreplaceable buildings, statues, and sculptures that are part of our nation's cultural heritage. Prior to falling to the earth, sulfur dioxide ($SO_2$) and nitrogen oxide ($NO_x$) gases and their particulate matter derivatives, sulfates and nitrates, contribute to visibility degradation and harm public health.

The **ecological** effects of acid rain are most clearly seen in the aquatic, or water, environments, such as streams, lakes, and marshes. Most lakes and streams have a pH between 6 and 8, although some lakes are naturally acidic even without the effects of acid rain. Acid rain primarily affects sensitive bodies of water, which are in watersheds whose soils have a limited ability to neutralize acidic compounds (called "buffering capacity"). Lakes and streams become acidic (i.e., the pH value goes down) when the water itself and its surrounding soil cannot buffer the acid rain enough to neutralize it. In areas where buffering capacity is low, acid rain releases aluminum from soil into lakes and streams; aluminum is highly toxic to many species of aquatic organisms.

Acid rain causes slower growth, injury, or death of **forests**. Of course, acid rain is not the only cause of such conditions. Other factors contribute to the overall stress of these areas, including air pollutants, insects, disease, drought, or very cold weather. In most cases, in fact, the impacts of acid rain on trees are due to the combined effects of acid rain and these other environmental stressors. Acid rain and the dry deposition of acidic particles contribute to the corrosion of **metals** (such as bronze) and the deterioration of paint and stone (such as marble and limestone). These effects significantly reduce the societal value of buildings, bridges, cultural objects such as statues, monuments, and tombstones, and cars (Figure 11.3).

**Figure 11.3** A gargoyle that has been damaged by acid rain (credit: chem.libretexts.org).

Sulfates and nitrates that form in the atmosphere from sulfur dioxide ($SO_2$) and nitrogen oxide ($NO_x$) emissions contribute to **visibility impairment,** meaning we cannot see as far or as clearly through the air. The pollutants that cause acid rain, sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_x$) damage **human health**. These gases interact in the atmosphere to form fine sulfate and nitrate particles that can be transported long distances by winds and inhaled deep into people's lungs. Fine particles can also penetrate indoors. Many scientific studies have identified a relationship between elevated levels of fine particles and increased illness and premature death from heart and lung disorders, such as asthma and bronchitis.

## Causes of Climate Change

### Earth's Temperature is a Balancing Act

Earth's temperature depends on the balance between energy entering and leaving the planet's system. When incoming energy from the sun is absorbed by the Earth system, Earth warms. When the sun's energy is reflected into space, Earth avoids warming. When energy is released back into space, Earth cools. Many factors, both natural and human, can cause changes in Earth's energy balance, including:

- Changes in the greenhouse effect, which affects the amount of heat retained by Earth's atmosphere
- Variations in the sun's energy reaching Earth
- Changes in the reflectivity of Earth's atmosphere and surface

These factors have caused Earth's climate to change many times.

Scientists have pieced together a picture of Earth's climate, dating back hundreds of thousands of years, by analyzing several indirect measures of climate such as ice cores, tree rings, glacier lengths, pollen remains, and ocean sediments, and by studying changes in Earth's orbit around the sun.

Historical records show that the climate system varies naturally over a wide range of time scales. In general, climate changes prior to the Industrial Revolution in the 1700s can be explained by natural causes, such as changes in solar energy, volcanic eruptions, and natural changes in greenhouse gas (GHG) concentrations. Recent **climate changes,** however, cannot be explained by natural causes alone. Research indicates that natural causes are very unlikely to explain most observed warming, especially warming since the mid-20th century. Rather, human activities can very likely explain most of that warming.

## The greenhouse effect causes the atmosphere to retain heat

When sunlight reaches Earth's surface, it can either be reflected into space or absorbed by Earth. Once absorbed, the planet releases some of the energy back into the atmosphere as heat (also called infrared radiation). Greenhouse gases (GHGs) like water vapor ($H_2O$), carbon dioxide ($CO_2$), and methane ($CH_4$) absorb energy, slowing or preventing the loss of heat to space. In this way, GHGs act like a blanket, making Earth warmer than it would otherwise be. This process is commonly known as the "greenhouse effect."

| **What is Global Warming?** |
|---|
| ***Global warming*** refers to the recent and ongoing rise in global average temperature near Earth's surface. It is caused mostly by increasing concentrations of greenhouse gases in the atmosphere. Global warming is causing climate patterns to change. However, global warming itself represents only one aspect of climate change. |
| **What is Climate Change?** |
| ***Climate change*** refers to any significant change in the measures of climate lasting for an extended period. In other words, climate change includes major changes in temperature, precipitation, or wind patterns, among other effects, that occur over several decades or longer. |

Humans are largely responsible for recent climate change

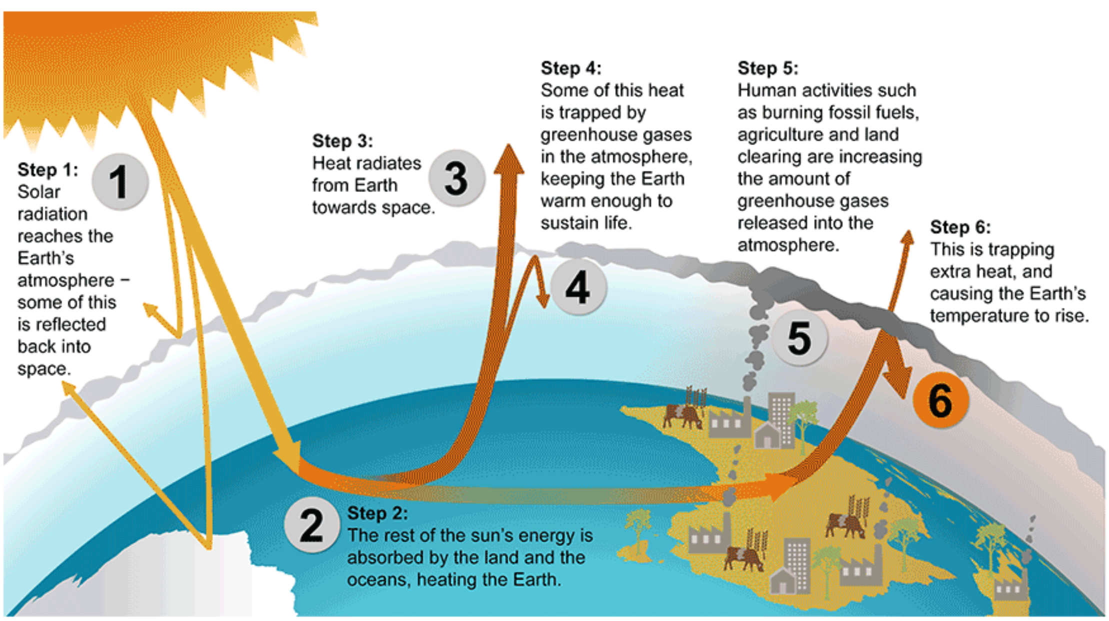


**Figure 11.4** Greenhouse effect (credit: NASA).

## The Main Greenhouse Gasses

The most important GHGs directly emitted by humans include $CO_2$, CH, nitrous oxide ($N_2O$), and several others. The sources and recent trends of these gases are detailed below.

***Carbon dioxide.*** Carbon dioxide ($CO_2$) is the primary greenhouse gas that is contributing to recent climate change. $CO_2$ is absorbed and emitted naturally as part of the carbon cycle, through animal and plant respiration, volcanic eruptions, and ocean-atmosphere exchange. Human activities, such as the burning of fossil fuels and changes in land use, release large amounts of carbon into the atmosphere, causing $CO_2$ concentrations in the atmosphere to rise.

Atmospheric $CO_2$ concentrations have increased by almost 40% since pre-industrial times, from approximately 280 parts per million by volume (ppmv) in the 18th century to 390 ppmv in 2010. The current $CO_2$ level is higher than it has been in at least 800,000 years. Some volcanic eruptions released large quantities of $CO_2$ in the distant past. However, the U.S. Geological Survey (USGS) reports that human activities now emit more than 135 times as much $CO_2$ as volcanoes each year. Human activities currently release over 30 billion tons of $CO_2$ into the atmosphere every year. This build-up in the atmosphere is like a tub filling with water, where more water flows from the faucet than the drain can take away.

***Methane***. Methane ($CH_4$) is produced through both natural and human activities. For example, natural wetlands, agricultural activities, fossil fuel extraction and transport all emit $CH_4$.
Methane is more abundant in Earth's atmosphere now than at any time in at least the past 650,000 years. Due to human activities, $CH_4$concentrations increased sharply during most of the 20th century and are now more than two and-a-half times pre-industrial levels. In recent decades, the rate of increase has slowed considerably.

***Nitrous oxide***. Nitrous oxide ($N_2O$) is produced through natural and human activities, mainly through agricultural activities and natural biological processes. Fuel burning and some other processes also create $N_2O$. Concentrations of $N_2O$ have risen approximately 18% since the start of the Industrial Revolution, with a relatively rapid increase towards the end of the 20th century. In contrast, the atmospheric concentration of $N_2O$ varied only slightly for a period of 11,500 years before the onset of the industrial period, as shown by ice core samples.

## Other Greenhouse Gasses

Water vapor is the most abundant greenhouse gas and the most important in terms of its contribution to the natural greenhouse effect, despite having a short atmospheric lifetime. Some human activities can influence local water vapor levels. However, on a global scale, the concentration of water vapor is controlled by temperature, which influences overall rates of evaporation and precipitation. Therefore, the global concentration of water vapor is not substantially affected by direct human emissions.

