TEACHER BACKGROUND

1.0 INTRODUCTION

We are fortunate to live in a society with abundant food. Most of us take for granted that we will always have enough to eat. If we do have any concerns about food, more than likely they relate to its nutritional value or to reducing the epidemic of obesity. Many of us have never visited a working farm, let alone tried to understand the techniques that farmers use to grow our food. A by-product of the success of modern agriculture is a society where the efforts of the few are adequate to feed the many. This situation allows the vast majority of people to engage in diverse occupations without worrying about the need to grow food to feed their families.

Of course, it has not always been this way. For most of human history, the world's population increased at a steady but slow rate. However, during the last 100 years, the rate of population growth increased to such an extent that more-efficient farming methods were not just desirable but essential to avoid massive famine. In 1950, the world's population reached 3 billion people. The population then doubled in just 50 years. The implementation of farming practices such as the increased use of commercial fertilizers to replenish soil nutrient deficiencies accompanied this rapid population growth. During this so-called Green Revolution, crop yields increased enough to keep pace with the demand for food.

In 1950, 1.7 billion acres of farmland were used to produce 692 million tons of grain. By 1992, essentially the same acreage produced 1.9 billion tons of grain.[10] Not only did the Green Revolution help feed our growing population; it also limited the amount of land that was cultivated to raise crops. If populous India had not used the high-yielding crops developed during the Green Revolution, then it would have had to farm additional acreage about the size of California to produce the same quantity of grain.[5]

However, the advances of the Green Revolution have almost reached their potential for increasing crop yields. At the same time, the human population shows no inclination to stop growing. It is estimated that by 2050, the world's population will increase from its present 7.1 billion people to approximately 9.6 billion people.[23] How will all of these people be fed? Most of the land suitable for farming is already being tilled. We have no choice but to explore other ways of increasing crop yields and sustaining the quality of our soil.

The challenge for the future is simple. We must feed a population that grows by 80 million people each year, using the same amount of farmland. Clearly, the farming practices of the past are not going to be able to sustain us in the future. Our response to this challenge involves making difficult decisions about land use, fertilizers, pesticides, and genetic engineering, among others. As a society, we will have to decide how agriculture can economically feed our growing population while at the same time help us protect our environment.

These issues will become increasingly important in the decades to come. As today's young people become adults and enter the workforce, they will be asked to make decisions regarding the use of natural resources such as farmland. Hopefully, they will make rational decisions about using technology to benefit society while minimizing its negative impacts. The aim of the *Nourishing the Planet in the 21st Century* module is to help prepare students to meet the challenges of the future. The lessons are designed to enhance students' basic understanding of plant biology and the process of scientific inquiry. They help develop critical-thinking skills in the real-world context of sustainably nourishing the planet's growing population. The module focuses on nutrients: exploring what they are, why they are important, where they come from, what their impacts are, and how they can be managed.

2.0 PLANTS AND THEIR ESSENTIAL ELEMENTS

All organisms must take in matter from their environment in order to survive. There are 92 naturally occurring elements on Earth. Living things need only a minority of them. For example, humans require about 21 different elements to be healthy.[8] Almost all of the mass of our bodies comes from just six of those elements **(CARBON, HYDROGEN, OXYGEN, NITROGEN, PHOSPHORUS,** and **CALCIUM).** These are the elements used to construct the carbohydrates, nucleic acids, proteins, and other molecules that make up our cells and carry out their chemistry. Other elements critical to our health are needed in very small amounts. Often, such elements are cofactors required by enzymes to catalyze specific chemical reactions. Regardless of whether elements are needed in large or small amounts, they must be obtained from the environment. Furthermore, it not enough that essential elements are present in the environment; they must be available in a chemical form that our bodies can use.

Not surprisingly, the situation in plants is similar. They, too, must carry out thousands of different chemical reactions, many of which are similar to those of humans. Scientists have identified 17 elements that are essential for plants *(see Table 9)*.[8] An element is described as being essential to the plant if the following conditions are met:

- The element must be required by the plant to complete its life cycle.
- The element cannot be replaced by another element.
- The element must be required for a specific biological function.[1]
- The element must be required by a substantial number of different plant species.

Essential elements can be classified as mineral or non-mineral nutrients. Carbon, hydrogen, and oxygen are classified as non-mineral nutrients because they are obtained from the atmosphere and water. Mineral nutrients can be further classified as being either macronutrients or micronutrients. As the name implies, macronutrients are needed in relatively large amounts. Nitrogen, phosphorous, and potassium are called primary macronutrients, while calcium, sulfur, and magnesium are called secondary macronutrients. The rest of the essential elements are called micronutrients because they are needed in small amounts. It is important to note that despite their name, micronutrients are just as essential to plant health as are macronutrients.

Plants absorb most of their essential elements from water in the soil. Usually the essential elements are taken up as a positively charged cation or a negatively charged anion.

TABLE 9. ESSENTIAL PLANT NUTRIENTS

ELEMENT TAKEN INTO THE PLANT	SYMBOL	CLASSIFICATION	CHEMICAL FORM
Hydrogen	H	Nonmineral nutrient	H_2O
Oxygen	O	Nonmineral nutrient	O_2 and CO_2
Carbon	C	Nonmineral nutrient	CO_2
Nitrogen	N	Primary macronutrient	NH_4+ and NO_3-
Phosphorus	P	Primary macronutrient	H_2PO_4- and HPO_{42}-
Potassium	K	Primary macronutrient	K+
Calcium	Ca	Secondary macronutrient	Ca_2+
Magnesium	Mg	Secondary macronutrient	Mg_2+
Sulfur	S	Secondary macronutrient	SO_{42}-
Boron	B	Micronutrient	$B(OH)_3$
Chlorine	Cl	Micronutrient	Cl-
Copper	Cu	Micronutrient	Cu_2+
Iron	Fe	Micronutrient	Fe_2+ and Fe_3+
Manganese	Mn	Micronutrient	Mn_2+
Molybdenum	Mo	Micronutrient	MoO_{42}-
Nickel	Ni	Micronutrient	Ni_2+
Zinc	Zn	Micronutrient	Zn_2+

3.0 THE NITROGEN CYCLE

Although the atmosphere is about 78 percent nitrogen, plants cannot make use of nitrogen gas (N_2). Instead, plants need to obtain their nitrogen by taking up the cation ammonium (NH_4+) or the anion nitrate (NO_3–) in the soil. These ionic forms of nitrogen are generated by the breakdown of organic material in the soil or through a process called nitrogen fixation that is carried out by soil microbes. Some crop plants (legumes such as peas, beans, peanuts, and soybeans) live in close association with nitrogen-fixing bacteria that live in their roots and convert N_2 gas to a form that plants can use. Such crops have a steady source of nitrogen and do not require nitrogen-containing fertilizers.

The nitrogen cycle describes the processes by which nitrogen moves between its various chemical forms. Biological or physical processes can cause these chemical conversions. Four processes are essential to the nitrogen cycle.

