

INTRODUCTION

Earth Summit Alternative Nongovernmental Sustainable Agriculture Treaty

Sustainable agriculture is a model of social and economic organization based on an equitable and participatory vision of development that recognizes the environment and natural resources as the foundation of economic activity. Agriculture is sustained when it is ecologically sound, economically viable, socially just, culturally appropriate, and based on a holistic scientific approach . . . Sustainable agriculture respects the ecological principles of diversity and interdependence and uses the insights of modern science to improve rather than displace the traditional wisdom accumulated over centuries by innumerable farmers around the world.

UNDERSTANDING THE SOIL ECOSYSTEM

The first step toward effective ecological soil management is an appreciation of the complex, living system known as soil. And to understand soil is to be aware of how everything affects and is affected by it. We are all part of the soil ecosystem.

Soil fertility can be described as its capacity to nurture healthy plants. Sustainable agriculture aims to protect the soil's ability to regenerate nutrients lost when crops are harvested—without dependence on “off-farm” fertilizers. This regenerative capacity, in turn, depends on the diversity, health, and vitality of the organisms that live, grow, reproduce, and die in the soil. Through the activities of soil microbes—which can number in the billions in every gram of healthy topsoil—the basic raw materials needed by plants are made available at the right time, and in the right form and amount.

**The basic aim of ecological soil
management is to provide hospitable
conditions for life within the soil.**

Your farm is both the product and producer of soil. Consider your farm to be a living organism that achieves its greatest long-term

productivity when its natural cycles and processes are enhanced. Shortcutting these cycles for short-term control or economic gain will eventually bear out the ecological maxim, "The creature that wins against its environment destroys itself."

The place to start is where you are. Thousands of soil types have been named, classified, and described. Knowing their names can tell you a lot about their general characteristics; but, like any living creature, each individual is unique. Find out what soils live in your area, how they are classified and described by soil scientists, and how that compares with what you observe about them yourself.

Soil classification schemes organize soils according to their different qualities, based on the kinds of minerals they contain, how they were formed, and various physical characteristics. The individual character of any soil arises from a combination of factors inherent to its particular geographic region (see table 1).

Table 1

ENVIRONMENTAL INFLUENCES ON SOIL

Climate. Temperature and precipitation affect the rate of organic matter accumulation and the presence of soluble soil minerals. For example, more organic matter accumulates where decomposition is slow due to cooler temperatures, while high rainfall leaches mineral nutrients from topsoil.

Native vegetation. Grasslands, forests, and transition zones each affect soil development in a different way. Leaf litter from pine forests, for example, increases soil acidity. Soil particles developed under grasslands are usually bound into stable aggregates by the activity of the plentiful microorganisms and roots found there.

Parent material. Underlying rock types from which it was formed determine a soil's mineral content and basic textural qualities. Limestone bedrock, for instance, helps counteract soil acidity. Red soils indicate that the parent material and derived soil is rich in iron. Volcanic ash eventually produces soils heavy in amorphous clays.

Topography. Soil may be eroded from slopes and deposited in lowlands. The legendary fertility of river valleys such as the Nile resulted from deposits of rich sediment carried from the highlands, while mountain farmers all over the world have problems holding onto precious topsoil.

Time. The availability of minerals and the extent of humus development in soil is also influenced by how long the native rock has been subject to weathering. Young soils, such as those in Hawaii and other areas of volcanic activity, may be low in clay, which is produced by the chemical effects of weathering on parent rocks.

Glaciation and geologic activity. In the north-temperate region, the advance and retreat of glaciers, most recently a mere 12,000 years ago, has had a significant effect on soil formation and quality. Volcanic activity has left nutrient-rich lava deposits in many areas.

Soils worldwide have been classified into ten major orders (see table 2). In humid temperate regions such as the northeastern United States, where forests are the predominant natural vegetation, the soil order of **spodosols** is most common. These soils are generally formed from coarse-textured parent material, and tend to be quite acidic and low in mineral nutrients. Prairie soils, which have developed under flat, grass-covered areas with modest rainfall, are classified as **mollisols**. They are among the most naturally productive soils, with high native organic matter and mineral content. In tropical regions with very high seasonal rainfalls, the heavily leached **ultisol** soils also tend to acidity. The Sahara, Gobi, and Turkestan Deserts, as well as South and Central Australia and the American Southwest are largely comprised of **aridisols**. If irrigated they can be productive, but great care must be taken to prevent toxic accumulations of soluble salts.

Each order is further broken down into suborders, great groups, and subgroups. Beyond this, soils are described in terms of families, associations, and series, which provide more information about their plant growth characteristics, organic and mineral content, structure, drainage, and color. Series are often named after the places—towns, rivers, or counties—where they are located.

Your local Extension or Soil Conservation Service office can probably give you a soil map for your land. They can also show you your county's soil survey, which provides detailed information on local soils and their best uses, as well as helpful climatological data.

Table 2
THE TEN MAJOR SOIL ORDERS

Entisols: Recently formed mineral soils with little evidence of horizon formation. Found in a wide range of climate zones, including the Rocky Mountains, the Sahara Desert, Siberia, and Tibet. May be highly productive, but most are relatively barren.

Vertisols: Mineral soils with a high content of swelling-type clays, which in dry seasons cause the soils to develop deep cracks. Found in some areas of the southern U.S., India, Sudan, and eastern Australia. Their physical properties make them difficult to till and cultivate.

Inceptisols: Young soils with limited horizon formation. May be very productive, as those formed from volcanic ash. Found in the Pacific Northwest (U.S.), along the Amazon and Ganges Rivers, North Africa, and eastern China.

Aridisols: Mineral soils found mostly in dry climates. Productive only if irrigated, and may become saline. Found in the southwestern U.S., Africa, Australia, and the Middle East.

Mollisols: Characterized by a thick, dark surface horizon, they are among the world's most productive soils, with high natural fertility and tilth. Generally found under prairie vegetation, such as the Great Plains (U.S.), Ukraine, parts of Mongolia, northern China, and southern Latin America.

Spodosols: Mineral soils characterized by distinct horizons, including subsurface organic matter, and aluminum and sometimes iron oxides. Coarse-textured, readily leached, and tending to be acid, they occur mostly in humid, cold temperate climates, generally under forests. Can be very productive if properly fertilized.

Alfisols: Moist mineral soils with high base status and presence of silicate clays. Found mostly in humid regions under deciduous forest or grass including parts of the U.S. Midwest, northern Europe, southern Africa, and Southeast Asia. Highly productive, good nutrient levels and texture.

Ultisols: Moist soils that develop under warm to tropical climates. Highly weathered, acidic, with red or yellow subsurface horizons. Found in the humid southeastern U.S., Southeast Asia, and southern Brazil. Can be highly productive, with good workability.

Oxisols: The most highly weathered soils, with a deep subsurface horizon of iron and aluminum oxides. High in clay, commonly deficient in phospho-

surfaces. Not well adapted to mechanized farming, they have been poorly researched.

Histosols: Organic soils that have developed in a water-saturated environment, with at least 20 percent organic content. Can be very productive if drained, especially for vegetable crops.

SOURCE: adapted from Nyle Brady, *The Nature and Properties of Soils*, 10th ed.

ORGANIC MATTER AND HUMUS

Soil health and **humus** are indivisible: health is the vitality of the soil's living population, and humus is the manifestation of its activities. As the cornerstone of the soil ecosystem, humus influences and is influenced by every other aspect of the soil. Building soil humus improves its physical and chemical properties as well as its biological health.

All humus is organic matter, but not all organic matter is humus. Raw organic matter consists of the waste products or remains of organisms that have not yet decomposed. Humus is one form of organic matter that has undergone some degree of decomposition. There is no hard and fast dividing line, but a continuum, with fresh, undecomposed organic materials—manure, sawdust, corn stubble, kitchen wastes, or insect bodies—at one end, and stable humus, which may resist decomposition for hundreds of years, at the other. Table 3 summarizes the attributes of different types of organic matter and humus.

Humus is dark brown, porous, spongy and somewhat gummy, and has a pleasant earthy fragrance. Chemically, it is a mixture of complex compounds, some of which are plant residues that don't readily decompose, such as waxes and lignins. The rest are gums and starches synthesized by soil organisms, primarily bacteria and fungi, as they consume organic debris. Humus is highly variable in its composition, depending on the nature of the original material and the conditions of its decomposition.

“Humus” is actually more a generic term than a precise one. Its qualities will reflect different origins and composition. Just as wine can vary widely in quality, so can humus. And, just as different wines are suitable for different culinary purposes, the varieties of humus serve varying soil functions.

Several classification schemes for humus have been suggested. Theories differ as to how it is formed, why it behaves as it does, and how it should be measured. Humus that can still decompose readily is known as effective or active humus. It consists of a high proportion of simple organic acids (fulvic acids), which will dissolve in either acids or bases. This type of humus is an excellent source of plant nutrients, released as soil organisms break it down further, but of little consequence for soil structure and long-term tilth. This kind of humus is mainly derived from the sugar, starch, and protein fraction of organic matter.