Tropospheric **ozone ($O_3$)**, which also has a short atmospheric lifetime, is a potent greenhouse gas. Chemical reactions create ozone layers from emissions of nitrogen oxides and volatile organic compounds from automobiles, power plants, and other industrial and commercial sources in the presence of sunlight. In addition to trapping heat, ozone layers are a pollutant that can cause respiratory health problems and damage crops and ecosystems.

Chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6), together called F-gases, are often used in coolants, foaming agents, fire extinguishers, solvents, pesticides, and aerosol propellants. Unlike water vapor and ozone, these F-gases have a long atmospheric lifetime, and some of these emissions will affect the climate for many decades or centuries.

## Changes in the sun's energy affect how much energy reaches Earth's system

Climate is influenced by natural changes that affect how much solar energy reaches Earth. These changes include changes within the sun and changes in Earth's orbit. Changes occurring in the sun itself can affect the intensity of the sunlight that reaches Earth's surface. The intensity of the sunlight can cause either warming (during periods of stronger solar intensity) or cooling (during periods of weaker solar intensity). The sun follows a natural 11-year cycle of small ups and downs in intensity, but the effect on Earth's climate is small. Changes in the shape of Earth's orbit as well as the tilt and position of Earth's axis can also affect the amount of sunlight reaching Earth's surface.

Changes in the sun's intensity have influenced Earth's climate in the past. For example, the so-called "Little Ice Age" between the 17th and 19th centuries may have been partially caused by a low solar activity phase from 1645 to 1715, which coincided with cooler temperatures. The "Little Ice Age" refers to a slight cooling of North America, Europe, and probably other areas around the globe. Changes in

Earth’s orbit have had a big impact on climate over tens of thousands of years. In fact, the amount of summer sunshine on the Northern Hemisphere, which is affected by changes in the planet’s orbit, appears to control the advance and retreat of ice sheets. These changes appear to be the primary cause of past cycles of ice ages, in which Earth has experienced long periods of cold temperatures (ice ages), as well as shorter interglacial periods (periods between ice ages) of relatively warmer temperatures. Changes in solar energy continue to affect climate. However, solar activity has been relatively constant, aside from the 11-year cycle, since the mid-20th century and therefore does not explain the recent warming of Earth. Similarly, changes in the shape of Earth’s orbit as well as the tilt and position of Earth’s axis affect temperature on relatively long timescales (tens of thousands of years) and therefore cannot explain the recent warming.

## Changes in reflectivity affect how much energy enters Earth’s system

When sunlight reaches Earth, it can be reflected or absorbed. The amount that is reflected or absorbed depends on Earth’s surface and atmosphere. Light-colored objects and surfaces, like snow and clouds, tend to reflect most sunlight, while darker objects and surfaces, like the ocean, forests, or soil, tend to absorb more sunlight.

The term **albedo** refers to the amount of solar radiation reflected from an object or surface, often expressed as a percentage. Earth has an **albedo** of about 30%, meaning that 70% of the sunlight that reaches the planet is absorbed. Absorbed sunlight warms Earth’s land, water, and atmosphere.
**Reflectivity** is also affected by **aerosols**. Aerosols are small particles or liquid droplets in the atmosphere that can absorb or reflect sunlight. Unlike greenhouse gases (GHGs), the climate effects of aerosols vary depending on what they are made of and where they are emitted. Those aerosols that reflect sunlight, such as particles from volcanic eruptions or sulfur emissions from burning coal, have a cooling effect. Those that absorb sunlight, such as black carbon (a part of soot), have a warming effect.

## The Role of Reflectivity in the Past

Natural changes in reflectivity, like the melting of sea ice or increases in cloud cover, have contributed to climate change in the past, often acting as feedback to other processes.
Volcanoes have played a noticeable role in climate. Volcanic particles that reach the upper atmosphere can reflect enough sunlight back to space to cool the surface of the planet by a few tenths of a degree for several years. These particles are an example of cooling aerosols. Volcanic particles from a single

eruption do not produce long-term change because they remain in the atmosphere for a much shorter time than GHGs.

## The Recent Role of Reflectivity

**Human changes** in land use and land cover have changed Earth's reflectivity. Processes such as deforestation, reforestation, desertification, and urbanization often contribute to changes in climate in the places they occur. These effects may be significant regionally but are smaller when averaged over the entire globe.

In addition, human activities have generally increased the number of aerosol particles in the atmosphere. Overall, human-generated aerosols have a net cooling effect offsetting about one-third of the total warming effect associated with human greenhouse gas emissions. Reductions in overall aerosol emissions can therefore lead to more warming. However, targeted reductions in black carbon emissions can reduce warming.

**Is there a scientific consensus on climate change?**

The major scientific agencies of the United States, including the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA), agree that climate change is occurring and that humans are contributing to it. In 2010, the National Research Council concluded that "Climate change is occurring, is very likely caused by human activities, and poses significant risks for a broad range of human and natural systems." Many independent scientific organizations have released similar statements, both in the United States and abroad. This doesn't necessarily mean that every scientist sees eye to eye on each component of the climate change problem, but broad agreement exists that climate change is happening and is primarily caused by excess greenhouse gases from human activities.

## Future Climate Change

Increasing greenhouse gas concentrations will have many effects. Greenhouse gas concentrations in the atmosphere will continue to increase unless the billions of tons of our annual emissions decrease substantially. Increased concentrations are expected to:

- Increase Earth's average temperature
- Influence the patterns and amounts of precipitation
- Reduce ice and snow cover, as well as permafrost

- Raise sea level
- Increase the acidity of the oceans

These changes will impact our food supply, water resources, infrastructure, ecosystems, and even our own health.

## Future changes will depend on many factors

The magnitude and rate of future climate change will primarily depend on the following factors:

- The rate at which levels of greenhouse gas concentrations in our atmosphere continue to increase
- How strongly features of the climate (e.g., temperature, precipitation, and sea level) respond to the expected increase in greenhouse gas concentrations
- Natural influences on climate (e.g., from volcanic activity and changes in the sun's intensity) and natural processes within the climate system (e.g., changes in ocean circulation patterns)

## Past and present greenhouse gas emissions effect on climate

Many greenhouse gases stay in the atmosphere for long periods of time. As a result, even if emissions stopped increasing, atmospheric greenhouse gas concentrations would continue to increase and remain elevated for hundreds of years. Moreover, if we stabilized concentrations and the composition of today's atmosphere remained steady (which would require a dramatic reduction in current greenhouse gas emissions), surface air temperatures would continue to warm. This is because the oceans, which store heat, take many decades to fully respond to higher greenhouse gas concentrations. The ocean's response to higher greenhouse gas concentrations and higher temperatures will continue to impact climate over the next several decades to hundreds of years. Because it is difficult to project far-off future emissions and other human factors that influence climate, scientists use a range of scenarios using various assumptions about future economic, social, technological, and environmental conditions.

## Future Temperature Changes

We have already observed global warming over the last several decades. Future temperatures are expected to change further. Climate models project the following key temperature-related changes.

### *Key Global Projections*

- Average global temperatures are expected to increase by 2°F to 11.5°F by 2100, depending on the level of future greenhouse gas emissions, and the outcomes from various climate models.
- By 2100, the average global temperature is expected to be warm at least twice as much as it has during the last 100 years.
- Ground-level air temperatures are expected to continue to warm more rapidly over land than oceans.
- Some parts of the world are projected to see larger temperature increases than the global average.

## Future Precipitation and Storm Events

Patterns of precipitation and storm events, including both rain and snowfall are also likely to change. However, some of these changes are less certain than the changes associated with temperature. Projections show that future precipitation and storm changes will vary by season and region. Some regions may have less precipitation, some may have more precipitation, and some may have little or no change. The amount of rain falling in heavy precipitation events is likely to increase in most regions, while storm tracks are projected to shift poleward. [4] Climate models project the following precipitation and storm changes

### *Key Global Projections*

- Global average annual precipitation through the end of the century is expected to increase, although changes in the amount and intensity of precipitation will vary by region.
- The intensity of precipitation events will likely increase on average. This will be particularly pronounced in tropical and high-latitude regions, which are also expected to experience overall increases in precipitation.
- The strength of the winds associated with tropical storms is likely to increase. The amount of precipitation falling in tropical storms is also likely to increase.
- Annual average precipitation is projected to increase in some areas and decrease in others. The figure to the right shows projected regional differences in precipitation for summer and winter.

## Future Ice, Snowpack, and Permafrost

Arctic sea ice is already declining. The area of snow cover in the Northern Hemisphere has decreased since about 1970. Permafrost temperature has increased over the last century. These are just three of the many forms of snow and ice found on Earth. To learn more about the different forms of snow and ice and how they affect the global climate system, visit the Snow and Ice page of the indicators section. Over the next century, it is expected that sea ice will continue to decline, glaciers will continue to shrink, snow cover will continue to decrease, and permafrost will continue to thaw. Potential changes to ice, snow, and permafrost are described below.

## Key Global Projections

For every 2°F of warming, models project about a 15% decrease in the extent of annually averaged sea ice and a 25% decrease in September Arctic Sea ice. The coastal sections of the Greenland and Antarctic ice sheets are expected to continue to melt or slide into the ocean. If the rate of this ice melting increases in the 21st century, the ice sheets could add significantly to global sea level rise. Glaciers are expected to continue to decrease in size. The rate of melting is expected to continue to increase, which will contribute to sea level rise.