- **NITROGEN FIXATION** refers to the process by which atmospheric nitrogen (N_2) is converted to nitrogen–containing compounds that are usable by plants. Nitrogen fixation can be accomplished through the action of lightning or bacteria in the soil.
- **AMMONIFICATION** refers to the process by which bacteria and fungi convert decomposed nitrogen-containing compounds into ammonium ions (NH_4+).
- **NITRIFICATION** refers to the process by which bacteria convert ammonium ions into nitrite (NO_2-). Other bacteria convert nitrite to nitrate (NO_3-). This is important because nitrites can reach levels that are toxic to plants.
- **DENITRIFICATION** refers to the process by which bacteria convert nitrates back to N_2.

So, let us summarize the nitrogen cycle. First, recall that plants cannot use the nitrogen in the air that is so plentiful. When plants and animals die and decompose, they add nitrogen to the soil. Bacteria in the soil convert the nitrogen into compounds that plants can use. Plants take in these nitrogen-containing compounds through their roots and use them to grow. Animals eat the plants, use the nitrogen, and return it to the soil when they die and decompose.

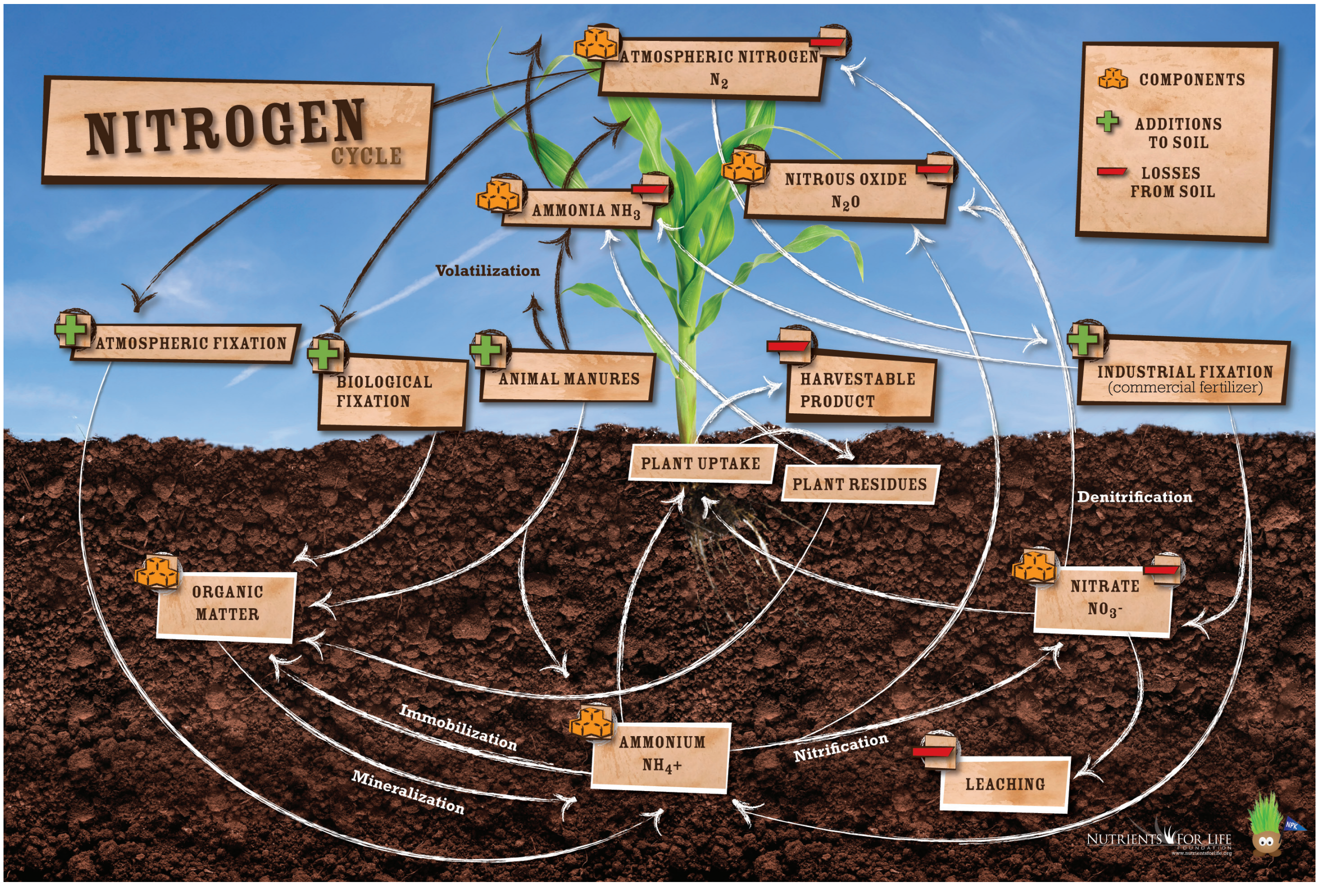

FIGURE 1. THE NITROGEN CYCLE DESCRIBES THE RELATIONSHIPS BETWEEN DIFFERENT FORMS OF NITROGEN IN THE ENVIRONMENT.

4.0 SOIL FORMATION

Most people take soil for granted. In fact, "soil" has a negative connotation. We call it dirt and wash it off our clothes and our bodies. In reality, soil is essential to our survival and that of nearly every organism on Earth. Our planet is mostly made of rock with an iron-nickel core. Plants and animals, including us, occupy a thin veneer on its surface. Our existence is possible because of a thin layer of soil that comes between the planet's rocky interior and us.

Soils vary. They are natural expressions of the environment in which they form. Scientists recognize five main factors that influence soil formation: **1) PARENT MATERIAL, 2) CLIMATE, 3) LIVING ORGANISMS, 4) TOPOGRAPHY,** and **5) TIME.**[2]

PARENT MATERIAL

Parent material refers to both the organic and mineral material in which soil formation takes place. Mineral can include weathered rock, ash from volcanos, and sediments deposited by wind and water. Soil formation will happen more quickly in materials that are more permeable to water.

CLIMATE

Climate influences the amount of water available for weathering the parent material and the temperature at which it occurs. A warm, moist climate fosters plant growth and speeds up decomposition, both of which contribute to faster soil formation.

LIVING ORGANISMS

Plants supply soil with organic material and help prevent erosion. Deep-rooted plants have a greater impact on soil formation than shallow-rooted plants because they create larger channels for water movement. Insects, earthworms, fungi, and bacteria are important because they help decompose organic material releasing plant nutrients.

TOPOGRAPHY

The three dimensional shape of the land influences water movement and therefore the speed of soil formation. Since water flows downward due to gravity, soils on slopes are prone to erosion. Areas that are very wet or very dry may not be fertile and the resulting lack of plant growth can slow the rate of soil formation.