Humic acids, which dissolve in bases but not in acids, characterize more stable or passive humus; humins, which are highly insoluble and may be so tightly bound to clay particles that microbes can't penetrate them, are the main constituents of the most stable humus. Because stable humus resists decomposition it does little to add nutrients to the soil system, but it is essential to improving the soil's physical qualities. Carbon-14 dating has revealed that very stable humus complexes may survive unchanged for thousands of years. Stable humus originates from woodier plant residues, which contain lots of cellulose and lignin.

The status of soil organic matter and humus is a dynamic one, continually changing through the activities of all the creatures that live there. Ideally, there should be a rough equilibrium among the different kinds of humus at any one time, with the more active fractions predominant when plant nutrient needs are highest, then giving way to more stable forms after harvest or when plants are dormant. Fungi and actinomycetes, which are more abundant than bacterial decomposers under cool, damp conditions, are also more important in the creation of stable humus.

The changes are fastest under optimum conditions for soil biological activity, and fresh supplies of raw organic matter must continually be added to keep the cycles moving. Anything that harms or disrupts one member of the soil community can lead to a form of "indigestion" in the soil. For example, if large amounts of nitrate fertilizer flood the soil system, the bacteria responsible for converting protein fragments into nitrates will be suppressed, in turn "backing up" the whole organic decomposition process. They will recover after a while, but if this process is repeated year after year, the capacity of that soil to digest fresh organic matter will be seriously damaged.

The process by which organic matter and humus breaks down in the soil is called **mineralization**. While humus is the product of organic matter mineralization, it too can be mineralized under the right conditions. Organic matter management, discussed in chapter 3, requires that you understand what conditions speed up or slow down mineralization.

Mineralization occurs quickly when conditions are perfect for bacteria to reproduce: high aeration, adequate moisture, good pH, and balanced mineral nutrients. Cultivation speeds it up by introducing air; if soil is dry, irrigation will also stimulate mineralization. Increasing soil temperature with dark mulch or row covers, or actually heating the soil in a greenhouse bed, also encourages the faster release of nutrients to plants.

As is true with fertilizing, it's important to understand the concept of "enough" when you choose to stimulate mineralization. Too quick a release of nutrients from organic matter can cause problems, which parallel those of overfertilizing: excess plant nitrate uptake or possible leaching of nutrients into groundwater. It's also important to avoid "burning up" vital, stable humus reserves by making sure to add enough organic matter to replenish what is mineralized.

Humus tends to accumulate fastest under conditions unfavorable to mineralization: cool temperatures, low pH, and poor aeration. While to some extent this is desirable, the extreme example of going too far is the case of a peat bog, composed of almost pure hu-

mus. The key here is balance: an active, healthy biological population will continually be mineralizing humus at the same time that it is being formed. As you become attuned to the signs of biological activity and health in your soil, as well as the rhythms of growth and rest in your crops, you will develop a better sense of “enough” when it comes to humus formation and decay.

BENEFITS OF HUMUS

- Humus can hold the equivalent of 80 to 90 percent of its weight in water, so soil rich in humus is more drought-resistant.
- Humus is light and fluffy, allowing air to circulate easily, and making soil easy to work.
- The sticky gums secreted by microbes while forming humus hold soil particles together in a desirable crumb structure.
- Humus is extremely effective at holding mineral nutrients safe from being washed away in rain or irrigation water, and in a form readily available to plants. Ample reserves of humus also provide additional plant nutrients in times of need.
- Humus is able, because of its biochemical structure, to moderate excessive acid or alkaline conditions in the soil—a quality known as buffering.
- Many toxic heavy metals can be immobilized by soil humus, and prevented from becoming available to plants or other soil organisms.
- Although the color of humus can vary, it is usually a dark brown or black color, which helps warm up cold soils quickly in the spring.

Table 3

THE NATURE AND FUNCTION OF ORGANIC MATTER AND HUMUS

	<i>Raw organic matter</i>	<i>Effective humus</i>	<i>Stable humus</i>
NATURE			
Source	Wastes, residues, and remains of living organisms.	Decomposed raw organic matter.	Decomposed raw organic matter or effective humus.
Composition	Complex organic compounds, such as proteins, cellulose, lignins, fats, starches and sugars.	Characterized by high ratio of fulvic acids (small, soluble molecules).	Mostly long-chained humic acids, or humins bonded to clay particles.
Characteristics	Heterogeneous, coarse, lumpy material.	A colloid, more homogeneous in texture and color.	Homogeneous, resistant to chemical action.
FUNCTION			
Physical	Improves aeration, drainage, and moisture retention. "Trash mulch" protects soil from weathering. If too coarse and abundant, may hinder seed preparation.	Creates "crumb structure"—spongy, porous, and sticky—that makes an excellent soil conditioner. Dark brown color improves heat retention by soil.	Same as effective humus.
Chemical	Provides some soluble nutrients, especially from manures. Leaves a reserve supply of nutrients in the soil. Releases much carbon dioxide as it decomposes.	Mobile in soil; readily releases nutrients to plants. Holds nutrient anions in a form available to plants, but safe from leaching. Increases cation exchange capacity.	Provides long-term nutrient storage and maintains good cation exchange capacity. Toxic substances (as well as nutrients) can be chelated and prevented from entering the ecosystem.
Biological	Provides food for microbial decomposers. However, if too carbonaceous, can overstimulate microbes and lock up available nitrates.	Provides nutrients to microbes as it decomposes. Releases vitamins, hormones, antibiotics, and other biotic substances.	Provides microbial habitat and evidence of healthy biological activity.

PHYSICAL FACTORS: SOIL STRUCTURE AND TILTH

Tilth is to soil what health is to people. A soil in good tilth is in good physical condition for supporting soil life. Good tilth also means soil is loose and easy to work, so tools as well as plant roots can readily dig in. Moisture and aeration are the key physical qualities of soil. The ability of soil to hold water without becoming soggy, and to allow air to penetrate to plant roots and other soil organisms, is vital to every aspect of fertility.

The tilth of your soil is a composite of its texture, structure, aggregation, density, drainage, and water-holding capacity. No matter what kind of soil you start out with, most of these qualities can be improved by increasing its organic matter and humus content.

Soil Composition

About half the volume of a good, loamy soil is pore space—the area between particles where air and water can penetrate. The pore space is generally an equal volume of air and water, which clings to the surface of soil particles. Don't discount the importance of pore spaces. All the fertilizer in the world won't solve the problems created by dense, compacted soil that is deficient in pore space.

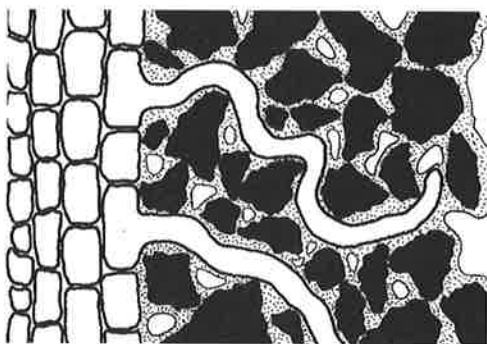


FIGURE 1. *Soil particles and pore spaces, showing a thin film of water covering each particle.*

(Drawing by Timothy Rice.)

Of the solid half of the soil, about 90 percent is composed of small bits of the rocks and minerals from which the soil was formed, as well as clays created by the weathering of the parent rock. The remaining 10 percent is the organic fraction. The influence of this small part of the soil on its ability to support plant growth is tremendous.

The sand and clay components of a soil are largely unalterable—there's not much you can do to change them. But how you manage your soil can have a profound influence on the amount and quality of organic matter it contains. The organic fraction of the soil is a dynamic substance, constantly undergoing change. It consists of living organisms, including plant roots and bacteria, as well as dead plant residues and other wastes. The total weight of the living organisms in the top six inches of an acre of soil can range from 5,000 to as much as 20,000 pounds.

Fundamental Qualities

Every soil has its own unique physical characteristics, which are determined by how it was formed. Some of these qualities can be improved with proper management—or made worse by abuse—but others must simply be considered the basic starting point you must work with. There's not much you can feasibly do to change the depth of bedrock or water table, or to eliminate a steep slope. You can pick rocks out of a very stony soil, but in cold climates, frost-heaving will only bring more rocks to the surface each spring.

Soil texture is one such inherent quality. Texture can range from very fine, mostly clay particles, to coarse and gravelly ones. Any extreme is undesirable: the ideal loamy texture is a balance of fine clay and silt, combined with coarse sand. The texture of your soil will influence its nutrient status, workability, aeration, and drainage. Clay soils hold water and nutrients well, but can be poorly drained and difficult to work. When they dry out, they form hard clumps, and can take on the consistency of concrete. Sandy soils are generally

easy to work and well drained, but have poor nutrient- and water-holding ability. Their very high aeration means organic matter decomposes too rapidly, and little stable humus is formed. (Refer to chapter 3 for instructions on evaluating your soil's texture and other physical qualities.)

Structure and Aggregation

Good tilth is less dependent on the composition of your soil than on how it holds together. The ability of soil particles to form stable aggregates, giving it a crumbly, cake-like consistency, determines its structural soundness. The ideal crumb structure, illustrated below, is very much a product of biological activity. Humus plays a central role in forming soil aggregates, but many soil creatures—most notably earthworms—secrete the sticky gums that are crucial for holding soil particles together. Structure and aggregation can be dramatically improved by increasing humus content and stimulating soil biological activity.