## Future Sea Level Change

Warming temperatures contribute to sea level rise by expanding ocean water; melting mountain glaciers and ice caps; and causing portions of the Greenland and Antarctic ice sheets to melt or flow into the ocean. Since 1870, global sea level has risen by about 8 inches. Estimates of future sea level rise vary for different regions, but global sea level for the next century is expected to rise at a greater rate than during the past 50 years. The contribution of thermal expansion, ice caps, and small glaciers to sea level rise is relatively well-studied, but the impacts of climate change on ice sheets are less understood and represent an active area of research. Thus, it is more difficult to predict how much changes in ice sheets will contribute to sea level rise. Greenland and Antarctic ice sheets could contribute an additional 1 foot of sea level rise, depending on how the ice sheets respond.

Regional and local factors will influence future relative sea level rise for specific coastlines around the world. For example, relative sea level rise depends on land elevation changes that occur because of subsidence (sinking) or uplift (rising). If these historical geological forces continue, a 2-foot rise in the global sea level by 2100 would result in the following relative sea level rise:

- 2.3 feet in New York City
- 2.9 feet at Hampton Roads, Virginia
- 3.5 feet at Galveston, Texas

- 1 foot at Neah Bay in Washington state

Relative sea level rise also depends on local changes in currents, winds, salinity, and water temperatures, as well as proximity to thinning ice sheets.

## Future Ocean Acidification

Corals require the right combination of temperature, light, and the presence of calcium carbonate (which they use to build their skeletons). As atmospheric carbon dioxide ($CO_2$) levels rise, some excess $CO_2$ dissolves into ocean water, reducing its calcium carbonate saturation. As the maps indicate, calcium carbonate saturation has already been reduced considerably from its pre-industrial level, and model projections suggest much greater reductions in the future. The blue dots indicate current coral reefs. Note that under projections for the future, it is very unlikely that calcium carbonate saturation levels will be adequate to support coral reefs in any U.S. waters. Oceans become more acidic as carbon dioxide ($CO_2$) emissions in the atmosphere dissolve in the ocean. This change is measured on the pH scale, with lower values being more acidic.

The pH level of the oceans has decreased by approximately 0.1 pH units since pre-industrial times, which is equivalent to a 25% increase in acidity. Ocean acidification adversely affects many marine species, including plankton, mollusks, shellfish, and corals. As ocean acidification increases, the availability of calcium carbonate will decline. Calcium carbonate is a key building block for the shells and skeletons of many marine organisms. If atmospheric $CO_2$ concentrations double, coral calcification rates are projected to decline by more than 30%. If $CO_2$ concentrations continue to rise at their current rate, corals could become rare on tropical and subtropical reefs by 2050.

## Climate change affects all lives

**Our lives are connected to the climate.** Human societies have adapted to the relatively stable climate we have enjoyed since the last ice age which ended several thousand years ago. A warm climate will bring changes that can affect our water supplies, agriculture, power and transportation systems, the natural environment, and even our own health and safety.

**Some changes to the climate are unavoidable.** Carbon dioxide can stay in the atmosphere for nearly a century, so Earth will continue to warm in the coming decades. The warmer it gets, the greater the risk of more severe changes to the climate and Earth's system. Although it's difficult to predict the exact impacts of climate change, what's clear is that the climate we are accustomed to is no longer a reliable guide for what to expect in the future.

**We can reduce the risks we will face from climate change.** By making choices that reduce greenhouse gas pollution, we can reduce risks from climate change. Our decisions today will shape the world our children and grandchildren will live in.

## You Can Act

You can take steps at home, on the road, and in your office to reduce greenhouse gas emissions and the risks associated with climate change. Many of these steps can save you money; some, such as walking or biking to work can even improve your health! You can also get involved on a local or state level to support energy efficiency, clean energy programs, or other climate programs.

### Climate Change Policies

According to the Intergovernmental Panel on Climate Change (IPCC), to keep global warming below 2°C, emissions of carbon dioxide (CO2) and other greenhouse gases must be halved by 2050 (compared with 1990 levels). Developed countries will need to reduce more – between 80% and 95% by 2050; advanced developing countries with large emissions (e.g. China, India and Brazil) will have to limit their emission growth. Agreed in 1997, UNFCCC's Kyoto Protocol is a first step towards achieving more substantial global emission reductions. It sets binding emission targets for developed countries that have ratified it, such as the European Union (EU) Member States, and limits the emission increases of the remaining countries for the first commitment period from 2008 to 2012. The 15 pre-2004 EU Member States (the EU-15) have a joint emission reduction target of 8 % below 1990 levels. Through the internal EU "burden-sharing agreement", some EU Member States are permitted increases in emissions, while others must decrease them. Most Member States that joined the EU after 1 May 2004 have targets of -6 % to -8 % from their base years (mostly 1990).

EU emissions represent about 10% of total global emissions. The United States, which has a large share of total global GHG emissions, has not ratified the protocol. China and several other countries with large GHG emissions do not have binding emission targets under the protocol. Countries are expected to meet their target mainly through domestic policies and measures. They may meet part of their emission reduction targets by investing in emission-reducing projects in developing countries (the Clean

Development Mechanism (CDM)) or in developed ones (Joint Implementation (JI)). The CDM is also meant to support sustainable development, e.g. by financing renewable energy projects.

The **Cancún Agreements**, adopted at the UN Climate Conference in Mexico (December 2010), include a comprehensive finance, technology and capacity-building support package to help developing nations adapt to climate change and adopt sustainable paths to low-emission economies. The agreements also include a time schedule for reviewing the objective of keeping the average global temperature rising below 2 °C. The agreements confirm that developed countries will mobilize USD 100 billion in climate funding for developing countries annually by 2020 and establish a Green Climate Fund through which much of the funding will be channeled.

The **Durban Platform for Enhanced Action**, adopted at the UN conference in South Africa (Dec 2011) agreed a roadmap towards a new legal framework by 2015, applicable to all Parties to the UN climate convention. It also foresees a second commitment period of the Kyoto Protocol, starting in 2013. Agreement was also reached on the design and governance arrangements for the new **Green Climate Fund**.

## Adaptation to Climate Change

Adaptation means anticipating the effects of climate change and taking appropriate action to prevent or minimize the damage they can cause or exploit opportunities. Early action will save on damage costs later. Adaptation strategies are needed at all levels of administration, from the local to the international level. Adaptation affects most economic sectors and involves many levels of decision-making. It should be increasingly integrated in numerous policy areas: disaster risk reduction, coastal zone management, agriculture and rural development, health services, spatial planning, regional development, ecosystems and water management. Low-regret measures (suitable under every plausible scenario) and a variety of adaptation options should be considered, e.g. technological measures, ecosystem-based measures, and measures addressing behavioral changes. Adaptation measures include using scarce water resources more efficiently, adapting building codes to future climate conditions and extreme weather events, building flood defenses and raising the levels of dikes, developing drought-tolerant crops, choosing tree species and forestry practices less vulnerable to storms and fires, and setting aside land corridors to help species migrate.

# Chapter Twelve: Environmental Economics and Policies

## Objectives

- Define cost-benefit analysis.
- Explain why discounting is controversial.
- Explain the concept of external cost.
- Understand incentive policies, what they do, and their strengths and weaknesses.
- List the major international and US environmental laws and regulations.

## Introduction to Environmental and Natural Resource Economics

Environmental and natural resource economists study trade-offs associated with nature, considered one of the most important scarce resources. Efficiency in economics means maximizing social welfare, defined as total net benefits, which is the difference between total benefits from market goods/services and the total costs of producing them. Environmental economists enhance welfare definition by including values of environmental goods and costs of environmental damage.

## Market Efficiency

- Under ideal conditions, market outcomes are efficient, producing goods where marginal cost equals marginal benefit, maximizing net benefits.
- For non-renewable resources, efficient use implies that prices rise at the rate of interest, encouraging conservation and investment in alternatives, leading to a switch to backstop technologies when prices get too high.

## Market Failures and Deadweight Loss

- Market failures occur when conditions prevent market outcomes from maximizing social welfare, resulting in deadweight loss.
- Common in environmental settings due to externalities and public goods.

## Definition of Terms in environmental economics and policies

- **Externalities**: Costs or benefits not reflected in market transactions.
- **Negative Externality**: Cost not borne by the producer, leading to social costs exceeding private costs (e.g., pollution).

- **Positive Externality**: Benefit not borne by the producer, resulting in under-provision (e.g., environmental conservation efforts).

### *Public Goods and Common-Pool Resources*

- **Public Goods**: Non-exclusive and non-rival. Examples include clean air and national defense.
- **Common-Pool Resources**: Non-exclusive but rival. Examples include fisheries and forests.
- **Tragedy of the Commons**: Overuse of common-pool resources due to lack of exclusive ownership.

### *Incentive Policies*

- **Taxing Pollution**: Internalizes external costs, aligning private production costs with social costs. Taxes should be set at the social cost of externality but face challenges in setting the correct level and enforcement.
- **Tradable Permits**: Cap-and-trade systems set a cap on total pollution and allow trading permits, leading to cost-effective pollution reduction.

### *Discounting and Cost-Benefit Analysis*

- **Discounting**: Converts future costs/benefits into present values, affecting long-term environmental policy attractiveness.
- **Cost-Benefit Analysis**: Compares total present discounted values of costs and benefits of a policy/project. A project is favorable if net present value of the net is positive and the benefit/cost ratio exceeds one.