TIME

The weathering of rock slowly produces soils. Constant exposure to wind and rain cause the rocky crust to break slowly down into smaller particles. It can take centuries to produce fertile topsoil. As rainwater seeps into cracks, temperature extremes cause the water to freeze. The rock expands, contracts, and fractures. Organisms that live on and in the soil help these weathering actions along.

Of course, in addition to these five factors, human activity also can influence soil formation. Agricultural practices and urban development especially can interfere with the naturally occurring process of soil formation.

5.0 SOIL HORIZONS

The gradual process of soil formation produces a series of horizontal layers. A soil horizon is a layer generally parallel to the soil surface, whose physical and chemical characteristics differ from the layers above and beneath. A given type of soil usually has three or four horizons. Horizons are characterized by the obvious physical characteristics of color and texture. The formation of soil horizons is influenced by factors such as air, water, sunlight, and plant material. The weathering of the parent material occurs first at the surface and then works its way downward. This means that the uppermost layers are changed (weathered) the most, while the deepest layers are the most similar to the original parent material.

To visualize the soil horizons, scientists dig a hole several meters deep to expose the layers. Most soils display a similar pattern of horizons. Each horizon is labeled with its own capital letter that identifies its place. A typical soil horizon sequence is described as **O-A-B-C-R.**[18]

- **O** refers to organic matter that is relatively undecomposed and lies on the surface.
- **A** refers to organic material mixed with mineral that makes up the surface soil.
- **B** refers to the subsoil. This layer reflects the chemical and physical alteration of the original parent material.
- **C** refers to the parent material
- **R** refers to the bedrock. The R layer is mostly composed of hard rock that cannot be excavated by hand.

FIGURE 2. PHOTO SHOWING SOIL HORIZONS

6.0 SOIL TRIANGLE

During soil formation, inorganic material is broken down by weathering into particles of various sizes. Soil texture refers to the relative proportions of different-sized particles found in the soil. Scientists classify soil particles into three categories. The smallest particles, which measure less than 0.002 millimeters, are called clay.[9] Clay is important in holding nutrients. Clay particles form plate-like structures that attract and hold nutrients through chemical bonds. These nutrients can be displaced off the clay by another nutrient, absorbed by a plant root or soil microbe, or chemically absorbed into the clay particle itself. The next-largest particles are called silt. Silt particles range in size from 0.002 millimeters to 0.06 millimeters. Sand refers to the largest particles. Sand grains range in size from 0.06 millimeters to 2 millimeters. Soils vary in their proportions of clay, silt, and sand. Soil scientists classify different soil types using the soil triangle. Each side of the soil triangle represents the amount of a particle of a certain size—clay, silt, or sand. The relative amounts of these three soil components intersect within the triangle and determine to what type of soil those proportions correspond.

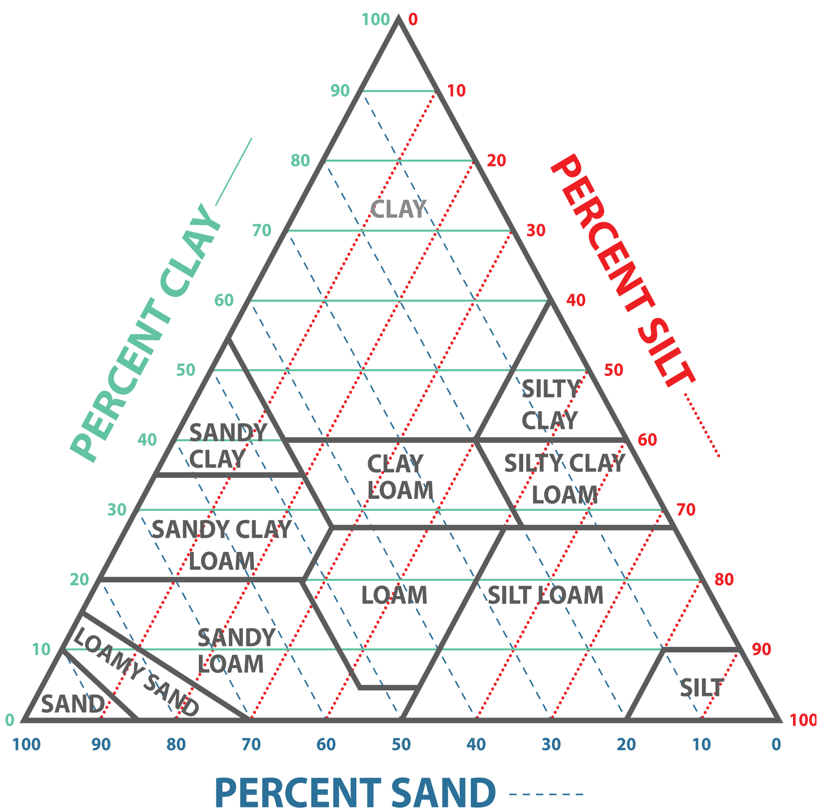

FIGURE 3. THE SOIL TRIANGLE IS USED TO CLASSIFY SOIL TYPES.

The ability of a soil to accept and retain water is largely determined by the relative amounts of clay, silt, and sand present. Porosity refers to spaces in the soil that can hold either air or water. Permeability is defined as the rate at which water can travel through soil. *Table 10* lists properties of particle size that relate to soils' interactions with water. Soils with desirable properties for farming are called loams. Loamy soils typically contain about 50 percent air space, which allows root systems to "breathe" (i.e., obtain O_2 for respiration). The solid half of loamy soils is about 90 percent minerals and 10 percent organic material. Usually, loamy soils have names that more accurately reflect their composition, such as clay loam or silt loam.

TABLE 10. PROPERTIES OF SOIL PARTICLES

PROPERTY	CLAY	SILT	SAND
POROSITY	Mostly small pores	Mostly small pores	Mostly large pores
PERMEABILITY	Slow	Slow to moderate	Rapid
WATER-HOLDING CAPACITY	Large	Moderate	Limited

Although the organic fraction of most soils is small in volume compared to the mineral fraction, it plays an important role in supporting plant growth. The organic material is composed of living organisms, plant roots, and plant and animal residue. A single gram of healthy topsoil may contain 100 nematodes (small roundworms), 1 million fungi, and 1 billion bacteria.[27] Earthworms and a wide variety of insects may be present in smaller numbers. Organic material contains a significant amount of nutrients, and it, together with plant roots, helps

- decrease erosion;
- increase water infiltration and storage;
- act as a pH buffer (to maintain an acid-base balance);
- decompose organic material, releasing nutrients;
- recycle carbon, nitrogen, and other nutrients; and
- retain available nutrients such as metal ions.

The soil is a "bank" for nutrients that are taken up by plants, and these nutrients must be replenished for continued plant growth. Before the advent of modern agriculture, farmers relied solely upon tillage to break down existing organic material and release existing soil nutrients. This practice is still used in many less-developed countries.