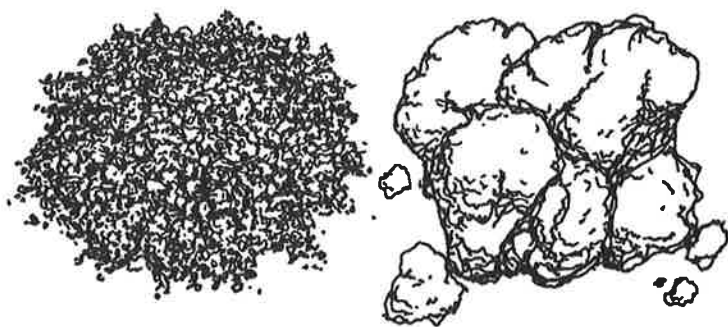


FIGURE 2. Comparison of good crumb-like soil structure (left), with a poor, clod-like structure (right).

(Drawing by Stewart Hoyt.)

A good crumb structure implies that soil is well aerated, since there will be plenty of pore spaces between the granules. Structure is also essential to the ability of soil to conduct soil moisture upward toward plant roots. This feature is referred to as capillary action, and it works in much the same way that oil is taken up into the wick of a lamp. If soil structure is good, the surface may dry out, but moisture will still reach the root zone from deeper soil levels. Adequate soil moisture is crucial not only to replenish what is lost through transpiration from plant leaves, but also because plant roots take up most of their nutrients when they are dissolved in the thin film of water that coats soil particles.

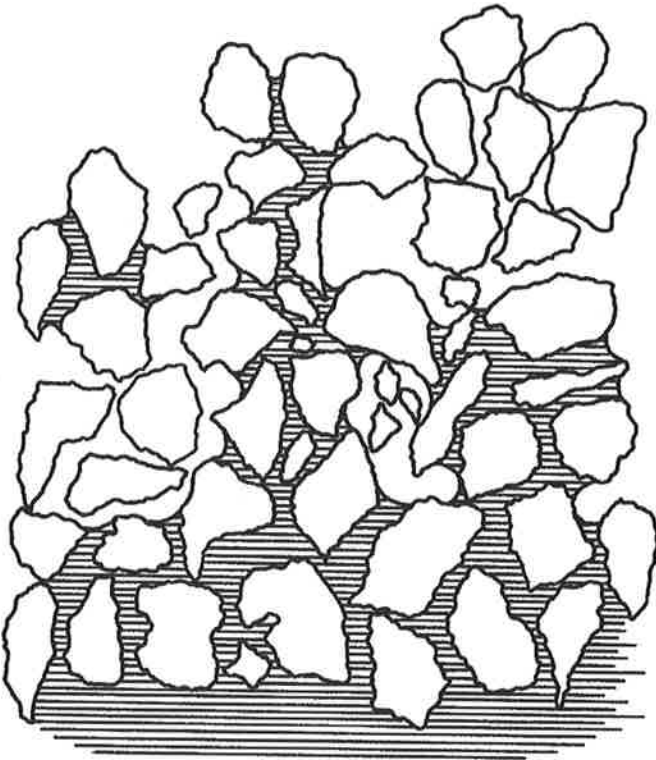


FIGURE 3. *Moisture moving upward in soil by capillary action.*
(Drawing by Timothy Rice.)

Table 4

PHYSICAL PROPERTIES OF SOIL

<i>Property and definition</i>	<i>Significance in soil</i>	<i>Influence of organic matter</i>
Bulk Density: The weight of unit volume of dry soil, including pore spaces. Expressed as grams per cubic centimeter (gm/cm^3).	Indicates how dense the soil is and, therefore, how easily air, water, and plant roots can penetrate. (Optimum range: 1.0–1.8 gm/cm^3 for compact subsoil).	Increased organic matter leads to decreased bulk density, because organic matter is less dense than soil minerals and gas is released during decomposition.
Pore Space: The portion occupied by air and water per unit volume of soil. Expressed as a percentage of volume.	Indicates specific aeration and drainage qualities. (Optimum range: 35%–60% for topsoil; 25%–30% for compact subsoil.)	Increased organic matter leads to increased pore space. Soil organisms also increase pore space by burrowing and eating.
Structure and Aggregation: Refers to the arrangement of soil particles, their shape, size, and stability.	The structure that encourages the most plant growth is granular: rounded aggregates that stick together, but shake apart easily. Especially porous granules are called “crumbs.”	Biological activity is virtually essential for proper granulation. Humus provides a perfect crumb structure that resists compaction.
Oxygen Diffusion Rate: The rate at which oxygen can be replenished as it is used by respiring organisms. Expressed as grams per cubic centimeter per minute ($\text{gm}/\text{cm}^3/\text{min}$).	Indicates the aeration status of the soil. In addition to pore space for air to enter, there must also be continual diffusion of fresh air into the soil to replace carbon dioxide with oxygen. (Minimum level for root growth is $20 \times 10^{-8} \text{ gm}/\text{cm}^3/\text{min}$.)	Increased organic matter leads to an increased oxygen diffusion rate. Decomposing organic matter (especially plant roots) and mobile soil organisms create air passages in soil.
Field Capacity: The amount of water held in pore spaces after a fully saturated field has been allowed to drain for 24 hours. Expressed as a percentage of volume.	Indicates the drainage qualities of the soil. A low field capacity means that water runs out too quickly; with a high field capacity, water remains too long in pore spaces. (Well granulated silt loam has a field capacity of about 15%.)	By improving the soil structure, organic matter modulates the field capacity of soils that would otherwise be too wet or too dry.

CHEMICAL FACTORS: NUTRIENT CYCLES AND BALANCES

The conventional approach to soil management has been labeled “chemical,” in contrast to the “organic” method, which rejects the use of synthetic, petrochemical fertilizers and pesticides. The chemical approach holds that plant roots require certain chemical nutrients, but how these nutrients get to the roots and where they come from matters little. The nutrient elements must be present in a soluble, inorganic form in order for plants to use them.

The ecological viewpoint holds that the effect of fertilizers on soil organisms and the environment is of equal importance to their value as plant food. “Feed the soil, not the plant,” organic growers maintain, and soil organisms will provide a balanced diet to crops. Highly soluble chemicals, though readily taken up by plants, can inhibit or kill soil microbes, and can be washed away to pollute groundwater. Moreover, plants are also able to absorb and benefit from complex biochemicals such as vitamins and antibiotics, which are not present in artificially synthesized fertilizers.

Public concern over groundwater contamination by nitrate fertilizers, as well as other agrichemicals, has stimulated greater interest in soil management practices that do not rely on highly soluble materials.

Soil Chemistry Simplified

Regardless of which approach you adhere to—chemical or organic—the fundamentals of soil chemistry remain the same. Most chemical interactions, in the soil or anywhere else, take place between particles that carry either a positive or a negative charge when dissolved in water. Positively charged particles are called *cations* (pronounced “CAT-ions”), while *anions* (“AN-ions”) carry a negative charge. These particles may be a single element, such as calcium (Ca^{2+}), or a compound, such as nitrate (NO_3^-). The behavior of nutrients in the soil ecosystem is determined by whether they exist as cations or anions.

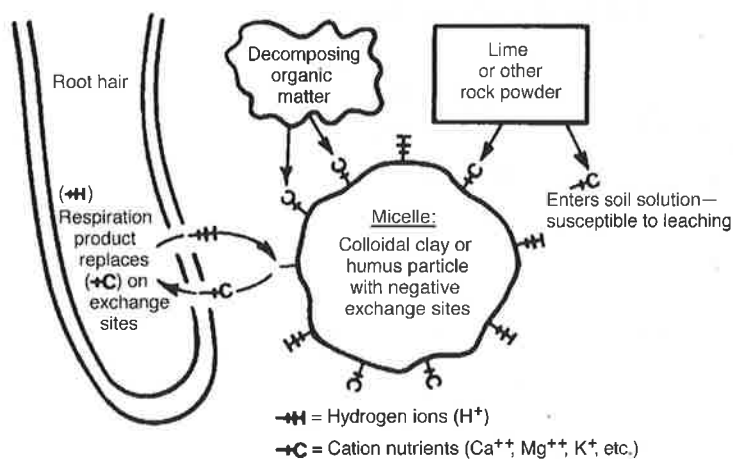


FIGURE 4. *Cation Exchange Capacity (CEC). The higher the CEC, the more nutrients can be kept available to plants, yet safe from leaching. Cations held on the exchange sites are said to be absorbed.*

The Basics of Cations

Cation nutrients tend to be metallic mineral elements, important for both plant and microbial nutrition as components of enzymes. They are generally quite water soluble, and enter the soil either through the recycling of organic matter or by addition of mineral nutrient sources such as limestone. Cations are called base elements because they form bases in solution. In humid climates, where there is over thirty inches of precipitation a year, cations tend to become leached out of the topsoil—more slowly if they are stored by soil colloids such as clay and humus. Soils in arid climates, conversely, are usually rich in minerals and so extremely productive when irrigated.

The major cation nutrients include calcium, magnesium, and potassium; their functions are summarized in the chart that follows. Other cation nutrients, needed in minute quantities, are described in the discussion of micronutrients (see page 23).