### *Evaluative Criteria for Policies*

- **Efficiency**: Maximizes net benefits by equating marginal benefits and costs.
- **Cost Effectiveness**: Achieves goals in the least expensive way.
- **Incentives to Innovate**: Encourages technological advancements to reduce environmental costs.
- **Fairness**: Considers equitable distribution of costs and benefits within society.

### *Economic Indicators and Alternatives*

- **GDP and GNP**: Measure economic output but not social/environmental conditions.
- **Human Development Index (HDI)**: Measures quality of life based on life expectancy, literacy rate, and per capita GNP.
- **Genuine Progress Index (GPI)**: Includes health, safety, environmental quality, pollution, and crime.

- **Environmental Performance Index (EPI)**: Tracks protection of human health from environmental harm and ecosystem protection.

### *Major Environmental Laws and Regulations*

*US Laws:*

- **Clean Air Act**: Regulates air emissions from stationery and mobile sources.
- **Clean Water Act**: Regulates discharges of pollutants into US waters.
- **Endangered Species Act**: Protects critically endangered species from extinction.
- **Resource Conservation and Recovery Act (RCRA)**: Controls hazardous waste from creation to disposal.

## International Agreements

- **Kyoto Protocol**: Sets binding emission reduction targets for developed countries.
- **Paris Agreement**: Aims to limit global warming to below 2°C above pre-industrial levels.
- **Convention on Biological Diversity (CBD)**: Promotes sustainable development and biodiversity conservation.

These expanded notes provide a comprehensive overview of key concepts in environmental economics and policies, emphasizing the importance of understanding and addressing market failures, externalities, and the need for effective environmental regulations and incentive policies.

## Historical Context and Development of Environmental Law

### *Early Legislation*

Efforts to legislate environmental controls can be traced back to ancient civilizations. In 2,700 B.C., the civilization in Ur enacted laws to protect the few remaining forests in the region. In 80 A.D., the Roman Senate passed a law to safeguard water reserved for essential urban functions, including street and sewer cleaning. In colonial America, Benjamin Franklin championed public rights laws to combat industrial pollution caused by tanneries in Philadelphia.

### *20th Century Onwards*

The early 20th century marked significant progress in environmental legislation in the United States. The **Antiquities Act of 1906** empowered the president to designate national monuments on federal lands, setting a precedent for the protection of natural resources. Alice Hamilton's early 20th-century advocacy for regulations on toxic industrial chemicals, although unsuccessful in banning lead in gasoline, highlighted the dangers of industrial pollution.

Rachel Carson's **"Silent Spring"** (1962) catalyzed public awareness and regulatory action on pesticides like DDT, emphasizing the need for government intervention to protect both wildlife and human health.

## Establishment of the EPA and Key Federal Laws

The establishment of the **Environmental Protection Agency (EPA)** in 1970 marked a pivotal moment in environmental law, transforming it into a specialized field. The EPA's creation was followed by the enactment of several cornerstone environmental laws:

- **National Environmental Policy Act (NEPA) (1969)**: mandates federal agencies to evaluate the environmental impacts of their actions via Environmental Impact Statements (EIS).
- **Clean Air Act (1970, 1977, 1990)**: Set national air quality standards and regulate emissions from various sources.
- **Clean Water Act (1972, 1977, 1987)**: Established water quality standards and regulated pollutant discharges into navigable waters.
- **Safe Drinking Water Act (1974, 1977, 1986)**: Set standards for drinking water quality and regulate pollutant discharges into underground sources.
- **Toxic Substances Control Act (1976)**: Allowed the EPA to regulate chemical substances and ensure their safety.
- **Resource Conservation and Recovery Act (1976)**: Provided comprehensive regulations for the management of hazardous waste.
- **Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (1980)**: Known as the Superfund program, it facilitated the cleanup of the most hazardous waste sites.

## State and International Efforts

Many states, such as California, enacted their own environmental laws and established agencies to enforce them. California's environmental regulations often preceded federal laws, including the state's early air quality programs and stringent vehicle emission standards.

Internationally, various treaties and conventions have addressed global environmental issues, albeit with varying degrees of enforcement success. Notable agreements include:

- **Montreal Protocol (1987)**: Phased out the production of ozone-depleting substances.
- **Rotterdam Convention (1998)**: Required informed consent for the international trade of hazardous chemicals.
- **Kyoto Protocol (1997)**: Aimed to reduce greenhouse gas emissions, although the United States ultimately did not ratify it.

Environmental laws have evolved significantly from early historical attempts to comprehensive modern regulations. These laws are designed to prevent, minimize, and remediate environmental damage while balancing the interests of economic development and environmental protection. The complexity of environmental law necessitates expertise in law, science, and public policy, highlighting the multifaceted approach required to address contemporary environmental challenges.

Environmental and natural resource economists study the tradeoffs associated with one of the most important scarce resources we have. Economists mean something very specific when they use the word **efficiently**. In general, an allocation is efficient if it maximizes social well-being, or **welfare**. Traditional economics defines welfare as total net benefits—the difference between the total benefits all people in society get from market goods and services and the total costs of producing those things. Environmental economists enhance the definition of welfare. The values of environmental goods like wildlife count on the "benefit" side of net benefits and damages to environmental quality from production and consumptive processes count as costs.

Under ideal circumstances, market outcomes are efficient. In perfect markets for regular goods, goods are produced at the point where the cost to society of producing the last unit, **the marginal cost**, is just equal to the amount a consumer is willing to pay for that last unit, the **marginal benefit**, which means that the net benefits in the market are maximized. Regular goods are supplied by industry such that supply is equivalent to the marginal production costs to the firms, and they are demanded by consumers in such a way that we can read the marginal benefit to consumers off the demand curve; when the market equilibrates at a price that causes quantity demanded to equal quantity supplied at that price, it is also true that marginal benefit equals marginal cost. Even non-renewable resources such as oil would be used efficiently by a well-functioning market. It is socially efficient to use a non-renewable resource over time such that the price rises at the same rate as the rate of interest.

Increasing scarcity pushes the price up, which stimulates efforts to use less of the resource and to invest in research to make “backstop” alternatives more cost-effective. Eventually, the cost of the resource rises to the point where the backstop technology is competitive, and the market switches from the non-renewable resource to the backstop. We see this with copper, high prices of non-renewable copper trigger substitution to other materials, like fiber optics for telephone cables and plastics for pipes. We would surely see the same thing happen with fossil fuels; if prices are allowed to rise with scarcity, firms have more incentives to engage in research that lowers the cost of backstop technologies like solar and wind power, and we will eventually just switch. Unfortunately, many conditions can lead to **market failure** such that the market outcome does not maximize social welfare. The extent to which net benefits fall short of their potential is called **deadweight loss**.

**Deadweight loss** is a societal cost that occurs when supply and demand are out of equilibrium, or when resources are allocated inefficiently. It's economic inefficiency that can be caused by several factors, including:

- **Price ceilings**: When producers can't charge enough per unit to make it worthwhile producing more, supply doesn't keep up with demand, and a shortage occurs.
- **Price floors**: Minimum wage and living wage laws are examples of price floors.
- **Taxes**: When the government taxes goods and services, the cost of production increases, which can lead to higher prices for consumers. This can cause production and consumer supply to drop, which creates a gap between taxed and tax-free production volumes.
- **Monopolies**: Monopolies can also lead to deadweight loss.

Deadweight loss can exist when not enough of a good is produced, or too much of a good is produced, or production is not done in the most cost-effective (least expensive) way possible, where costs include environmental damage. Some types of market failures (and thus deadweight loss) are extremely common in environmental settings.

## Externalities

In a market economy, people and companies make choices to balance the costs and benefits that accrue to them. These side effects can be seen as ways in which the actions of a producer impact the well-being of a bystander. The market fails to allocate adequate resources to address such side effects because it is only concerned with buyers and sellers, not with the well-being of the environment. When this is true economists say there are externalities, and individual actions do not typically yield efficient outcomes.

A **negative externality** is a cost associated with an action that is not borne by the person who chooses to take that action. When external costs occur, a company's private production cost and the social cost of production are at odds. The firm does not consider the cost of pollution cleanup to be relevant, while society does. The social costs of production include the negative effects of pollution and the cost of treatment. As a result, the social costs end up exceeding the private production costs. When external pollution and treatment costs are included in the production cost of the product, the supply curve intersects the demand curve at a higher price point. As a result of the higher price there will be less demand for the product and less pollution produced.

For example, exhaust pollutants from automobiles adversely affect the health and welfare of the human population. However, oil companies consider their cost of producing gasoline to include only their exploration and production costs. Therefore, any measures to reduce exhaust pollutants represent an external cost. The government tries to help reduce the problem of exhaust pollutants by setting emissions and fuel-efficiency standards for automobiles. It also collects a gasoline tax that increases the final price of gasoline, which may encourage people to drive less. Sometimes, pollution results from the production process because no property rights are involved. For example, if a paper manufacturer dumps waste in a privately owned pond, the landowner generally takes legal action against the paper firm, claiming compensation for a specific loss in property value caused by the industrial pollution. In contrast, the air and most waterways are not owned by individuals or businesses but instead are public goods. Because no property rights are involved, the generation of pollution does not affect supply and demand.

Firms have an incentive to use public goods in the production process because doing so does not cost anything. If the paper manufacturer can minimize production costs by dumping waste for free into the local river, then it will do so. The consequences of this pollution include adverse impacts on the fish and animal populations that depend on the water, degradation of the surrounding environment, decrease in the quality of water used in recreation and business, human health problems and the need for extensive treatment of drinking water by downstream communities. An important role of the government is to protect public goods, especially those with multiple uses, from pollution by companies seeking to minimize company costs and to maximize profits. People desire clean water for recreation and drinking, and the government must act to protect the broad interests of society from the narrow profit-driven focus of companies.