7.0 PLANT-SOIL INTERACTIONS

Plants use their root systems for structural support, stability, and nourishment. If you have ever seen a tree toppled by high winds, you have some idea of why trees are so stable. The primary function of the root system is to absorb water and nutrients from the soil. To do this, the root system is ever changing over the course of the plant's life, capable of growing year-round, if conditions for growth are met and there is not competition from the plant's top system. Roots also may serve as storage organs for starch or sugars. Carrots, beets, radishes, turnips, and potatoes are examples of storage roots.

The growth of roots is similar to the growth of shoots. However, there are important differences. In general, the more extensive a root system is, the more water and nutrients it can absorb. If you examine a root using a magnifying glass, you will see a large number of delicate root hairs growing out from the surface of the root *(see Figure 4)*. This system of root hairs greatly increases the surface area of the root available to contact and absorb water. A single rye plant 60 centimeters tall is estimated to have a root system with a total length of 480 kilometers. Its surface area is more than 600 square meters—twice that of a tennis court![6]

The tip of an actively growing root is called the root cap *(see Figure 5)*. The root cap produces a slimy secretion called mucilage that helps lubricate the root as it pushes its way through the soil. Just behind the root cap is the zone of active cell division, and behind it is a zone of cell elongation. The cells of the elongation zone grow by taking in water and swelling. The root cells contain salt and sugars. Because the root cells contain more solutes than the water in the soil, water flows into the cells by diffusion. This causes the cells to elongate, forcing the root deeper into the soil. Behind the elongation zone is the zone of cell differentiation. The cells in this area give rise to the cells of the vascular system, which transport water up the stem and sugars down from the leaves.

Roots may stop growing during the winter not because they have become dormant like the buds at the top of the plant, but rather because the temperature is too cool to support growth. In order for roots to grow, they must have adequate moisture and temperature. Many people are under the misconception that roots grow in search of water. This is not the case. Roots can only grow where the conditions are suitable for growth. This means that roots grow where water is already present.

FIGURE 4. A RADISH SEEDLING SHOWING ROOT HAIRS

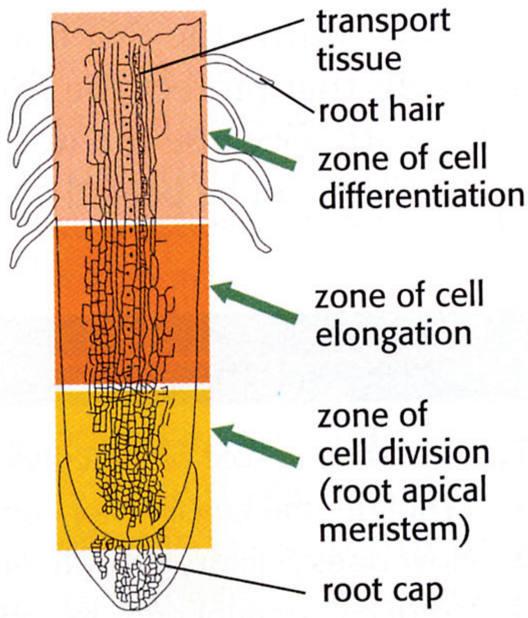

FIGURE 5. A LONGITUDINAL SECTION OF A ROOT TIP

The transport of water and nutrients into, within, and out of a plant depends on three important processes:

DIFFUSION refers to the movement of a liquid or gas from a region of higher concentration to one of lower concentration. This movement is a natural consequence of random molecular movement and does not require added energy to accomplish. During photosynthesis, carbon dioxide moves down its concentration gradient to enter a leaf cell. At the same time, oxygen moves down its concentration gradient to exit the leaf cell.

OSMOSIS is a process similar to diffusion but refers to the movement of water. When water enters plant roots, it moves down its concentration gradient since the concentration of water is higher in the soil than in the root tip.

ACTIVE TRANSPORT refers to the movement of a liquid or gas from a region of lower concentration to an area of higher concentration. This movement against a concentration gradient can only be accomplished by using energy to help molecules move opposite the direction that diffusion would take them.

WATER is absorbed by the root hairs and brings along with it any chemicals, including nutrients that are dissolved in it. Most nutrients are present in higher concentration in the root hairs as compared with the soil water. Active transport is used to move the nutrients deeper into the root system until they reach cells of the vascular system. The importance of active transport can be demonstrated by exposing plants to a chemical that interferes with cellular respiration. Without a supply of energy-containing ATP molecules produced through respiration, the rate of nutrient movement slows greatly.

8.0 THE PLANT VASCULAR SYSTEM

Although plants do not have a circulatory system like humans, they still must transport material from one part of the organism to another. The plant stem contains a vascular system that connects the leaves to the roots. The plant's vascular system is composed of xylem tissue that transports water from the roots to the rest of the plant and phloem tissue that transports sugars produced in the leaves to the nonphotosynthetic parts of the plant *(see Figure 6).* The xylem is composed of dead cells that form long, empty tubes. Some tubes are wide, and others are narrow. The cell walls within the tubes are either missing or contain a series of holes that permits the passage of water. The cells that gave rise to the xylem lay down thick cell walls that contain a polymer called lignin. Lignin lends strength to the xylem and prevents it from collapsing under pressure.

The capability of xylem tissue is truly amazing. In the case of the tallest trees, water must be transported from the roots up, over 100 meters and against gravity, to the leaves. Water is thought to move through the xylem by a process known as cohesion-tension. According to this view, water can be pulled upward if the diameter of the tube is sufficiently small and that the column of water is continuous, that is, without air bubbles. A further requirement is that the tube be made of a material to which water molecules will adhere. Within each xylem tube, the water molecules are attracted to adjacent water molecules, forming an unbroken chain. The plant loses water through evaporation from its leaves by a process called transpiration. As water is lost, a negative pressure or tension is created that pulls water up from the xylem. Transpiration is the process that drives the transport of water from the roots up through the stems to the leaves.

While water is moving up the plant, sugars and amino acids must move from the leaves downward to the non-photosynthetic parts of the plant. Phloem tissue is composed of tubes made from living cells called sieve cells. Holes at the ends of their cell walls form sieve plates. The cytoplasm of one sieve cell connects with the cytoplasm of adjacent sieve cells through these holes, forming a continuous cell-to-cell sieve tube. As the sieve cells mature, they lose their nuclei and other organelles.