Table 5
MAJOR CATION NUTRIENTS

<i>Nutrient</i>	<i>Natural sources</i>	<i>Forms in soil</i>	<i>Function in plants</i>	<i>Deficiency symptoms</i>
Calcium (Ca ²⁺)	Dolomite, calcite, apatite, calcium feldspars, gypsum.	Most is present as Ca ²⁺ ion on cation exchange sites, or in soil solution. At high pH, calcium forms insoluble precipitates with phosphorus and some micronutrients.	Essential for nitrogen uptake and protein synthesis. Also has a role in enzyme activation and cell reproduction	Stunted root growth, undeveloped terminal buds, and leaf curl. Pit rot in carrots, blossom-end rot in tomatoes.
Magnesium (Mg ²⁺)	Mica, hornblende, dolomite, serpentine, certain clays.	Present as Mg ²⁺ ion on cation exchange sites, or in soil solution.	Essential part of chlorophyll molecule. Necessary for phosphorus metabolism and enzyme activation. Often concentrated in seeds.	Yellowing of lower leaves, with venation in green; reduced yields.
Potassium (K ⁺)	Feldspars, mica, granites, certain clays.	Available as K ⁺ on cation exchange sites or in soil solution. (Less than 1% of total soil K ⁺ is in available form.)	Essential for carbohydrate metabolism and cell division. Regulates absorption of calcium, sodium, and nitrogen.	Weakened stems, scorched leaf edges, necrotic spots, stunted growth, susceptible to disease.

CATION EXCHANGE CAPACITY

Cation Exchange Capacity, or CEC, is an important measurement of the amount of cation nutrients a given soil is able to store on its clay and humus colloid particles. Colloids, as described on page 25, have a large number of negatively charged sites all over their surface. Positively charged cations are held on these sites, largely protected from leaching away in water, but still available to plant roots. As plants give off hydrogen ions, a waste product that is also positively charged, it is exchanged for needed nutrients like calcium, magnesium, and potassium. Nutrients held in colloidal exchange sites may not show up in soil tests because they are not dissolved in water, but they are still available to plants through direct contact between roots and soil colloids. This process is referred to as adsorption.

Soils with a high clay and humus content will have the highest CEC, which is measured by how many thousandths of a gram of hydrogen—called milliequivalents—can be held by 100 grams of dry soil. Different kinds of clays have CECs ranging from 10 to as much as 100, while the CEC of pure humus can approach 200. Very sandy soils will have a CEC of 5 or less.

Think of your soil's CEC as a kind of nutrient savings account. As nutrients are "withdrawn," whether by removing crops or through the prolonged action of water, it is important to replace them in order to maintain your reserves. These reserves must be well stocked before plants are able to draw on them, so a soil with a high CEC but depleted nutrients will require greater applications of mineral nutrients to restore its fertility than will a similarly depleted but low CEC soil. A high CEC soil with an acid pH will require a larger amount of calcium, in the form of limestone, to correct it than will a low CEC soil with the same pH. Knowing your soil's CEC will help you better understand and interpret your soil test recommendations, as discussed in chapter 3.

COLLOIDS

One of the most important characteristics of humus is its colloidal nature. *Colloids* are substances composed of many tiny particles suspended in a gel-like mass, giving them a lot of surface area in proportion to their weight. Protein, which makes up all living cells, is a colloid. Other examples of colloids are milk, mayonnaise, rubber, and gelatin. Clay is also a colloid, and the clay component of the soil behaves similarly to humus. Physically, colloids tend to be sticky and absorbent.

Colloids are important chemically because they are covered with negatively charged particles. This makes them able to hold onto positively charged chemical particles, many of which are important soil nutrients. All soil chemical interactions are affected by the soil's clay-humus colloidal content.

Cations, pH and Fertility

When cation or base nutrients are deficient in soil, it becomes acid. pH (which stands for "potential hydrogen") is a measure of the acidity or alkalinity of soil, determined by the concentration of hydrogen ions in a water or salt solution. Acidity is indicated by a pH below 7.0, which is neutral; pH values over 7.0 indicate alkalinity.

As hydrogen ions replace the cation nutrients held in soil colloidal reserves, soil pH decreases. The solubility, and thus availability to plants, of most nutrients is highest at a slightly acid pH—around 6.3 to 6.8 is optimum. This is also the most favorable range for the functioning of most soil bacteria, though fungi can tolerate a wider pH range. At low pH—below 5.5—most major nutrients and some micronutrients assume insoluble forms. Phosphorus becomes chemically immobilized at both low and high pH, requiring a range between 6.0 and 7.0 for maximum availability.

Many cation micronutrients, including iron, manganese, zinc, copper, and cobalt, become more soluble at low pH but are unavailable under alkaline conditions. In some cases, acid conditions can induce toxicity of these elements. This is also true of certain heavy metals, most notably aluminum, which is naturally present in most soils, and lead, which can sometimes be a contaminant. Neutralizing the pH also neutralizes the heavy metal hazard.

When correcting soil acidity, the object is not so much to neutralize pH as it is to replenish the appropriate cation nutrients—usually calcium and sometimes magnesium in the form of limestone. Applying other alkaline materials, such as sodium bicarbonate, may neutralize the pH, but won't improve soil fertility.

“Acid soil syndrome” is a common problem in areas of high precipitation, where soluble soil bases tend to leach out into the subsoil. Some of the problems associated with acid soil include:

- Interference with the availability of nutrients to plants.
- Increased solubility of iron, manganese, and especially aluminum to undesirable levels.
- Reduced bacterial activity, especially of nitrogen-fixing rhizobia, and slower release of nutrients contained in organic matter.
- Lower total CEC, which further increases nutrients' leachability.

Alkaline soils can be even more difficult to correct. The addition of acid-forming minerals like sulfur is more expensive and temporary than the addition of limestone to acid soils. In many places where soil is naturally alkaline, improper irrigation practices may cause salts to build up in the surface layer, a condition known as **salinization**. This happens when nutrient-rich water rises to the surface through capillary action and then evaporates, leaving its minerals behind. Some soils in arid areas are naturally saline. It is difficult and costly to reverse these effects, and it is generally done by leaching the area with large amounts of fresh water—a resource usually in short supply in affected regions.

Among the problems associated with alkaline soils are:

- Unavailability of many nutrients, especially most micronutrients.
- Saline seep, causing soil crusting.
- Toxic levels of sodium, selenium, and other minerals.
- Chemical destruction of organic matter.

Soil Anions and Their Cycles

Anion nutrients differ from cations in that they are not stored chemically by soil colloids, and form acids in solution. Reserves of anion nutrients are held in the organic portion of the soil, and are released to plants through the decay of organic matter or through the air and water. Depending on the status of soil organisms and the decay cycle, soil anions continually change in form and quantity. As the major building blocks of proteins and carbohydrates, anions are required in larger quantities than are cation nutrients. It is helpful to think of anions as large, soft, and changeable in form, while cations are small, hard, and durable.

When added to the soil as soluble fertilizers, anion nutrients may be lost because they volatilize into the atmosphere, leach away, or revert to more stable, insoluble forms. These soluble fertilizers may be acid-forming, or otherwise harmful to soil organisms. When substituted for nutrient sources rich in organic matter, they can be likened to an addiction: Higher doses will be required to replace the nutrients that were previously supplied naturally by the soil's ecosystem.

- **Nitrogen** tends naturally toward the gaseous state as its most stable and plentiful form. The nitrate form, in which it is present in the soil solution, is extremely transitory and will fluctuate significantly from day to day and even at different times of day. Although plants cannot use atmospheric nitrogen directly, certain soil microbes, most notably the rhizobia

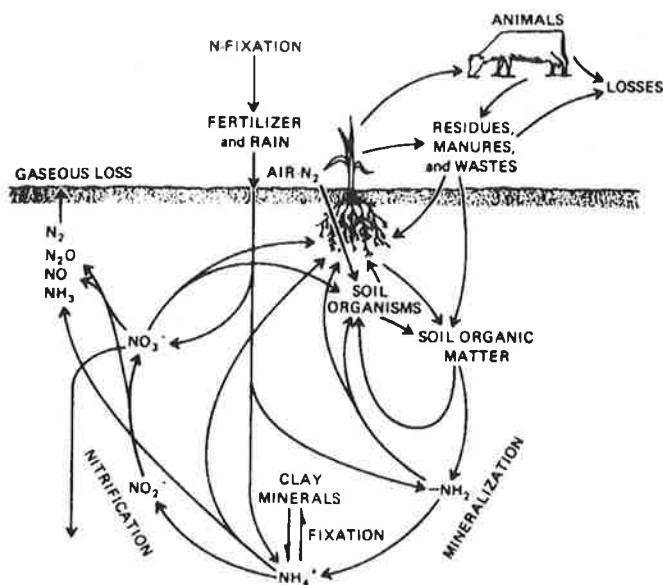


FIGURE 5. *The Nitrogen Cycle. Plants cannot utilize nitrogen in its gaseous form. In order to pass from atmosphere to plant (and then to animals and people), nitrogen must first be fixed by soil microorganisms. To make synthetic fertilizers, atmospheric nitrogen is artificially fixed through use of huge quantities of natural gas. (33,000 to 40,000 cubic feet of natural gas is required to produce one ton of ammonia.)*

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bacteria that live on the roots of legumes, are able to capture it from the air and transform it into a biologically useful form. Free-living soil bacteria such as azotobacter and clostridia are even more important for nitrogen fixation. Still other bacteria transform the nitrogen from ammonium to nitrite and then to nitrate form; each step in the natural nitrogen cycle is essential for plant nutrition.