Other examples of negative externalities in environmental settings include:

- Companies that spill oil into the ocean do not bear the full costs of the resulting harm to the marine environment, which include everything from degraded commercial fisheries to reduced endangered sea turtle populations).
- Commuters generate emissions of air pollution, which lowers the ambient quality of the air in areas they pass through and causes health problems for other people.
- Developers who build houses in bucolic exurban settings cause habitat fragmentation and biodiversity loss, inflicting a cost on the public at large.

A **positive externality** is a benefit associated with an action that is not borne by the person who chooses to take that action. Positive externalities exist in the world of actions and products that affect the environment including:

- A homeowner who installs a rain barrel to collect unchlorinated rainwater for her garden also improves stream habitat in her watershed by reducing stormwater runoff.
- A delivery company that re-optimizes its routing system to cut fuel costs also improves local air quality by cutting its vehicle air pollution emissions.
- A farmer who plants winter cover crops to increase the productivity of his soil will also improve water quality in local streams by reducing erosion.

## Public Goods and Common-Pool Resources

Market outcomes are almost never efficient in two broad kinds of cases: public goods and common-pool resources. The market failures in these settings are related to the problems we saw with externalities. Pure public good is defined as being nonexclusive and nonrival in consumption. If something is nonexclusive, people cannot be prevented from enjoying its benefits. A private house is exclusive because doors, windows, and an alarm system can be used to keep non-owners out. A lighthouse, on the other hand, is non-exclusive because ships at sea cannot be prevented from seeing its light. A good that is nonrival in consumption has a marginal benefit that does not decline with the number of people who consume it. A sandwich is completely rival in consumption: if I eat it, you cannot. On the other hand, the beauty of a fireworks display is completely unaffected by the number of people who look at it. Some elements of the environment are pure public goods: Clean air in a city provides health benefits to everyone, and people cannot be prevented from breathing.

The efficient amount of public goods is still where social marginal benefit equals the marginal cost of provision. However, the social benefit of one unit of a public good is often very large because many people in society can benefit from that unit simultaneously. One lighthouse prevents all the ships in an area from running aground in a storm. In contrast, the social benefit of a sandwich is just the marginal benefit gained by the one person who gets to eat it. Society could figure out the efficient amount of public goods to provide, say, how much it would cost on cleaner cars that reduce air pollution in a city. Unfortunately, private individuals acting on their own are unlikely to provide an efficient amount of public goods because of the free rider problem.

## Tragedy of the commons

In contrast, a common-pool resource (also sometimes called an open-access resource) suffers from big multilateral negative external problems. This situation is sometimes called the "**tragedy of the commons**." Like public goods, common-pool resources are non-excludable. However, they are highly rival in use. Many natural resources have common pool features: Water in a river can be removed by anyone near it for irrigation, drinking, or industrial use; the more water one set of users removes, the less water there is available for others. Swordfish in the ocean can be caught by anyone with the right boat and gear, and the more fish are caught by one fleet of boats, the fewer remain for other fishers to catch. Old growth in a developing country can be cut down by many people, and slow re-growth means that the more timber one person cuts the less there is available for others. One person's use of a common-pool resource has negative effects on all the other users. Thus, these resources are prone to overexploitation.

One person in Indonesia might want to try to harvest tropical hardwood timber slowly and sustainably, but the trees they forebear from cutting today might be cut down by someone else tomorrow. The difficulty of managing common-pool resources is evident around the world in rapid rates of tropical deforestation, dangerous over-harvesting of fisheries, and battles fought over mighty rivers that have been reduced to dirty trickles. The tragedy of the commons occurs most often when the value of the resource is great, the number of users is large, and the users do not have social ties with one another, but common-pool resources are not always abused.

## Incentive Policies

Incentive policies try to make use of market forces for what they do best, allocating resources cost-effectively within an economy, while correcting the market failures associated with externalities, public goods, and common pool resources.

## Taxing Pollution

One way to "internalize" some of the external costs of pollution is for the government to tax pollution. A pollution tax would require that polluting firms pay a tax based on the air, water and land pollution that they generate. This tax would raise the private production cost of a company to include the social cost of production. In addition, the tax revenue generated could be used by the government to help mitigate the effects of pollution. Thus, if we think the social cost of tons of carbon dioxide (because of its contribution to climate change) is $20, then we could charge a tax of $20 per ton of carbon dioxide emitted. The easiest way to do this would be to have a tax on fossil fuels according to the amount of carbon dioxide that will be emitted when they are burned.

If a price is placed on carbon dioxide, all agents would have an incentive to reduce their carbon dioxide emissions to the point where the cost to them of reducing one more unit (their marginal abatement cost) is equal to the per unit tax. Therefore, several good things happen. All carbon dioxide sources are abating to the same marginal abatement cost, so the total abatement is accomplished in the most cost-effective way possible. Furthermore, total emissions in the economy overall will go down to a socially efficient level. Firms and individuals have very broad incentives to change things to reduce carbon dioxide emissions, reduce output and consumption, increase energy efficiency, switch to low carbon fuels, and strong incentives to figure out how to innovate so those changes are less costly. Finally, the government could use the revenue it collects from tax to correct any inequities in the distribution of the program's cost among people in the economy or to reduce other taxes on things like income. While taxes on externality-generating activities have many good features, they also have several drawbacks and limitations. **First**, while an externality tax can yield an efficient outcome (where costs and benefits are balanced for the economy as a whole), that only happens if policy makers know enough about the value of the externality to set the tax at the right level. If the tax is too low, we will have too much harmful activity; if the tax is too high, the activity will be excessively suppressed. **Second**, even if we can design a perfect externality tax in theory, such a policy can be difficult to enforce. The enforcement agency needs to be able to measure the total quantity of the thing being taxed. In some cases that is easy, in the case of carbon dioxide, for example, the fixed link between carbon dioxide emissions and quantities of fossil fuels burned means that through the easy task of measuring fossil fuel consumption we can measure many carbon dioxide emissions. However, many externality-causing activities or materials are difficult to measure in total. Nitrogen pollution flows into streams because of fertilizer applications on suburban lawns, but it is impossible to measure the total flow of nitrogen from a single lawn over the course of a year so that one could tax the homeowner for that flow. **Third**, externality taxes face strong political opposition from companies and individuals who don't want to pay the tax. Even if the government uses the tax revenues to do good things or to reduce other tax rates, the group that disproportionately pays the tax has an incentive to lobby heavily against such a policy. This phenomenon is at least partly responsible for the fact that there are no examples of pollution taxes in the U.S. Instead, U.S. policy makers have implemented mirror-image subsidy policies, giving subsidies for activities that reduce negative externalities rather than taxing activities that cause those externalities.

## Tradable Permits

Another major type of incentive policy is a tradable permits scheme. Tradable permits are actually very similar to externality taxes, but they can have important differences. These policies are colloquially known as "cap and trade." If we know the efficient amount of the activity to have (e.g., number of tons of pollution, amount of timber to be logged) the policy maker can set a cap on the total amount of the activity equal to the efficient amount. Permits are created such that each permit grants the holder permission for one unit of the activity. The government distributes these permits to the affected individuals or firms and gives them permission to sell them to one another. To follow the policy (and avoid punishment, such as heavy fines) all agents must hold enough permits to cover their total activity for the period. The government doesn't set a price for the activity in question, but the permit market yields a prize for the permits that gives all the market participants strong incentives to reduce their externality-generating activities, to make cost-effective trades with other participants, and to innovate to find cheaper ways to be complying.

Tradable permit policies have been used in several environmental and natural resource policies. The European Union used a tradable permit market as part of its policy to reduce carbon dioxide emissions under the Kyoto protocol. Individual tradable quotas for fish in fisheries of Alaska and New Zealand have been used to rationalize fishing activity and keep total catches down to efficient and sustainable levels. Economists do think differently about costs than engineers or other physical scientists, and several key insights about the economics of cost evaluation are important for policy analysis. Viewed through an inverse lens, all these ideas are important for benefit estimation as well.

## Discounting and Cost Benefit Analysis

Economists have developed a tool for comparing net benefits at different points in time called **discounting**. Discounting converts a quantity of money received at some point in the future into a quantity that can be directly compared to money received today, controlling for the time preference. A particular cost or benefit is worth less in present value terms the farther into the future it accrues and the higher the value of the discount rate. These fundamental features of discounting create controversy over the use of discounting because they make projects to deal with long-term environmental problems seem unappealing. The most pressing example of such controversy swirls around analysis of climate-change policy. Climate-change mitigation policies typically incur immediate economic costs (e.g. switching from fossil fuels to more expensive forms of energy) to prevent environmental damage from climate change for several decades in the future. Discounting lowers the present value of the future improved environment while leaving the present value of current costs largely unchanged.

**Cost-benefit analysis** is just that: analysis of the costs and benefits of a proposed policy or project. To carry out a cost-benefit analysis, one carefully specifies the change to be evaluated, measures the costs and benefits of that change for all years that will be affected by the change, finds the totals of the presented discounted values of those costs and benefits, and compares them. Some studies look at the difference between the benefits and the costs (the net present value), while others look at the ratio of benefits to costs. A “good” project is one with a net present value greater than zero and a benefit/cost ratio greater than one. The result of a cost-benefit analysis depends on many choices and assumptions. What discount rate is assumed? What is the status quo counterfactual against which the policy is evaluated? How are the physical effects of the policy being modeled? Which costs and benefits are included in the analysis, are non-use benefits left out? Good cost-benefit analyses should make all their assumptions clear and transparent. Cost-benefit analysis gives us a rough sense of whether a project is a good idea. However, it has many limitations. Here we discuss several other measures regarding whether a project is desirable. Economists use all these criteria and more when evaluating whether a policy is the right approach for solving a problem with externalities, public goods, and common-pool resources.