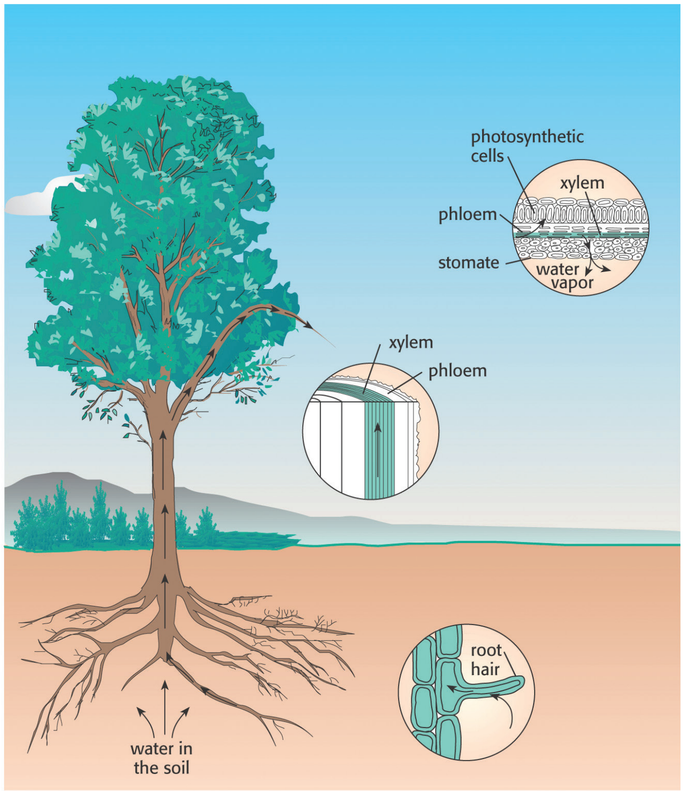

FIGURE 6. WATER TRANSPORT IN A TREE

Beside each sieve cell is a smaller companion cell that has a nucleus. The companion cells are thought to regulate the activity of the sieve cells.

Experiments have demonstrated that this movement occurs at a rate that is thousands of times faster than could be achieved by diffusion. Sugars are thought to move through the phloem by a process called pressure-flow. According to this view, water and dissolved sugars flow through sieve tubes from areas of higher pressure to ones of lower pressure. Sugars made in the leaves are transported into the phloem by active transport. The high concentration of sugar causes water to flow into the phloem cells, increasing what is called the turgor pressure within the cell. This high turgor pressure forces the sugar-water solution into the adjacent phloem cell, increasing its turgor pressure. This process repeats, moving from cell to cell until the solution reaches a cell where it will be used. Once at its destination, the sugar is removed from the phloem by active transport. Water, too, is removed from the phloem cell, regenerating the lower turgor pressure needed to keep the flow moving.

9.0 NUTRIENT DEFICIENCIES OF PLANTS

People and plants are very different types of organisms. For example, people have blood, while plants have sap. People are consumers, while plants are producers. Despite their many differences, both people and plants are made up of cells. In order for cells to be healthy, they must have certain nutrients. If a person is lacking a needed vitamin, mineral, or essential element, then a deficiency is the result. We are familiar with the results of some nutrient deficiencies. For example, if a person lacks iron, he or she becomes anemic, or if a person lacks calcium, his or her bones become brittle. As discussed in *Section 2.0, Plants and Their Essential Elements,* plants require a variety of elements to be present in different amounts in order to support healthy growth. A nutrient deficiency results if a particular nutrient is not available in sufficient quantity to meet the needs of the growing plant. Nutrient toxicity occurs when a nutrient is present in such an excess that it harms the plant. *Table 11* lists most of the essential plant nutrients and describes what happens when plants have too little or too much of them.

TABLE 11. SYMPTOMS OF PLANT DEFICIENCIES AND TOXICITIES

PLANT NUTRIENT	CONDITION	SYMPTOMS
NITROGEN	DEFICIENCY	Light green to yellow leaves; stunted growth; low protein level; poor fruit development
	TOXICITY	Dark green leaves; susceptible to drought, disease, and insects
PHOSPHORUS	DEFICIENCY	Purple coloration on leaves; stunted growth and delay in development; increased disease; reduced drought tolerance
	TOXICITY	Micronutrient deficiencies, especially zinc or iron
POTASSIUM	DEFICIENCY	Yellowing on edges of older leaves, dead leaves; irregular fruit development; reduced drought tolerance
	TOXICITY	Micronutrient deficiencies, especially zinc or iron
CALCIUM	DEFICIENCY	Poor fruit development and appearance; symptoms appear in new leaves and shoots
	TOXICITY	Deficiencies in magnesium or potassium (from precipitation in soil)
MAGNESIUM	DEFICIENCY	Yellowing on older leaves; poor fruit development
	TOXICITY	Growth reduction possibly due to imbalance with calcium and potassium
SULFUR	DEFICIENCY	Yellowing on younger leaves; otherwise similar to nitrogen deficiency
	TOXICITY	Premature dropping of leaves

TABLE 11. CONTINUED

IRON	**DEFICIENCY**	Yellow or white areas on young leaves, leading to spots of dead tissue
	TOXICITY	Bronzing of leaves with small brown spots
MANGANESE	**DEFICIENCY**	Yellowing or mottling on young leaves
	TOXICITY	Brown spots on older leaves
ZINC	**DEFICIENCY**	Yellowing on young leaves; stunted growth; delayed maturity
	TOXICITY	Possible iron deficiency
BORON	**DEFICIENCY**	Deformed and discolored leaves; death of growing points
	TOXICITY	Yellowed leaf tips, scorched appearance; premature leaf dropping
MOLYBDENUM	**DEFICIENCY**	Overall chlorosis, mottled spotting
	TOXICITY	Bright orange leaves

Adapted from Bennett, W. (Ed.). (1993). Nutrient deficiencies and toxicities in crop plants. St. Paul, MN: APS Press.

As shown in *Table 11*, when a plant is out of nutrient balance, it displays symptoms that are characteristic for that particular nutrient. A farmer concerned for the health of his or her crops must use scientific tools to prevent deficiencies and, if necessary, to examine these symptoms and diagnose problems, much like a physician does when encountering a patient with a dietary deficiency. Soil and plant tissue tests are used to detect nutrient imbalances. Once the problem has been identified, steps are taken to correct the imbalance. Farmers prescribe fertilizers for their crops in a manner similar to doctors prescribing vitamins for their patients.

10.0 NOURISHING CROPS WITH FERTILIZERS

As discussed above, plants grown in soil depleted of nutrients can display a wide variety of symptoms and greatly limit the quantity and quality of harvested crops. Fertilizer is essentially "plant food". It is added to replenish nutrients that people indirectly extract from the soil by harvesting plants. In non-agricultural ecosystems, the nutrients removed by plants are returned to the soil after the plants die and decompose. On farms, some of these nutrients are removed in the form of harvested crops, so it is often necessary to replace them with fertilizers. The essential components of most fertilizers are the macronutrients nitrogen, phosphorus, and potassium. All three of these elements play essential roles in allowing plants to access the free energy of the sun through photosynthesis and must be present in adequate amounts to ensure healthy crop growth.