- **Carbon**, the major constituent of plant (and animal) tissue, is more truly the “food” consumed by plants than any mineral. Although abundant in the organic fraction of the soil, carbon

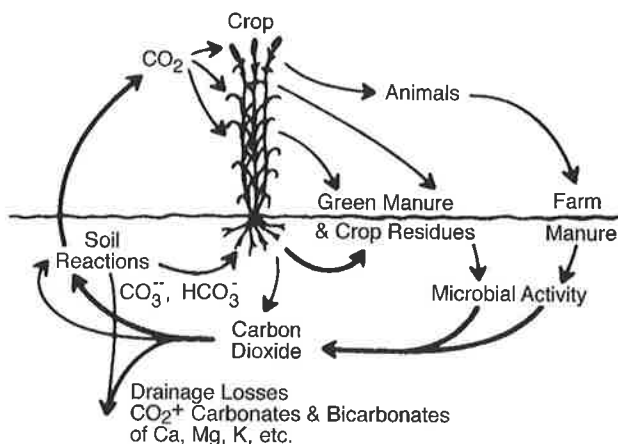


FIGURE 6. *The Carbon Cycle. Gaseous carbon dioxide is transformed by plants into living tissue. Carbohydrates, proteins, and fats are decomposed by soil organisms, thereby replenishing the supply of atmospheric carbon dioxide.*

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is taken in by plants almost entirely from the atmosphere, as carbon dioxide. The carbon dioxide concentration close to the ground can be substantially enriched by the presence of actively decaying organic matter, which directly stimulates plant growth. Lack of carbon dioxide can be a problem in greenhouses, where air circulation must be artificially maintained. An indoor compost pile can add carbon dioxide—and extra heat—to the greenhouse environment.

- **Phosphorus** undergoes some of the most complex chemical interactions of all the elements of soil fertility. It is easily immobilized in the soil through its tendency to form insoluble compounds with calcium and other minerals. At a pH near neutral, even highly soluble phosphorus fertilizers will soon revert to forms indistinguishable from the “natural” rock powders from which they were manufactured. Once added to the soil, immobilized phosphorus stays there a long time;

Table 6
MAJOR ANION NUTRIENTS

<i>Nutrient</i>	<i>Natural sources</i>	<i>Forms in soil</i>	<i>Function in plants</i>	<i>Deficiency symptoms</i>
Carbon (C)	Organic matter, respiration of soil organisms.	Organic compounds, carbon dioxide gas in air spaces, and weak carbonic acids.	Basic constituent of all living cells.	If atmospheric carbon dioxide is limited, plant growth is slowed.
Nitrogen (N)	Organic matter, atmospheric nitrogen fixed by microbes, small amounts dissolved in rain water.	Organic compounds, nitrites, nitrates, and ammonium (soluble forms).	Basic constituent of protein and genetic material.	Thin stems; yellowing (chlorosis) of leaves, beginning with lower leaves; slowed growth.
Phosphorus (P)	Organic matter, mineral powders, some parent materials.	Organic compounds; soluble phosphates; insoluble compounds of iron, aluminum, manganese, magnesium, and calcium.	Essential for genetic material, membrane formation, and energy transfer.	Purpling of leaves, beginning on undersides; stunted roots; slowed growth.
Sulfur (S)	Organic matter, atmospheric sulfur fixed by microbes, pollutants in rain water.	Organic compounds; soluble sulfates, sulfites, and sulfides.	Important constituent of proteins and certain vitamins.	Deficiency is hard to detect, but resembles nitrogen deficiency, with yellowing of whole plant.

many soils, especially in the Midwest, have phosphorus reserves created by government encouragement of excessive fertilizer applications.

Phosphorus is most readily available to plants when released gradually through the decomposition of organic mat-

ter. Its relative immobility means that distribution of phosphorus throughout the soil is only accomplished through the movement of earthworms and other soil organisms. Otherwise, insoluble soil phosphorus reserves can become available to plants through the activities of soil microbes.

- **Sulfur**, an essential component of protein and fats, acts much like nitrogen in the soil ecosystem and is particularly important for nitrogen-fixing microorganisms. A special group of microbes transforms organic sulfur into the sulfate form utilized by plants. Sulfur deficiency is rarely a problem, especially where adequate soil organic matter levels are maintained. Air pollution also has had unintended beneficial effects on the sulfur content of soils downwind. Deficiencies have risen with increased use of highly concentrated phosphate and nitrate fertilizers, which lack the sulfur impurities found in the lower grades. Sulfur is often needed as a nutrient and an acidifier for alkaline soils.

Micronutrients

Micronutrients are elements that are important in very small amounts for the proper functioning of biological systems. Sometimes called “trace elements,” over a dozen of them have been identified as essential in minute quantities for plant, animal, or microbial enzyme functions. Most of the important micronutrients, such as iron, zinc, copper, and manganese, are cations; boron and molybdenum are the most important anion micronutrients.

Micronutrients occur, in cells as well as in soil, as part of large, complex organic molecules in chelated form. The word *chelate* (pronounced “KEE-late”) comes from the Greek word for “claw,” which indicates how a single nutrient ion is held in the center of the larger molecule. The finely balanced interactions between micronutrients are complex and not fully understood. We do know that balance is crucial; any micronutrient, when present in excessive amounts, will

become a poison, and certain poisonous elements, such as chlorine, are also essential micronutrients.

For this reason natural, organic sources of micronutrients are the best means of supplying them to the soil: they are present in balanced quantities and not liable to be overapplied through error or ignorance. When used in naturally chelated form, excess micronutrients will be locked up and prevented from disrupting soil balances. Soil humus reserves also serve to chelate excess metals—nutrients as well as toxins. Unless a specific micronutrient deficiency has been diagnosed by a soil test, the best way to provide adequate supplies is by building organic matter and applying balanced sources of minerals such as rock powders and seaweed. See chapter 4 for more information on micronutrient fertilizers.

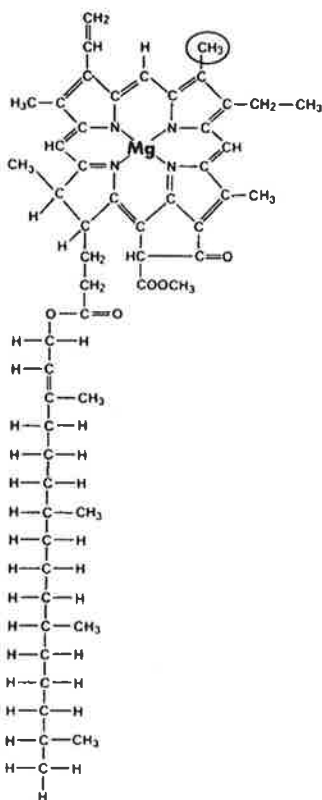


FIGURE 7. Chelation illustrated by the chlorophyll molecule.

Table 7
SOME IMPORTANT MICRONUTRIENTS

<i>Nutrient</i>	<i>Desired amount in soil (ppm)*</i>	<i>Function in plants</i>	<i>Deficiency symptoms</i>
Iron (Fe)	25,000	Chlorophyll synthesis, oxidation, constituent of various enzymes and proteins.	Chlorosis (yellowing), larger veins remain green; short and slender stems.
Manganese (Mn)	2,500	Synthesis of chlorophyll and several vitamins, carbohydrate and nitrogen metabolism.	Yellow mottling of leaves, pale overall coloring, poor maturation and keeping quality.
Zinc (Zn)	100	Formation of growth hormones, protein synthesis, seed and grain production and maturation.	Late summer mottling of leaves. Early defoliation of fruit trees.
Copper (Cu)	50	Catalyst for enzyme and chlorophyll synthesis, respiration, carbohydrate and protein metabolism.	Yellowing and elongation of leaves. Onions are soft, with pale yellow scales.
Boron (B)	50	Protein synthesis, starch and sugar transport, root development, fruit and seed formation, water uptake and transport.	Growing tips die back. Heart rot of root crops, corky core of apples, poor legume nitrogen fixation.
Molybdenum (Mo)	2	Essential for symbiotic nitrogen fixation and protein synthesis.	Pale, distorted, narrow leaves, leaf roll, poor nitrogen fixation.

*Approximate values indicate relative proportions.