### *Efficiency*

A policy is efficient if it maximizes the net benefits society could get from an action of that kind. Such efficiency will occur when the marginal benefits of the policy are equal to its marginal costs. Sometimes a cost-benefit analysis will try to estimate the total costs and benefits for several policies with different degrees of stringency to try to see if one is better than the others. However, only information about the marginal benefit and marginal cost curves will ensure that the analyst has found the efficient policy. Unfortunately, such information is often very hard to find or estimate.

### *Cost Effectiveness*

It can be particularly difficult to estimate the benefits of environmental policy, and benefit estimates are necessary for finding efficient policies. Sometimes policy goals are just set through political processes—reducing sulfur dioxide emissions by 10 million tons below 1980 levels in the Clean Air Act acid rain provisions, cutting carbon dioxide emissions by 5% from 1990 levels in the Kyoto protocol—without being able to know whether those targets are efficient. However, we can still evaluate whether a policy will be cost effective and achieve its goal in the least expensive way possible. For example, for total pollution reduction to be distributed cost-effectively between all the sources that contribute pollution to an area (e.g. a lake or an urban airshed), it must be true that each of the sources is cleaning up such that they all face the same marginal costs of further abatement. If one source had a high marginal cost and another's marginal cost was very low, total cost could be reduced by switching some of the cleanup from the first source to the second.

### *Incentives to Innovate*

At any one point in time, the cost of pollution control or resource recovery depends on the current state of technology and knowledge. For example, the cost of reducing carbon dioxide emissions from fossil fuels depends in part on how expensive solar and wind power are, and the cost of wetland restoration depends on how quickly ecologists can get new wetland plants to be established. Everyone in society benefits if those technologies improve and the marginal cost of any given level of environmental stewardship declines. Thus, economists think a lot about which kinds of policies do the best job of giving people incentives to develop cheaper ways to clean and steward the environment.

### *Fairness*

A project can have very high aggregate net benefits but distribute the costs and benefits very unevenly within society. We may have both ethical and practical reasons not to want a policy that is highly unfair. Some people have strong moral or philosophical preferences for policies that are equitable. In addition, if the costs of a policy are borne disproportionately by a single group of people or firms, that group is likely to fight against it in the political process. Simple cost-benefit analyses do not speak to issues of equity. However, it is common for policy analyses to break total costs and benefits down among subgroups to see if uneven patterns exist in their distribution.

Studies can break down policy effects by income category to see if a policy helps or hurts people disproportionately depending on whether they are wealthy or poor. Other analyses carry out regional analyses of policy effects. For example, climate-change mitigation policy increases costs disproportionately for poor households because of patterns in energy consumption across income groups. Furthermore, the benefits and costs of such policy are not uniform across space in the U.S. The benefits of reducing the severity of climate change will accrue largely to those areas that would be hurt most by global warming (coastal states hit by sea level rise and more hurricanes, Western states hit by severe water shortages) while the costs will fall most heavily in regions of the country with economies dependent on sales of oil and coal.

Some of our evaluative criteria are closely related to each other; a policy cannot be efficient if it is not cost-effective. However, other criteria have nothing to do with each other; a policy can be efficient but not equitable, and vice versa. Cost-benefit analyses provide crude litmus tests; we surely do not want to adopt policies that have costs exceeding their benefits. However, good policy development and evaluation considers a broader array of criteria.

## Gross National Product and Its Alternatives

Most countries strive to increase their abilities to produce goods and services and consider doing so as a positive sign of development. Economic growth is stimulated by population growth, which in turn increases the consumption of natural resources and increases the per capita consumption of goods and services. Various indicators are used to measure economic growth. One of them is the Gross National Product (GNP), which represents the total market value of final goods and services produced by a country during a given period (usually one year). Unfortunately, GNP does not consider the global nature of many companies. If a company produces goods in a foreign country, then the "home" country does not really benefit from that production. Thus, if Pepsi bottles and sells soda in Japan, those revenues should not be included in the GNP of the United States. GDP (Gross Domestic Product) provides a better indicator of the health of a country's economy. This measure refers to the value of the goods and services produced within the boundaries of an economy during a given period.

Both the GNP and Gross Domestic Product (GDP) are economic measures and indicate nothing about social or environmental conditions within a country. They are not measures of the quality of life. In fact, severe environmental problems can raise the GNP and GDP, because the funds used to clean up environmental contamination (such as hazardous waste sites) help to create new jobs and increase the consumption of natural resources. Alternative systems to GDP have been suggested that are based on genuine wellbeing and progress. The UN Human Development Index is an estimate of the quality of life in a country based on three indicators: life expectancy, literacy rate and per capita GNP. The Genuine Progress Index (GPI) is based on measures that include health care, safety, clean environment, pollution and crime. The Environmental Performance Index (EPI) is based on indicators tracked in two categories: protection of human health from environmental harm and protection of ecosystems.

Although environmental laws are generally considered a 20th century phenomenon, attempts have been made to legislate environmental controls throughout history. In 2,700 B.C., the middle eastern civilization in Ur passed laws protecting the few remaining forests in the region. In 80 A.D., the Roman Senate passed a law to protect water stored for dry periods so it could be used for street and sewer cleaning. During American colonial times, **Benjamin Franklin** argued for "public rights" laws to protect the citizens of Philadelphia against industrial pollution produced by animal hide tanners.

Significant environmental action began at the beginning of the 20th century. In 1906, Congress passed the "Antiquities Act," which authorizes the president to protect areas of federal lands as national monuments. A few years later, **Alice Hamilton** pushed for government regulations concerning toxic industrial chemicals. She fought, unsuccessfully, to ban the use of lead in gasoline. She also supported the legal actions taken by women who were dying of cancer from their exposure to the radium then used in glow-in-the-dark watch dials. During the early 1960's, biologist **Rachel Carson** pointed out the need to regulate pesticides such as DDT to protect the health of wildlife and humans.

With the establishment of the **Environmental Protection Agency (EPA)** in 1970, environmental law became a field large enough to occupy lawyers on a full-time basis. Since then, federal and state governments have passed numerous laws and created a vast network of complicated rules and regulations regarding environmental issues. Moreover, international organizations and agencies including the **United Nations**, the **World Bank**, and the **World Trade Organization** have also contributed to environmental rules and regulations.

Because of the legal and technical complexities of the subjects covered by environmental laws, people dealing with such laws must be knowledgeable in the areas of law, science and public policy. Environmental laws today encompass a wide range of subjects such as air and water quality, hazardous waste and biodiversity. The purpose of these environmental laws is to prevent, minimize, remedy and punish actions that threaten or damage the environment and those that live in it. However, some people believe that these laws unreasonably limit the freedom of people, organizations, corporations and government agencies by placing controls on their actions.

## Federal Laws

Early attempts by Congress to enact laws affecting the environment included the **Antiquities Act** in 1906, the **National Park Service Act** in 1916, the **Federal Insecticide**, **Fungicide and Rodenticide Act** in 1947 and the **Water Pollution Control Act** in 1956. The **Wilderness Act** of 1964, protected large areas of pristine federal lands from development and ushered in the new age of environmental activism that began in the 1960's. However, it was the **National Environmental Policy Act (NEPA)** enacted in 1969 and the formation of the Environmental Protection Agency (EPA) in 1970 that started environmental legislation in earnest. The main objective of these two federal enactments was to ensure that the environment would be protected from both public and private actions that failed to consider the costs of damage inflicted on the environment.

Many consider NEPA to be the most far-reaching environmental legislation ever passed by Congress. The basic purpose of NEPA is to force governmental agencies to comprehensively consider the effects of their decisions on the environment. This is affected by requiring agencies to prepare detailed **Environmental Impact Statements** (EIS) for proposed projects. The EPA is the government's environmental watchdog. It is charged with monitoring and analyzing the state of the environment, conducting research, and working closely with state and local governments to devise pollution control policies. The EPA is also empowered to enforce those environmental policies. Unfortunately, the agency is sometimes caught up in conflicts between the public wanting more regulation for environmental reasons and businesses wanting less regulation for economic reasons. Consequently, the development of a new regulation can take many years.

Since 1970, Congress has enacted several important environmental laws, all of which include provisions to protect the environment and natural resources. Some of the more notable laws include:

- The **Federal Clean Air Act** (1970, 1977 & 1990) established national standards for regulating the emission of pollutants from stationery and mobile sources.
- The **Federal Water Pollution Control Act** (1972) amended by the **Clean Water Act** (1977, 1987), established water quality standards; provides for the regulation of the discharge of pollutants into navigable waters and for the protection of wetlands.
- The **Federal Safe Drinking Water Act** (1974, 1977 & 1986) set drinking water standards for levels of pollutants, authorizing the regulation of the discharge of pollutants into underground drinking water sources.
- The **Toxic Substances Control Act** (1976) provided for the regulation of chemical substances by the EPA and the safety testing of new chemicals.
- The **Resource Conservation and Recovery Act** (1976) established cradle-to-grave regulations for the handling of hazardous waste.
- The **Comprehensive Environmental Response**, **Compensation and Liability Act** (1980), also known as the **Superfund** program, provided for the cleanup of the worst toxic waste sites.
- The **Food Security Act** (1985, 1990) was later amended by the **Federal Agriculture Improvement and Reform Act** (1996), discouraged cultivation of environmentally sensitive lands, especially wetlands, and authorized incentives for farmers to withdraw highly erodible lands from production.