TABLE 12. IMPORTANCE OF SOME ESSENTIAL MACRONUTRIENTS

NITROGEN	• Component of proteins and nucleic acids • Required for chlorophyll production
PHOSPHORUS	• Component of nucleic acids and some proteins • Required for energy transfer • Important for seed germination and water use
POTASSIUM	• Required as a regulator involved in - efficient use of water - transfer of food - protection against stresses
SULFUR	• Component of proteins • Required as a regulator involved in - efficient use of water - transfer of food - protection against stresses

Humans have been raising crops for nearly 10,000 years. Even ancient farmers fertilized their crops. The use of human and animal waste to increase soil fertility was recorded in China over 2,000 years ago. During the "golden age" of Greece from 800 to 200 BC, historians discussed methods for using sewage and classifying manures according to their value for crop production. Although these ancient cultures lacked our understanding of chemistry, they were observant and learned through trial and error how to help their crops grow. Mineral fertilizer in the form of saltpeter or potassium nitrate is mentioned by early Greek and Roman writers and in the Bible. Ancient Greeks also used salt brines to fertilize palm trees.[3]

Justus von Liebig (1803–1873) is known as the founder of the modern fertilizer industry. Using the contributions of other scientists and his own discoveries, Liebig formulated the "mineral theory," which held that crops "grow or diminish in exact proportion" to the amount of nutrient applied. Leibig stressed the value of replacing nutrients to maintain soil fertility. He also developed the "law of the minimum," which states that if one essential element is deficient, then plant growth will be lacking even when all other essential elements are abundant. If the deficient element is supplied, then growth will increase up to the point where the supply is no longer the limiting factor.[12]

The concept of the law of the minimum has been modified through the years as scientists have achieved a better understanding of the variables affecting plant growth. Moisture, temperature, insect control, weed control, light, plant population, and genetic capabilities of plant varieties are now part of this rule.

Today, commercial fertilizers are obtained from a variety of natural sources. The world's first commercial fertilizer was sodium nitrate mined from natural deposits in Chile and imported into Europe and the United States starting around 1830. Around the same time, ammonium sulfate, a by-product of the manufacture of coal gas used for illumination, was sold as a commercial fertilizer.

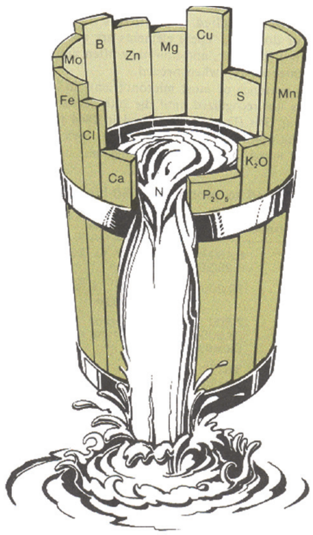

FIGURE 7. ACCORDING TO THE LAW OF THE MINIMUM, PLANT GROWTH WILL BE REDUCED IF JUST ONE ESSENTIAL ELEMENT IS LACKING.

10.1 NITROGEN (THE BUILDER)

NITROGEN (N) is a primary building block for all organisms. It is a component of every amino acid and therefore essential to making proteins. As part of the chlorophyll molecule, nitrogen helps keep plants green. Nitrogen, along with magnesium, is the only element in the chlorophyll molecule that the plant obtains from the soil.

Vigorous plant growth is associated with adequate nitrogen nutrition, in part because nitrogen plays a key role in cell division. If cell division is slowed or stopped, so is leaf growth, which affects the surface area of the leaf exposed to the Sun. A smaller surface area reduces the plant's ability to produce biomass (yield). In addition to increasing yield, nitrogen also improves crop quality by increasing its protein content. Crop plants generally require more nitrogen to grow at their full potential than non-crop plants.

In 1918, scientists Fritz Haber (1868–1934) and Carl Bosch (1874–1940) were awarded the Nobel Prize for developing nitrogen fertilizer by synthesizing ammonia from nitrogen gas and hydrogen. While this process has been modified several times, today the Haber-Bosch process remains the method by which nitrogen fertilizer is commercially produced. Some academics have even suggested that this process has been of greater fundamental importance to the modern world than the invention of the airplane, nuclear energy, space flight, or television.[22] The Haber-Bosch process has increased the amount of plant-available nitrogen produced on land by 60–70 percent compared to the natural processes of biological nitrogen fixation and lightning.[26] Ammonia can be used in a wide variety of field conditions and is a major source of nitrogen applied to crops in the United States. Ammonia contains 82 percent nitrogen and is an important component for most nitrogen-based fertilizers. Another nitrogen source is urea, which is made by reacting ammonia with carbon dioxide and is 45 percent nitrogen.

Organic sources of nitrogen have long been used as fertilizers. Between the years 1850 and 1900, the major natural organics were human excrement, cottonseed meals, fish scrap, and slaughterhouse wastes. In 1910, approximately 90 percent of the nitrogen used in the United States came from organic sources. As competition from commercial fertilizers grew, the contributions from organics decreased to 34 percent in 1920 and to 3.4 percent in 1950.[3]

A new form of fertilizer was developed in the 1950s called activated sewage sludge. This material is made by passing wastewater through filters and centrifuging it to remove debris, oil, grease, and grit. The wastewater is then oxygenated to help microorganisms break down the biomass. Excess water is removed, and the final product is a thick, fibrous cake that is dried in kilns at high temperature to kill any remaining microorganisms or pathogens.

FIGURE 8. THE CORN LEAF ON THE LEFT IS HEALTHY. THE LEAVES TO THE RIGHT HAVE INCREASING LEVELS OF NITROGEN DEFICIENCY.

10.2 PHOSPHORUS (THE ENERGY SUPPLIER)

PHOSPHORUS (P) is found in every living cell. In plants, it serves as both a structural element and as a catalyst for biochemical reactions. Phosphorus is a component of DNA and ATP (the cell's energy molecule). It also plays vital roles in capturing light during photosynthesis, helping with seed germination, and helping plants use water efficiently. Plants also use phosphorus to help fight external stress and prevent disease.

Animal and human bones contain insoluble calcium phosphate. As early as 2,000 years ago, Chinese farmers treated bones with lime and spread them on their fields. The lime treatment was necessary to convert the calcium phosphate into a more soluble form that plant roots could absorb. In the 1800s, fertilizer manufacturers wanted to produce phosphorus fertilizers that were more effective and plentiful than bones. They turned to natural deposits of phosphate rock in the fossilized remains of ancient marine life found in rock deposits around the world. The phosphate in these deposits exists in various forms of a very stable compound called apatite. To make the fertilizer called superphosphate, the phosphate rock is treated with acid or heat to render the phosphorus more soluble. Superphosphate production began in the United States in South Carolina in 1849.

FIGURE 9. CORN PLANTS DEFICIENT IN PHOSPHORUS HAVE SOME LEAVES WITH PURPLISH DIATION.