A Balancing Act

Balance is the crucial concept for understanding the relationship between chemical nutrients and soil fertility. Fertility requires not only sufficient quantities of nutrients, but their presence in balanced form. In many cases, too much of one nutrient will lock up or interfere with the absorption of another. Phosphorus is the classic example; it will become immobilized at low pH by high concentrations of zinc and iron, and at high pH by too much calcium. Potassium and magnesium will each interfere with the availability of the other, when present in excess. In the case of carbon and nitrogen, too much

Table 8
NUTRIENT INTERACTIONS

<i>Nutrient</i>	<i>Deficiency may be induced by excess of</i>	<i>Excess may induce deficiency of</i>
CATIONS		
Calcium	Aluminum	Magnesium, potassium, iron, manganese, zinc, phosphorus, boron
Magnesium	Calcium, potassium, ammonium	Potassium, zinc, boron, manganese
Potassium	Magnesium, calcium, ammonium	Magnesium, boron
Iron	Phosphorus (high pH), manganese (low pH), calcium, copper, aluminum, zinc	Zinc, manganese
Manganese	Iron, copper, zinc, calcium, magnesium	Iron
Zinc	Phosphorus, nitrogen, magnesium, iron, copper, calcium, aluminum	Iron, copper, manganese
Copper	Phosphorus, zinc, nitrogen	Iron, zinc, manganese
ANIONS		
Carbon	Sulfur, nitrogen, phosphorus	Sulfur, nitrogen, phosphorus
Nitrogen	Carbon, phosphorus	Phosphorus
Phosphorus	Calcium, nitrogen, iron, aluminum, manganese	Zinc, copper, nitrogen
Sulfur	Carbon, nitrogen	
Boron	Calcium, potassium	
Molybdenum	Sulfur, copper	Iron, copper

carbon will stimulate soil microbes to grow and take up all the available soil nitrogen, resulting in a temporary deficiency until the microbes die and release their nutrients to the soil system.

Cation balances have received a lot of scientific attention. **Base saturation** refers to the percentage of a soil's CEC (see box, page 24) occupied by bases—cations other than hydrogen or aluminum.

Some efforts have been made to find the “ideal” cation balance or base saturation ratio. One very influential scientist was Dr. William Albrecht, who conducted research at the University of Missouri in the 1940s. Albrecht's key contribution was to point out the importance of calcium as a major ingredient of fertility, contending that it was the calcium in limestone, not its acid-neutralizing ability, that made it an important fertilizer. He also developed a formula for an optimum base saturation ratio, emphasizing calcium, which has been used by many soil labs to evaluate mineral balances. While it is a useful guideline, Albrecht's ratio is not universally accurate, and should not be relied on exclusively to determine fertilizer needs.

The ideal proportion of anion nutrients is the balance that is normally found in humus: 100 parts carbon to 10 parts nitrogen to 1 part phosphorus to 1 part sulfur. The importance of the carbon to nitrogen ratio was described earlier; however, the ratio of nitrogen to phosphorus is also important to proper plant nutrition, since inadequate nitrogen slows the growth of roots and therefore their ability to reach phosphorus supplies.

Micronutrient problems are as often a result of imbalances as of absolute deficiencies. New information is continually being discovered about previously unknown interactions between major and minor nutrients in the soil ecosystem. This is why the “cookbook” approach to soil chemistry can get you into trouble; the best nutrient sources are those that are naturally balanced. The chart on page 34 will give you some indication of the complexity of known nutrient interactions.

BIOLOGICAL FACTORS: The Living Soil Community

The cycles that permit nutrients to flow from soil to plant are all interdependent, and proceed only with the help of the living organisms that constitute the soil community. Soil microorganisms are the essential link between mineral reserves and plant growth. Animals and people are also part of this community. Unless their wastes are returned to the soil, for the benefit of the organisms that live there, the whole life-supporting process will be undermined.

Soil organisms—from bacteria and fungi to protozoans and nematodes, on up to mites, springtails, and earthworms—perform a vast array of fertility maintenance tasks. Ecological soil management aims at assisting these creatures in their work, rather than substituting a simplified chemical system to provide nutrients to plants. For, once disrupted by the excessive use of soluble fertilizers, the restoration of a healthy soil ecosystem can be a long and costly process.

Soil Inhabitants

Microscopic plants and animals form the basis for the soil food web. Most contribute directly to humus formation and the release of nutrients from organic matter. Stable humus, in fact, consists largely of microbial remains. In cool, humid climates, fungi and molds are more significant than bacteria for humus development. Beyond their importance for soil health, these microbial decomposers are essential to all life on Earth, since they are responsible for virtually all organic waste recycling.

Other creatures, both microscopic and visible, make important contributions to soil health, most notably the earthworm. Plant roots themselves are major participants in the soil ecosystem, and significantly affect the environment that sustains them. Once you become aware of the astonishing number and variety of life forms that are constantly growing, reproducing, and dying in every crumb

of soil—billions in each gram of healthy topsoil—it is impossible to pick up a handful of earth without feeling a sense of awe. Each organism has a role to play in the soil ecosystem:

- **Producers** create carbohydrates and proteins from simple nutrient elements, almost always by capturing energy from sunlight through photosynthesis. Green plants, including blue-green algae, are the producers of the soil. A few specialized bacteria, known as **autotrophs**, are also able to synthesize their own food from carbon dioxide and mineral elements in the soil.
- **Consumers** are just about everyone else, who all depend on the food created by green plants for their nourishment. Primary consumers eat plants directly, while secondary and tertiary consumers feed on other consumers. All animal life, from simple protozoans to humans, as well as nonphotosynthesizing plants, such as yeasts and certain other fungi, fall into this category.
- **Decomposers** perform the critical function of bringing the basic chemical nutrients full circle, from consumers back to producers. They are all bacteria or fungi, and are found almost exclusively in the soil; about 60 to 80 percent of the total soil metabolism is accounted for by microbial decomposers. Without them, life would grind to a halt as we suffocated in our own wastes.

What They Need

If the surest route to improving soil fertility is to provide the most hospitable conditions for soil life, understanding the basic needs of soil organisms is the first step. Successful composting requires the same knowledge: Provide soil beasties with adequate food, air, and water, and—depending on other environmental factors, such as temperature—they will flourish.

Table 9
SOIL ORGANISMS

<i>Organism</i>	<i>Approximate soil population</i>	<i>Special requirements</i>	<i>Source of nutrition</i>	<i>Role in ecosystem</i>
MICROFLORA				
Fungi: yeast, molds, mycorrhizae.	10 ⁵ –10 ⁶ per gram	Will tolerate wide pH and temperature ranges.	Organic matter or nutrients from plant roots.	Humus formation, and aggregate stabilization. Create antibiotics, cause plant diseases, make phosphorus available.
Actinomycetes.	10 ⁷ –10 ⁸ per gram	Need aeration, moisture, and pH 6.0–7.5.	Organic matter.	Humus formation.
Bacteria	10 ⁸ –10 ⁹ per gram	Most need air (aerobes), and exchangeable calcium.	Autotrophs consume simple nutrients from soil and air.	Autotrophs are nitrogen-fixers, sulfur oxidizers, nitrifiers. Some cause disease.
Autotrophs: <i>Azotobacter,</i> <i>Rhizobia,</i> <i>Nitrobacter.</i>		Temperature of 70°–100°F, pH 6–8.	Heterotrophs break down organic matter.	Heterotrophs are decomposers.
Heterotrophs: decay organisms.				
Algae: green, blue-green.	10 ⁴ –10 ⁵ per gram		Photosynthesis.	Add organic matter to soil. Some fix nitrogen.
MICROFAUNA				
Nematodes.	10–100 per gram		Organic matter, other microbes, plant roots.	Secondary consumers. Some are pests and parasites.
Protozoa, rotifers.	10 ⁴ –10 ⁵ per gram			
INSECTS & MOLLUSCS				
Mites, springtails, spiders, sowbugs, ants, beetles, centipedes, millipedes, slugs, snails.	10 ³ –10 ⁵ per m ²		Microflora, microfauna, other insects, plant roots and residues, nematodes, molluscs, detritus (waste matter), organic matter, weak plants.	Aerate and mix soil. Leave remains for decomposers. Cull weak or diseased plants.

Table 9 (continued)

SOIL ORGANISMS

<i>Organism</i>	<i>Approximate soil population</i>	<i>Special requirements</i>	<i>Source of nutrition</i>	<i>Role in ecosystem</i>
EARTHWORMS				
Earthworms.	30–300 per m ²	Raw organic matter.	Aerate and mix soil.	Leave nutrient-rich casts.
MAMMALS				
Moles, mice, goundhogs.	Variable	Earthworms, insects, molluscs.		Mix and pulverize soil. Leave wastes.
PLANT ROOTS				
Roots.	100–6,000 lbs. per acre.		Photosynthesis; nutrient ions and molecules.	Remove water and nutrients; leave residues and exudates.

Both soil and compost creatures need the same food: raw organic matter with a balanced ratio of carbon to nitrogen—approximately 25 or 30 parts to 1. Carbon, in the form of carbohydrates, is really the main course for soil organisms: they will grow quickly given lots of it, and will scavenge every scrap of nitrogen from the soil system to go with it. That's why adding lots of high-carbon materials to your soil can cause nitrogen deficiencies in plants. In the long term, though, carbon is the ultimate fuel for all soil biological activity, and is therefore crucial to humus formation and plant productivity. A balanced supply of mineral nutrients is also essential for soil beasts, and micronutrients are key to the many bacterial enzymes involved in their biochemical transformations. Balanced nutrients also provide a favorable pH, though different organisms are more sensitive to acid or alkaline conditions.