The application, or enforcement, of an environmental law is not always straightforward, and problems can arise. Often, the biggest problem is that Congress fails to allocate the funds necessary for implementing or enforcing the laws. Administrative red tape may make it impossible to enforce a regulation in a timely manner. It also may be unclear as to which agency (or branch of an agency) is responsible for enforcing a particular regulation. Furthermore, agency personnel decline to enforce a regulation for political reasons.

## State Laws

Most states, like California, have enacted their own environmental laws and established agencies to enforce them. California faced some of its first environmental challenges in the mid-1800's, regarding debris from the hydraulic mining of gold. Water quality concerns, dangers of flooding, negative impact on agriculture and hazards to navigation prompted the state to act. Some of California's environmental regulations preceded similar federal laws. For example, California established the nation's first air quality program in the 1950s. Much of the federal Clean Air Act amendments of 1990 were based upon the **California Clean Air Act of 1988**. California also pioneered advances in vehicle emission controls, control of toxic air pollutants and control of stationary pollution sources before federal efforts in those areas. The **Porter-Cologne Act of 1970**, upon which the state's water quality program is based, also served as the model for the federal Clean Water Act.

## International Treaties and Conventions

Conventions, or treaties, generally set forth international environmental regulations. These conventions and treaties often result from efforts by international organizations such as the **United Nations (UN)** or the **World Bank**. However, it is often difficult, if not impossible, to enforce these regulations because of the sovereign rights of countries. In addition, rules and regulations set forth in such agreements may be no more than non-binding recommendations, and often countries are exempted from regulations due to economic or cultural reasons.

Despite these shortcomings, the international community has achieved some success via its environmental agreements. These include an international convention that placed a moratorium on whaling (1986) and a treaty that banned the ocean dumping of waste (1991).
The UN often facilitates international environmental efforts. In 1991, the UN enacted an **Antarctica Treaty**, which prohibits the mining of the region, limits pollution of the environment and protects its animal species. The United Nations Environment Program (UNEP) is a branch of the UN that

specifically deals with worldwide environmental problems. It has helped with several key efforts at global environmental regulations:

- **The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer**. As a result of this global agreement, industrialized countries have ceased or reduced the production and consumption of ozone-depleting substances such as chlorofluorocarbons.
- **The Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade**. This agreement enhances the world's technical knowledge and expertise on hazardous chemicals management.
- **The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)**. This agreement protects over 30,000 of the world's endangered species.
- In 1995 **UNEP and the International Olympic Committee (IOC)** signed a partnership agreement to develop environmental guidelines for sports federations and countries bidding to host the Olympic games.
- **The Rotterdam Convention** (1998) addressed the growing trade in hazardous pesticides and chemicals. Importing countries must now give explicit informed consent before hazardous chemicals can cross their borders.
- **The International Declaration on Cleaner Production** (1998). The signatories commit to their countries to implement cleaner industrial production and subsequent monitoring efforts.

In 1992, the UN member nations committed their resources to limiting greenhouse gas (e.g., carbon dioxide) emissions at or below 1990 levels, as put forth by the **UN Framework Convention on Climate Change**. Unfortunately, the agreement was non-binding and by the mid-1990's, it had had no effect on carbon emissions. The 1997 **Kyoto Protocol** was a binding resolution to reduce greenhouse gases. Although the United States initially supported the resolution, the Senate failed to ratify the treaty, and by 2001 the resolution was opposed by President Bush as threatening the United States economy.

California's state environmental regulations are sometimes more stringent than the federal laws (e.g., the California Clean Air Act and vehicle emissions standards). In other program areas, no comparable federal legislation exists. For example, the California **Integrated Waste Management Act** established a comprehensive, statewide system of permitting, inspections, enforcement and maintenance for solid waste facilities and set minimum standards for solid waste handling and disposal to protect air, water and land from pollution. Also, **Proposition 65** (**Safe Drinking Water and Toxic Enforcement Act**) requires the Governor to publish a list of chemicals that are known to the State of California to cause cancer, birth defects or other reproductive harm.

Despite the state's leadership in environmental programs and laws, the creation of a cabinet-level environmental agency in California lagged more than two decades behind the establishment of the federal EPA. Originally, the organization of California's environmental quality programs was highly fragmented. Each separate program handled a specific environmental problem (e.g., the **Air Resources Board**), with enforcement responsibility falling to both state and local governments. It was not until 1991 that a California EPA was finally established and united the separate programs under one agency.

## The European Green Deal

The proposed financing of the EU Green Deal is set out in the EU Green Deal Investment Plan. It comprises two principal financing streams totaling €1 trillion. Over half of the budget, €528 billion, will come directly from the EU budget and the EU Emissions Trading System. The remainder will be sourced through the Invest EU program, which combines €279 billion from the public and private sectors to 2030 and €114 billion from national co-financing. It will provide an EU budget guarantee to allow the EIB Group and others to invest in higher-risk projects, enabling private investment. The European Innovation Council has also set aside a €300 million budget to invest in market-creating innovations that contribute to the goals of the EU Green Deal. There is recognition in the EU Green Deal that transition can only succeed if it is conducted in a fair and inclusive way. As a result, a Just Transition Mechanism is proposed to exclusively focus on the regions and sectors that are most affected by the transition. It draws upon both the EU budget and Invest EU program to generate €100 billion of funding. This will be available for the regions and sectors that depend on fossil fuels or carbon-intensive processes.

### *Elements of the EU Green Deal*

The main elements of the EU Green Deal are:

- Climate action.
- Clean energy.
- Sustainable industry.
- Buildings and renovations.

- Sustainable mobility.
- Eliminating pollution.
- Farm to Fork.
- Preserving biodiversity.
- Research and development.
- Preventing unfair competition from carbon leakage.

## Climate action

Between 1990 and 2018, greenhouse gas emissions in the EU were reduced by 23 per cent. A central objective of the EU Green Deal is to set out the trajectory for the EU to be climate neutral by 2050. As a milestone towards this target, the EU Commission proposed a 2030 target to reduce greenhouse gas emissions by 55 per cent compared to 1990. This 2030 target is proposed to be reflected in a European Climate, which will also enshrine the 2050 climate neutrality objective of the EU Green Deal in legislation.

The European Climate Law requires that all EU policies contribute to achieving the EU Green Deal objective. As a result, the EU Commission are reviewing every EU law to ensure its alignment with the EU emission reduction targets, under an exercise termed the "Fit for 55 packages." This lengthy process has already begun. A selection of the key legislation that the EU Commission proposes to revise considering the revised emissions reduction target is:

- the Renewable Energy Directive.
- the Energy Efficiency Directive.
- the Emissions Trading System.
- the Effort Sharing Regulation.
- the Land Use, Land Use Change and Forestry Regulation.
- the Energy Performance of Buildings Directive; and
- the Energy Taxation Directive.

This review is intended to be effective by the time Member States begin updating their national energy and climate plans in 2023, so that these plans reflect the new climate ambition.

### Clean energy

The production and use of energy across economic sectors currently accounts for more than 75 per cent of the EU's greenhouse gas emissions. The Clean Energy policy area aims to reduce this figure by developing a power sector based largely on renewable sources and an integrated, interconnected and digitalized EU energy market. The offshore renewable energy strategy encourages the investment of almost €800 billion between now and 2050 in offshore energy infrastructure and research. This should increase the EU's offshore wind capacity from its current level of 12 GW to 300 GW by 2050 and the EU's offshore ocean capacity from its current level of 13 MW to 40 GW by 2050. For further information about the offshore renewable energy strategy, please see our briefing: "EU sets out vision for offshore power."

The EU Hydrogen Strategy explores the potential of clean hydrogen to contribute to decarbonization. The adopted strategy promotes clean hydrogen innovation and the installation of hydrogen electrolyzers. The strategy includes a target to install at least 6 GW of green hydrogen electrolyzers within the EU, producing up to 1 million tons of hydrogen by 2024. By 2030 the ambition is to install at least 40 GW of electrolyzers, producing up to 10 million tons of hydrogen in the EU. The Clean energy for all Europeans package will facilitate the strategy for energy system integration, which aims to improve the coordination of planning and operation of the energy system 'as a whole', across multiple energy carriers, infrastructure, and end uses. The EU institutions will discuss the strategy that outlines a vision to create a smarter, more integrated energy system. A revision of the Trans-European Networks for Energy Regulation (the TEN-E Regulation) has also been proposed. The revised framework reflects the accelerated take-up of renewable energy sources, smart sector integration, the modernization of the EU's cross-border energy infrastructure and mandatory sustainability criteria for all projects. Together, these EU initiatives will work in synergy to lay the foundation for the decarbonized EU energy system.

## Sustainable industry

At present, industry accounts for 20 per cent of the EU's greenhouse gas emissions. The EU Green Deal therefore includes actions to strengthen the decarbonization efforts, ranging from product sustainability to the supply of raw materials. The adopted Circular Economy Action Plan presents initiatives to increase the duration of a product in order to alleviate pressure on natural resources. It includes a Sustainable Products Policy, which regulates the improvement of product reusability, reparability and integration of recycled contents. The aim of the adopted EU Industrial Strategy is to develop markets for climate neutral and circular products and to encourage the digital transition in the EU. The EU Green Deal notes that these measures are necessary to ensure the supply of the critical raw materials needed for clean technologies such as clean hydrogen, fuel cells and other alternative fuels, energy storage, and carbon capture, storage and utilization.