10.3 POTASSIUM (THE REGULATOR)

POTASSIUM (K) is essential to the workings of every living cell. Although potassium is not a part of any important plant structure, it plays critical roles in several physiological processes. Potassium activates enzymes that catalyze chemical reactions involved with growth. It plays an important role in water balance by regulating the opening and closing of stomates (the pores in leaves through which gases are exchanged). Potassium also helps regulate the rate of photosynthesis through its role in the production of ATP. Other aspects of plant health influenced by potassium include the growth of strong stalks, protection from extreme temperatures, and the ability to fight stress and pests such as weeds and insects.

Potassium used in the manufacture of fertilizers comes from sedimentary salt beds left behind following the evaporation of ancient seas and lakes. Nearly all potassium fertilizer is in the form of potassium chloride. The potassium fertilizer industry started in Western Europe, where there are significant deposits of such ores. North America has the world's largest reserves of potassium deposits. Other parts of the world containing potassium deposits include Brazil, China, Israel, Jordan, and Russia.

FIGURE 10. LEAF FROM A POTASSIUM-DEFICIENT CORN PLANT. THE DARK SPOTS ARE AREAS WHERE CELLS HAVE BEEN KILLED.

10.4 SULFUR (THE SYNTHESIZER)

SULFUR (S) is one of the most abundant elements in the soil and is one of the first elements scientists described. Like nitrogen, it is an essential component in the life of a cell. Sulfur is a component of the amino acids methionine and cysteine, which are used in the synthesis of proteins in all living things. Sulfur also is needed by enzymes associated with photosynthesis and chlorophyll synthesis. Sulfur is extracted from deep, naturally occurring underground deposits; from natural gas and crude oil; from the smelting of certain metal ores; and from gases produced by burning coal.

10.5 CALCIUM (THE SUPPORTER)

CALCIUM (Ca) plays a role in plants that is in some sense similar to that in humans. It is required for healthy growth and proper structural support. Calcium promotes proper cell elongation and is an essential part of the cell wall, helping to provide stability and bind cells together. In addition to its structural role, calcium participates in metabolic activities that help plants take up other nutrients and protect themselves against the effects of heat stress and infection by pathogens. Agricultural lime is used to supply plants with an external source of calcium. It is made from pulverized limestone or chalk, and the active ingredient is calcium carbonate.

11.0 THE DUST BOWL

The importance of maintaining healthy soil was made clear by the events of the so-called Dust Bowl that affected a large area of the Great Plains in the 1930s. During the late 1800s, an unusual amount of rain fell on the Great Plains. This led farmers and agricultural experts to overestimate how much rainfall the region could expect. This unusually wet period caused more people to settle in the area and begin farming. In 1930, an extended drought began, which caused crops to fail. High winds carried massive amounts of topsoil eastward. Throughout the 1930s, the area, including the Texas and Oklahoma panhandles as well as parts of New Mexico, Colorado, and Kansas, experienced a series of huge dust storms. Some of these storms blew dust all the way to Chicago and eventually to Cleveland, Buffalo, Boston, and New York City. During the winter of 1934–1935, red snow fell in New England.[19]

A number of factors worked together to create the Dust Bowl. Certainly, an extended period of high temperatures, wind, and drought were important. However, people too played a part. Early settlers used the land for grazing livestock. Later, as mechanized farming began to spread, many farmers used deep plowing techniques that eliminated the native grasses that held the soil together. High grain prices during World War I caused farmers to plant even more crops, which made the problem worse. Therefore, when the drought hit, the topsoil simply blew away.

To help prevent erosion, the federal government supported the planting of millions of trees from Canada to Texas. These trees helped to anchor and protect the soil. Farming practices too were modified. Farmers began to use a technique called contour plowing that helped the soil retain water. They also began to allow portions of their fields to lie fallow each year to help the soil regenerate.

FIGURE 13. A COMBINATION OF DROUGHT CONDITIONS AND POOR FARMING PRACTICES LED TO THE DUST BOWL OF THE 1930S

12.0 FERTILIZERS AND THE ENVIRONMENT

Nutrients provide the basic building blocks of life for all organisms. As has been discussed previously, proper nutrient application, through fertilizer, improves plant growth and crop yield. However, the nutrient cycle is very complex and humanity is still developing an understanding of the scientific details. Because nutrients occur naturally in the environment, fertilizer application augments nature's processes. Challenges arise when nutrients, through nitrogen-containing fertilizer, are applied improperly. If nutrients are applied at the wrong rate, in the wrong place, from the wrong fertilizer source, or at the wrong time, then the nutrients may be lost to the environment before the plant(s) can take them up and use them for growth. In such cases, nutrients can be lost from the field either through runoff (water) or through gasification and evaporation (air). In the case of runoff, nutrients can be lost to streams, rivers, lakes, and eventually the oceans. While the hydrologic cycle is very complex, excess nutrients in surface waters can promote growth of algae, which in turn can reduce oxygen concentrations in the water and degrade the overall water quality. In the case of gasification and evaporation, nitrogen is broken down by soil bacteria, is converted to N_2O, and moves into the atmosphere as a greenhouse gas.

12.1 NUTRIENT POLLUTION

Nutrients are a natural part of the environment and enter the biosphere from weathering and erosion processes. Nutrients can enter the environment through agriculture, sewage and wastewater treatment plants, coal-burning power plants, storm water runoff, and automobile exhaust. Nutrient sources vary greatly between urban and rural areas. Controlling nutrient loss means identifying its various sources and implementing policies that limit the loss of nutrients to the environment.

As discussed earlier, organisms require essential nutrients to survive, but they must be present in the proper amounts. Either too little or too much can adversely affect health. A similar situation exists with regard to the environment. The U.S. Environmental Protection Agency (EPA) estimates that almost 20 percent of the nation's lakes and 30 percent of streams have high levels of nitrogen and phosphorous pollution.[25] This type of nutrient pollution can cause massive overgrowth of algae. These so-called algal blooms also damage water quality. When large populations of algae die and decompose, they deplete the dissolved oxygen in the water. Marine animals that depend on this oxygen either die or leave the area.

Some species of algae emit toxins that can cause rashes, stomach aches and more serious problems for humans. The most severe acute health effect is methemoglobinemia, often called "blue baby syndrome". Recent evidence suggests that there is not a simple association between nitrate and blue baby syndrome, rather that nitrate is one of several interrelated factors that lead to methemoglobinemia. The disease is uncommon in the United States because potential exposure to high levels of nitrate is limited to a portion of the population that depends on groundwater wells, which are not regulated by the EPA. Public drinking water systems should contain nitrates at a level safe for consumption as nitrates can be removed by water filtration. Nitrogen pollution from cultivated soils, industry, and other sources contributes to global warming because a portion is released into the atmosphere as nitrous oxide (N_2O), a powerful greenhouse gas.

Excess nutrients can enter the environment through both natural and human-induced mechanisms. Sources of nutrient pollution are classified as being either point sources or nonpoint sources.