Air is also crucial for soil health, although certain bacteria can live without it (see box, page 42). In fact, much effort in soil management is directed toward improving soil aeration: no amount of

fertilizing can compensate for lack of air, since plant roots cannot take full advantage of available nutrients if they are suffocating.

Water is also strictly essential, but not to the extent that it drives out air. The ideal biological environment consists of a thin film of moisture clinging to each soil particle, with lots of air circulating between them. Rain and irrigation, of course, play a central role in adding needed soil moisture, but good structure is also required to conduct moisture upward from reserves in lower soil strata (see page 19).

Although temperature has critical effects on biological activity, every specific soil community has evolved to accommodate the natural climate variations in its environment. Your only role in adjusting the temperature might be to moderate severe winter cold or summer heat by mulching, or to heat up small areas with season extension devices.

Soil Superstars

Despite the many volumes that have been written about soil biology, knowledge of the kinds of organisms that live in soil and how they interact is extremely limited. Although some scientists have tried to work out biological assays to identify a soil's characteristics and needs by examining its living population, such tests are still extremely complex to carry out and difficult to interpret accurately.

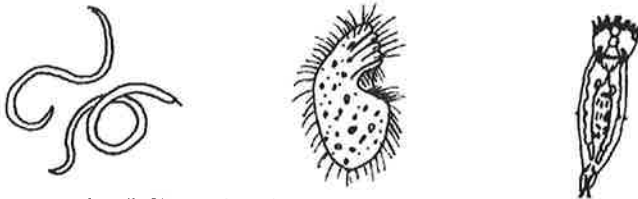
The table on pages 38–39 summarizes the major types of soil life forms. A few portraits of the more familiar and celebrated soil inhabitants, in order of size, follows:

Bacteria: Bacteria are the most numerous and varied of soil organisms, ranging from a few hundred million to three billion in every gram of soil. Under the right conditions they can double their population every hour. The top six to eight inches of soil may contain anywhere from a couple of hundred pounds to two tons of live bacteria per acre.

Bacteria vary in their requirement for air, but most beneficial ones need it (see box, page 42). If enough moisture and food are present, bacteria do best at temperatures of 70° to 100°F (21° to 38°C), and at a pH close to neutral. Adequate calcium is crucial, as is a balance of micronutrients, which are essential to the enzymes em-



The three most important plant microorganisms of the soil. Fungal mycelium (left), various types of bacteria cells (center), and actinomycetes threads (right). The bacteria and actinomycetes are much more highly magnified than the fungus.



Parasitic nematodes (left), a ciliated protozoan (center), and a common rotifer (right).



Some soil organisms especially important in the nitrogen cycle. Azotobacter (left), nitrate bacteria (center), and nodule organisms of alfalfa (right).

FIGURE 8. *Important Soil Organisms.*
(Drawing by Timothy Rice)

ployed by bacteria to perform their crucial biochemical tasks. Unfavorable conditions rarely kill bacteria off completely; they will either stop growing and form spores to wait for better times, or adapt to the changed conditions as genetic mutations quickly spread to new generations. This adaptability can work against you when the organism in question causes a plant disease, though. If any soil nutrient is in limited supply, bacteria will be the first to consume it; plants then must wait to partake until the microbes die and decompose.

BACTERIA AND BREATHING

The soil micro-universe is divided into two general types of bacteria: those that need air and those that don't. The availability of air thus determines which kinds of bacteria will flourish, and how vigorously they will grow.

- Aerobes require air in order to live. The bacteria that mediate the soil nitrogen and sulfur cycles, as well as many important decomposers, are aerobes. All other soil organisms are also aerobic, including plant roots. Some bacteria can survive in either aerobic or anaerobic conditions, but will only grow and thrive if they have air.
- Anaerobes can live happily without air, and in fact may be killed if exposed to it. The bacteria responsible for diseases like botulism and tetanus are famous examples. There are many anaerobic decomposers, which often generate some foul-smelling waste products, such as hydrogen sulfide, and the common term for the process of anaerobic decomposition is **putrefaction**. Anaerobic bacteria can also generate useful by-products such as methane gas, which is sometimes used as an energy source.

Bacteria have a virtual monopoly on three basic soil processes that are vital to higher plants: nitrification, sulfur oxidation, and nitrogen fixation. Nitrifying bacteria transform nitrogen in the form of ammonium, a product of protein decomposition, into nitrate, the form most available to plants. The sulfur oxidation process is analogous to nitrification. Nitrogen-fixing bacteria are able to transform elemental nitrogen from the atmosphere into protein, and eventually make it available to other organisms—a process imitated by humans at a high energy cost. They may live in symbiosis with plant roots, such as the members of the *Rhizobium* family, or they may be free-living soil dwellers, such as *Azotobacter*.

Fungi: Yeasts, molds, and mushrooms are all fungi, and only yeasts have little presence in the soil. Although they are plants, they do not contain chlorophyll and so must depend on other plants for their nourishment. Molds may be as numerous as bacteria in soil, and will outnumber them under conditions of poor aeration, low temperature, and acidity, which they tolerate more easily. Although many plant diseases are caused by soil-dwelling molds such as *Fusarium* and *Aspergillus*, those in the *Penicillium* family are well known as disease fighters. Molds are especially important for humus formation, predominating in humus-rich, acid forest soils.

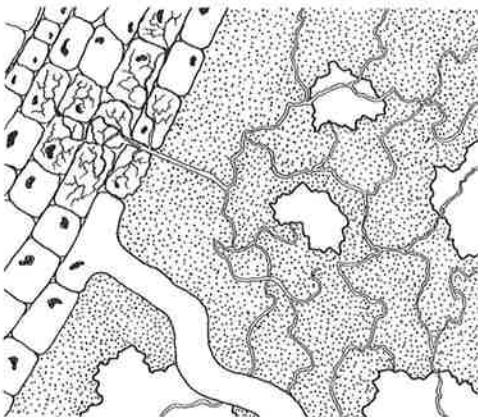


FIGURE 9. *Mycorrhizae* infecting a plant root and extracting nutrients from rock particles.

(Drawing by Timothy Rice.)

One extremely significant group of fungi are called mycorrhizae, a term meaning "fungus root." These mushrooms enter into symbiotic relationships with plant roots of many kinds, and are thought to be essential for the health of trees such as pine and birch. The fungi are able to convert otherwise insoluble nutrients, most notably phosphorus, into biological forms, and in turn receive carbohydrates from their host plants. Many crop plants are known to enter into **mycorrhizal associations**, but they are most significant for plants growing on poor soils, where the fungal ability to extract nutrients from rock particles is most critical to the host plant's nutrition.

Actinomycetes: These microbes are like a cross between bacteria and fungi, and are the most numerous soil organisms after bacteria. The characteristic aroma of freshly plowed earth is attributed to actinomycetes, which play a critical role in organic matter decomposition and humus formation. They need plenty of air and a pH between 6.0 and 7.5, but are more tolerant than either bacteria or fungi of dry conditions. Their intolerance of low pH can be used to advantage in preventing potato scab, a disease caused by an actinomycete. Manure is especially rich in actinomycetes, which is why many people consider manure to be essential for making high-quality compost.

Algae: Algae are single-celled plants, usually containing chlorophyll, and are slightly less numerous in the soil than are fungi. Blue-green algae are common in many kinds of soils, but are particularly important in paddy rice culture because of their tolerance for high moisture levels and their ability to fix atmospheric nitrogen. All algae growth is greatly stimulated by farm manure.

Microfauna: Microscopic soil animals including nematodes, protozoans, and rotifers. Nematodes, commonly called threadworms or eelworms, are extremely widespread and numerous in most soils.

PLANT-MICROBE SYMBIOSIS

The mutually beneficial relationships between plant roots and soil microbes are complex and widely varied. Some of these arrangements are well understood, but many remain mysterious. As we learn more about the workings of these microorganisms, they will undoubtedly be used more widely to improve crop production.

A few bacteria are able to convert nitrogen gas from the air into a form usable by the roots of the plant with which they associate. *Rhizobium* bacteria, for example, form visible nodules on the roots of legumes, whose growth is greatly enhanced by the nitrogen fixed there. When the legumes are returned to the soil, as with green manure crops, the nitrogen fixed by the rhizobia becomes available to the subsequent crop (see table 17). When a legume is grown in association with another crop, for example grasses or grains, the nitrogen fixed by the rhizobia is available to the associated crop while the two are growing together. Because not all soils contain these desirable nitrogen-fixing bacteria, when farmers plant legumes they often inoculate either their soil or seed with preparations containing rhizobia.

Other soil organisms, such as the actinomycete *Frankia*, the bacteria *Azotobacter*, and some blue-green algae, are likewise capable of fixing nitrogen, with and without host species.

It has been estimated that more than 80 percent of plants have symbiotic associations with fungal mycorrhizae, whose pervasive filaments extend the reach of plant roots in the soil, often improving the roots' ability to absorb nutrients. Some of these mycorrhizae are relatively nonspecific, able to penetrate the roots of many different species of plants in various ecosystems. Others are quite specific, surrounding the roots of only one plant species in one type of soil.