In relation to batteries, the European Commission's proposal for Sustainable batteries and a Regulation on batteries and waste batteries is seeking to strengthen the sustainability of supply chains and improve the recycling of industrial, automotive, electric vehicle and portable batteries placed on the market in the EU. The proposals include enhanced recycling targets, carbon footprint reporting requirements, moving to carbon intensity restrictions, as well as mandatory supply chain due diligence.

## Buildings and renovations

Buildings are responsible for approximately 40 per cent of the EU's energy consumption and 36 per cent of greenhouse gas emissions from energy. The objectives of the EU Green Deal require cleaner buildings and construction sectors. The Renovation Wave is a strategy to renovate buildings to increase their energy efficiency. It prioritizes the decarbonization of heating and cooling, tackling the worst performing building stock and the renovation of public buildings such as schools and hospitals. Energy efficiency in buildings will be a priority, and the EU Commission will explore the possibility of including emissions from buildings in the EU Emissions Trading System (EU ETS).

The EU Commission is also reviewing the Construction Products Regulation which sets the requirements for construction products in the Internal Market. A revised regulation has the potential to promote environmental goals and possibly product safety. In parallel, the EU Commission proposes to work on an open platform bringing together architects, engineers and local authorities to address the barriers to renovation. It could target energy service companies that could roll out renovation, such as through energy performance contracting. The reforms are intended to optimize the development of innovative financing in the construction sector and the promotion of energy efficient investments in buildings.

## Sustainable mobility

The Sustainable Mobility policy area comprises initiatives to reduce transport emissions, which account for 25 per cent of the EU's greenhouse gas emissions. The adopted Strategy for Sustainable and Smart Mobility lays the foundation for action to transform the EU transport sector, with the aim of a 90 per cent cut in emissions by 2050, delivered by a smart, competitive, safe, accessible and affordable transport system. Increased capacity and decreased congestion and pollution could all be attained because of efforts to promote more sustainable means of transport. The strategy sets several targets to 2030 including:

- At least 30 million zero-emission cars will be in operation on European roads.
- 100 European cities will be climate neutral.
- high-speed rail traffic will double across Europe.
- scheduled collective travel for journeys under 500 km should be carbon neutral.
- automated mobility will be deployed at large scale; and
- zero-emission marine vessels will be market-ready, with further targets to 2035 and 2040.

To meet these objectives, several proposals for revised legislation are being considered. One aspect is the review of the Directive on the Deployment of Alternative Fuel Infrastructure, which sets the requirements for expanding the EU's network of recharging and refueling stations for alternative vehicle fuels such as electric batteries and hydrogen. The Regulation setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles may also be revised in light of the EU carbon neutrality target. The revision would entail stricter emissions standards for road vehicles. The EU Commission also plans a revision of the Regulation on the trans-European transport network (the TEN-T Regulation) and of the Directive on intelligent transport systems. This aims to increase the uptake of zero-emission vehicles, make sustainable alternative solutions and support digitalization and automation.

Batteries will be important for electric vehicle deployment, as well as in energy system transformation. As a result, EU policy is also focused on sustainable battery supply chains covering the entire battery life-cycle, including recycling and re-use. In its proposal for a Regulation on batteries and waste batteries, the European Commission is seeking to strengthen the sustainability of supply chains and improve the recycling of industrial, automotive, electric vehicle and portable batteries placed on the market in the EU. The EU ETS has proved effective in the sectors in which it operates. Part of the EU Commission work plan includes the revision of the EU ETS rules for the aviation sector including a review of the proposals to reduce free allowances allocated to the sector. The update would involve carbon offsetting and a reduction scheme for international aviation. Moreover, the EU Commission proposes extending the EU ETS to the maritime sector and, subject to impact assessment, to road transport.

## Eliminating pollution

Pollution is the largest environmental cause of multiple mental and physical diseases, and of premature deaths. It is also a significant driver of biodiversity loss. Therefore, the EU Commission has proposed a Zero pollution action plan. This proposes that pollution elimination measures are incorporated into all policy developments and steps are taken to further decouple economic growth from the increase of pollution. The action plan comprises three headline actions on eliminating pollution. Firstly, a Chemical strategy for sustainability to protect the environment against hazardous chemicals. Second, a Zero pollution action plan for water, air and soil, to better prevent, remedy, monitor and report on pollution. Finally, the revision of measures to address pollution from large industrial installations to ensure that they are consistent with related EU Green Deal objectives. A revision of the Regulation on substances that deplete the ozone layer is also envisaged.

## Farm to Fork

Food systems handle around 21-37 per cent of global greenhouse gas emissions and use up significant natural resources. The Farm to Fork strategy aims to address these environmental issues as well as fairness, sustainability of the food system and the health of Europeans. The strategy will focus on reducing waste, and transforming the manufacturing, processing, retailing, packaging and transportation of food. The Farm to Fork strategy proposes to spend €10 billion on research and innovation on food, bioeconomy, natural resources, agriculture, fisheries, aquaculture and the environment, as well as digital technologies and nature-based solutions for agri-food, funded by Horizon Europe, the EU's research and innovation framework program. EU policies and legislation will focus on trade policy to obtain commitments from third countries in areas such as animal welfare, the use of pesticides and the fight against antimicrobial resistance. The Commission and food-chain stakeholders are developing an EU Code of conduct for responsible business and marketing practice as well as seeking commitments from food companies and organizations to start taking steps towards improving health, sustainability and the environment. Reform of the common agricultural policy (CAP) is also envisaged.

Separately, the EU Commission has proposed a Strategy to reduce methane emissions. Methane is the second biggest contributor to climate change after carbon dioxide and contributes to air pollution. Reducing methane emissions requires a cross-sector approach: in the EU, 53 per cent of anthropogenic methane emissions come from agriculture, 26 per cent from waste and 19 per cent from energy. The Methane strategy focuses on adequate reporting and opportunities for biogas production, as well as specific measures in the energy, agriculture and waste sectors.

## Preserving biodiversity

In the last 40 years, the population of wild species has fallen by 60 per cent due to human activities. The EU Biodiversity strategy for 2030 identifies the key drivers in biodiversity loss as changes in land and sea use, overexploitation, climate change, pollution, and invasive alien species. Biodiversity loss and climate change are intrinsically linked, and nature-based solutions will play an important role in mitigating, and adapting to, climate change. The European Commission identifies that the industries highly dependent on biodiversity are the construction, agriculture and food and drink sectors. The EU Biodiversity strategy will work in tandem with the Farm to Fork strategy by focusing on restoring forests, soil and wetlands and creating green spaces in cities. To address legislative gaps that hinder improving biodiversity standards across the EU, the EU will implement a new biodiversity governance framework. This framework includes imposing legally binding nature-restoration targets to restore degraded ecosystems, to be achieved by fully implementing the EU Pollinators initiative and the Habitats Directive, as well as via the CAP.

The European Commission estimates that €20 billion per year is needed to fund the biodiversity strategy. This will require the use of a combination of public and private funding on a national and EU level as well as from the EU budget. Part of the Renewed Sustainable Finance Strategy will focus on ensuring the financial system contributes to mitigating existing and future risks to biodiversity, recognizing the risk that biodiversity loss poses to the financial prospects of many sectors of the economy.

## Research and development.

Research and development underpin each element of the EU Green Deal. Many of the EU Green Deal initiatives require harnessing new technologies and transforming financial models and supply chains. Many research and development initiatives will be funded by Horizon Europe, which has pledged over 35 per cent of its €95.5 billion budget to achieving EU climate objectives. Under Horizon Europe, the EU will form green partnerships with various industries and its member states to focus on key areas such as batteries, clean hydrogen, low-carbon steel, the built environment and biodiversity.

## Preventing unfair competition from carbon leakage

The EU Green Deal will require significant reorientation of the EU economy towards a low carbon model. This brings with it the risk of carbon leakage. The EU Commission has identified this as the risk that either production is transferred from the EU to other countries with lower ambition for emission reduction, or that EU products are replaced by more carbon-intensive imports. Carbon leakage is currently controlled by the free allocation of allowances under the EU ETS, or compensation for energy intensive industries impacted by higher electricity costs because of carbon pricing under the EU ETS. The EU Commission is therefore proposing a Carbon Border Adjustment Mechanism to ensure that the price of imports reflects more accurately their carbon content. This measure is proposed to be designed to comply with World Trade Organization rules and other international obligations of the EU.

*Credit to Alysha Patel and Tay Robinson for their contributions.*

## Regenerative Agriculture and the Environment

Regenerative agriculture is a conservation-focused farming approach that aims to restore and enhance soil health, biodiversity, and ecosystem resilience. Unlike conventional methods that often degrade land over time, regenerative practices, such as cover cropping, reduced tillage, compost application, rotational grazing, and agroforestry, work in harmony with natural systems. These methods improve soil structure and fertility, increase water retention, and promote carbon sequestration, thereby reducing greenhouse gas emissions. Regenerative agriculture plays a critical role in reversing environmental degradation by rebuilding topsoil, restoring degraded landscapes, enhancing biodiversity, and improving the overall sustainability of food production systems. As such, it offers a promising solution to many pressing environmental challenges, including climate change, soil erosion, and water scarcity.

**Note:**

- Uncredited images were generated using artificial intelligence.
- Various artificial intelligence platforms and tools were used to organize the materials.
- The following resources were used to corroborate the notes that the author has gathered over time for his regular instructional lectures.

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