12.1a NUTRIENT POLLUTION POINT SOURCES

Point sources of nutrient pollution can be tied to specific locations. Typical point sources include factories, power plants, and wastewater treatment plants. In urban areas, wastewater treatment facilities can be the largest contributors to nutrient pollution. For example, in Long Island Sound off the East Coast, an estimated 60 percent of the nitrogen that enters the water comes from sewage discharge leaving New York City.

12.1b NUTRIENT POLLUTION NONPOINT SOURCES

Nonpoint sources of nutrient pollution are general sources such as agricultural areas, cities, and automobiles (golf courses, lawns, anything without a distinct discharge point). A major nonpoint source of nutrient pollution is urban development. For example, clearing of land for housing and industry creates sealed surfaces that do not absorb water and increase nutrient-laden runoff. A related nonpoint source of nutrient pollution is the septic systems that have proliferated as the suburbs extend beyond the reach of urban sewer systems. Automobile exhaust is another nonpoint source. This exhaust releases nitrogen into the atmosphere, but it returns to Earth's surface with the rain. Although definitive information is hard to come by, it has been estimated that up to 40 percent of the nitrogen entering aquatic environments in some areas can come from nitrogen in the air.[14] Agriculture is also a nonpoint source for nutrient pollution. Use of fertilizers can send excess nutrients into the environment, particularly when best practices are not used. To avoid introducing nutrient pollution, fertilizers must be applied using the right source, rate, time, and place. Increasingly, farmers are adopting nutrient management and precision agriculture measures that minimize the amount of this pollution.

12.1c REGULATION OF NUTRIENT POLLUTION

During the past 40 years, antipollution laws have been enacted to reduce the amounts of toxic substances released into our waters. States, territories, and tribes set water-quality standards. They classify a given water body according to the human uses the water quality will allow—for example, drinking water supply, contact recreation (swimming), and aquatic life support (fishing)—and the scientific criteria to support those uses. The Federal Clean Water Act mandates that if a water body is impaired by a pollutant, a total maximum daily load (TMDL) must be created. Total maximum daily load is a calculation of the maximum amount of a pollutant that a water body can receive and still meet water quality standards, and an allocation of that amount to the pollutant's sources. A TMDL is the sum of the allowable loads of a single pollutant from all contributing point and nonpoint sources. The calculation must include a margin of safety to ensure that the water body can be used for the purposes the state has designated, such as swimming and fishing.
The calculation must also account for seasonal variation in water quality.

GLOSSARY

ACTIVE TRANSPORT: the movement of substance across a biological membrane against its concentration gradient; from a less-concentrated area to a more-concentrated area. Active transport requires the input of energy and uses specific transport proteins.

ATP: adenosine triphosphate; a compound that has three phosphate groups and is used by cells to store energy.

COMMERCIAL FERTILIZER: commercially prepared mixtures of plant nutrients that include nitrogen, phosphorus, and potassium applied to the soil to restore fertility and increase crop yields. Commercial fertilizers contain nutrients in known amounts that plants can immediately use.

CONCENTRATION GRADIENT: a difference in the concentration of certain molecules over a distance.

COVER CROP: crops such as rye, alfalfa, or clover can be planted immediately after a crop harvest to hold the soil in place, preventing erosion and nutrient loss. They also represent an important type of fertilizer because they provide nutrient value when they are eventually plowed into the soil. These plant-based fertilizers are used on a small scale in comparison to animal manure-based fertilizers.

CROP: food crops, lawns, garden, and ornamental plants such as flowers.

DIFFUSION: the movement of a substance down its concentration gradient from a more-concentrated area to a less-concentrated area.

DUST BOWL: The Dust Bowl drought was a natural disaster that severely affected much of the United States during the 1930s. The soil, depleted of moisture, was lifted by the wind into great clouds of dust and sand which were so thick they concealed the Sun for several days at a time. The "dust bowl" effect was caused by sustained drought conditions compounded by years of poor land management practices that left topsoil susceptible to the forces of the wind.

GENETICALLY MODIFIED FOOD: a food product containing some quantity of a genetically modified organism (GMO) as an ingredient. A GMO is any organism that has had a gene from another species added to it using recombinant-DNA technology.

GREEN REVOLUTION: a term used to describe the transformation of agriculture in some developing nations between the 1940s and 1960s. During the Green Revolution, already existing technologies such as pesticides, irrigation, and use of inorganic fertilizers spread to developing countries resulting in increased crop yields.

INFILTRATION: the process by which water penetrates into soil from the ground surface.

INORGANIC FERTILIZER: commercially prepared mixtures of plant nutrients that include nitrogen, phosphorus, and potassium applied to the soil to restore fertility and increase crop yields. Inorganic fertilizers contain nutrients in known amounts that plants can immediately use.

LIGNIN: a non-carbohydrate polymer that binds cellulose fibers together. It adds strength and stiffness to plant cell walls.

LOAM: a rich soil consisting of a mixture of sand and clay and decaying organic materials.

MACRONUTRIENT: a nutrient that must be present in a relatively large amount to ensure the health of the organism. Macronutrients are building blocks used to make essential biomolecules.

MICRONUTRIENT: a nutrient required in small quantities to ensure the health of the organism. Micronutrients are often used as cofactors for enzymatic reactions.

MICROORGANISM: an organism too small to be seen with the unaided human eye. Bacteria are an important type of microorganism.

NITROGEN FIXATION: a biological or chemical process by which elemental nitrogen, from the air, is converted to organic or available nitrogen.

NONPOINT SOURCE: nutrient pollution that results from runoff and enters surface, ground water, and the oceans from widespread and distant activities. Because it comes from a number of different sources, a nonpoint source is much harder to trace and quantify than a point source of nutrient pollution.

NUTRIENT: any of 17 essential mineral and nonmineral elements necessary for plant growth.

NUTRIENT DEFICIENCY: a condition where the amount of a nutrient essential to the health of an organism is lacking or present in an insufficient amount.

NUTRIENT POLLUTION: the presence of excessive amounts of nutrients such as nitrogen and phosphorus in waterways. These nutrients stimulate the growth of algae, thus robbing the waters of oxygen and suffocating some aquatic organisms. Nutrient pollution comes from both natural and human-induced sources.

NUTRIENT TOXICITY: the presence of an excessive amount of a specific nutrient, which is harmful to the organism.

ORGANIC FERTILIZER: a fertilizer that undergoes little or no processing and includes plant, animal, and/or mineral materials.

PERCOLATION: the process by which water moves downward through openings in the soil.

PERMEABILITY: the ability of soil to allow the passage of water.

PHLOEM: a portion of the vascular system in plants, consisting of living cells arranged into tubes that transport sugar and other organic nutrients throughout the plant.

POINT SOURCE: nutrient pollution that comes from a specific source that can be identified such as a factory or a wastewater treatment plant.

POROSITY: the percentage of soil volume that is not occupied by solids.

TRANSPIRATION: the loss of water to the atmosphere by a plant through the stomates in its leaves.

XYLEM: conducting tissue that transports water and dissolved nutrients in vascular plants.