Although they are often thought of as troublesome plant pests, the most common kinds help break down organic matter or prey on bacteria, algae, or other soil animals. Some parasitic nematodes are used as biological control agents for soil-dwelling pests such as cabbage root maggots. Protozoans are one-celled animals that are larger than bacteria, often using them as a food supply. Rotifers are common in wet soils, feeding by spinning around and sweeping food particles into their “mouths.”

Earthworms and Other Macrofauna: Of the numerous animals who make their homes in the soil, from miniscule spiders to prairie dogs, the earthworm is the most closely identified with soil health (see box, “The Noble Worm”). Other small soil animals include mites and spiders, beetles, springtails, flies, termites, ants, centipedes, and slugs, as well as the larval forms of many butterflies and moths. Many of these creatures play an important role in breaking down organic materials into smaller pieces and simpler compounds; some are significant as plant pests. Mammals such as moles, voles, gophers, and other burrowers can sometimes be a nuisance when they decide your broccoli looks good to them; however, they too contribute to the soil ecosystem by keeping pest populations in check, mixing soil, and depositing their droppings.

Farm Animals: The importance of farm animals to soil fertility sometimes gets overlooked. Although modern “factory farming” concentrates too many animals on small areas, the ideal farming system should include some animals. Besides contributing valuable manure, farm animals are important for a number of ecological soil-building practices:

- Soil-building rotations require sod crops and legumes, which are often only economically feasible when used as animal feed.

- Animals are often the only means to harvest a crop (besides trees) on soils that are too wet, steeply sloping, or stony to cultivate.
- Pigs and chickens can improve the soil by acting as living rototillers, scratching and aerating a patch before crops are planted. They also eat weeds and ground-dwelling pests.

THE NOBLE WORM

A good earthworm population is universally considered a sign of healthy soil. Unparalleled as soil excavators, earthworms spend their lives ingesting, grinding, digesting, and excreting soil: as much as fifteen tons of soil per acre goes through earthworm bodies in a year. Earthworm castings are richer in nutrients and bacteria than the surrounding soil, and may add up to as much as eight tons of nutrients per acre in cultivated fields. Their contribution to drainage and aeration, soil aggregation, and transport of nutrients from the subsoil is significant as well. It is for good reason that Charles Darwin extolled earthworms as the “intestines of the soil.”

Of about two hundred known earthworm species, *Lumbricus terrestris* is the most common: interestingly enough, it is not native to North America, but came with the Europeans and turned out to be better adapted to cultivated conditions than its native predecessor. Earthworms, unlike the types of worms used for composting, prefer cool temperatures—about 50°F (10°C) is optimum. They need good aeration and enough but not too much moisture. Although some species can tolerate fairly acid soils, most require adequate calcium supplies and thus more neutral pH. They are also sensitive to many toxic pest- and weed-control chemicals, as well as fertilizers with a high salt index.

Life in the Root Zone

Plant roots themselves play an important role in soil ecology. The largest numbers and kinds of organisms are found in the uppermost layers of the soil, closer to fresh sources of air, water, and food. True, some biological activity happens even at fairly deep levels, especially where earthworms and other animals burrow, and where deep-rooted plants grow. However, in the area immediately surrounding plant roots, known as the **rhizosphere**, there are concentrations of ten to as many as one hundred times more organisms than can be found elsewhere in the soil. A soil such as that found under permanent grass sod, totally permeated by fibrous masses of roots, will inevitably have a healthier, more robust microbial population than one with cleanly cultivated row crops.

Most of the important soil biological transformations take place in the rhizosphere, especially nitrogen fixation and mycorrhizal associations. The outer coating of the growing root tip, called the **mucigel**, is a fascinating substance, a product of both the root and the microcommunity around it. A gelatinous substance secreted by the root, the mucigel is a rich mass of microbes and chemical nutrients that connects the plant directly to the life of the soil.

Some ways in which plant roots interact with the rest of the soil community include:

- Roots can take up cation nutrients directly from exchange sites on soil particles in exchange for hydrogen, through a process known as **adsorption** (see page 24).
- Plant roots give off carbon dioxide in the process of respiration, just as animals do. Together with the release of hydrogen described above, this creates slightly more acid conditions in the rhizosphere, since carbon dioxide forms a weak acid when dissolved in water. This slight acidity helps to make otherwise insoluble phosphorus and micronutrients more available.

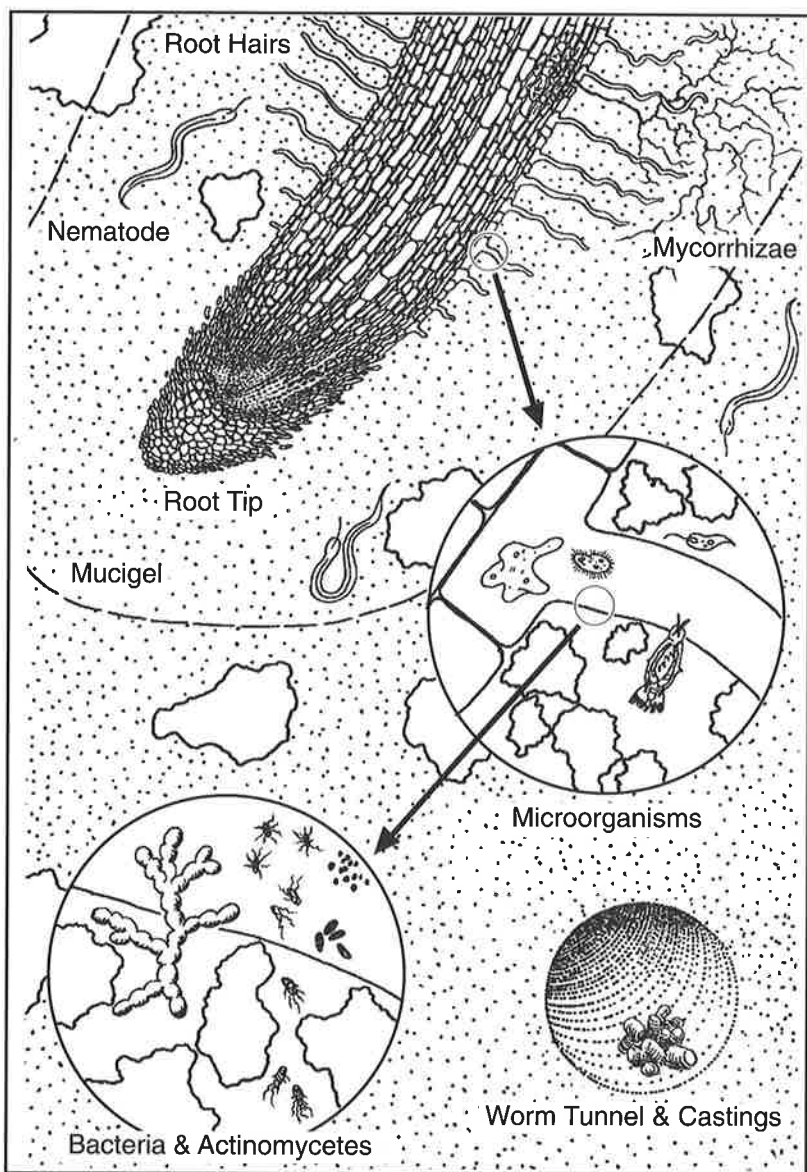


FIGURE 10. *The rhizosphere, a region approximately 3mm wide, and the zone of highest biological and chemical activity where soil, root, and microbes interact. Mucigel is a gelatinous substance surrounding the root that is both the mediator and the product of the root-soil-microbe community.*

(Drawing by Timothy Rice.)

- Roots give off certain biochemical compounds called **exudates**, which sometimes act as **phytotoxins**, chemical inhibitors of competing plant species—a process called **allelopathy**. Winter rye, for example, gives off exudates that suppress couchgrass growth.
- The dead tissue continually sloughed off by growing roots is excellent food for microorganisms. The organic contribution of the root portion of a green manure crop often is more substantial than the part you see above the surface.
- Plant roots are able to take up many complex organic compounds such as hormones, vitamins, antibiotics, and humus fractions, as well as toxic substances like pesticides and herbicides. This is an important counter to the argument that the source of plant nutrients—whether chemical fertilizers or compost—is irrelevant to plant health.

Soil and Civilization

All land-dwelling animals, including humans, are members of the soil community. Human societies disregard this fact at their own peril: soil fertility has historically been squandered for the immediate enrichment of a few at the expense of future generations. Cultural values—ethics, aesthetics, and spiritual beliefs—have a profound influence on how soil is treated.

Not only the farm itself, but also the society of which it is a part must be viewed as components of the soil ecosystem, for all support and maintain one another and none can exist independently. Without a good-sized nonfarm community nearby, for example, marketing becomes a problem for the farmer; yet too large a nonfarm community exerts pressure to convert productive farmland to other uses. A whole book could be written about the effects of political and economic pressures on soil fertility—especially in the “Third World,” where peasants are forced to produce export crops for foreign exchange instead of food for their families.

The 1992 United Nations Earth Summit acknowledged the importance of sustainable agriculture as a means of reversing worldwide environmental degradation. Implementing its recommendations will require widespread public consciousness-raising. Political and social activism are, more clearly than ever, essential components of soil stewardship.