2.2

Soil Chemistry and Fertility

Introduction: Soil Chemistry & Fertility

UNIT OVERVIEW

This unit introduces students to basic concepts in soil chemistry, with an emphasis on how soil chemistry relates to the development and maintenance of soil fertility.

The unit begins with a review of basic chemistry concepts and terminology, including atoms, compounds, ions, and chemical reactions. Soil nutrients essential to plant growth and the processes involved in nutrient uptake are introduced, with particular attention paid to cation exchange capacity (CEC) and base saturation as they relate to soil fertility. Soil pH and its effects on nutrient availability are also covered.

Lecture 2 provides an overview of the biogeochemical cycles involved in making essential nutrients available to plants; the physiological role of essential plant nutrients; the characteristic symptoms of plant nutrient deficiencies; and the soil amendments used to supply limiting nutrients for organic farming systems.

MODES OF INSTRUCTION

> LECTURE (2 LECTURES, 1.5–2.0 HOURS EACH)

Lecture 1 covers basic chemistry concepts and definitions relating to soil chemistry, in particular, nutrient uptake processes and plant nutrients.

In Lecture 2, the role of individual plant nutrients and nutrient cycling are discussed.

> DEMONSTRATIONS

Five suggested demonstrations are designed to be integrated into the lecture. They provide visual representations and analogies for the concepts presented in the outline.

> ASSESSMENT QUESTIONS (1.0 HOUR)

Assessment questions reinforce key unit concepts and skills.

LEARNING OBJECTIVES

CONCEPTS

- Basic chemistry concepts (atomic structure and atomic bonding) and terminology
- Principles and processes involved in cation exchange
- pH and its effects on nutrient availability
- Soil acidity
- Soil alkalinity
- Plant nutrients: What they are, their cycles and how they move through the soil, their use by plants, and the problems plants exhibit when deficient in nutrients

SKILLS

This material is primarily conceptual, providing background for the skill-based sessions in Part 1, Organic Farming and Gardening Skills

REQUIRED READINGS (SEE RESOURCES SECTION)

Gershuny, Grace. 1996. *Start With the Soil,* Chapter 5; Chapter 7, pages 163-173; Chapter 8, pages 187-195; Chapter 9, pages 200-205

Brady, Nyle C., and Ray R. Weil. 2008. *The Nature and Properties of Soils,* Chapter 1, 1.15-1.16; Chapter 16: 16.1-16.4; 16.12

RECOMMENDED READINGS

Stell, Elizabeth P. 1998. *Secrets to Great Soil,* Chapter 2; Chapter 6; Chapter 7, pp. 150-157

Parnes, Robert. 1990. *Fertile Soil: A Grower's Guide to Organic and Inorganic Fertilizers,* Chapter 2, pp. 9-19; Chapter 16 (micronutrients)

Lecture 1: Basic Soil Chemistry Concepts & Nutrient Uptake

Pre-Assessment Questions

1. What are the three most important plant nutrients? What are three other essential plant nutrients?
2. How do plants obtain nutrients from the soil?
3. What might happen if levels of one essential plant nutrient are very low or very high?
4. What is soil pH and why is it important to know the pH of your soil?
5. How does the organic matter content of the soil influence soil fertility?

A. Introduction to Basic Chemistry Concepts

1. Atoms and elements

   Element: a basic unit of matter that can't be further simplified, such as oxygen or iron. Elements are the building blocks of nature. Each element is assigned a symbol of one or more letters, such as O for oxygen and Fe for iron.

   Atom: the smallest part of an element that cannot be broken down by chemical means. Each atom is in turn made up of protons, neutrons, and electrons. Protons have positive electrical charges, electrons have negative charges, and neutrons have no charge. Protons and neutrons are in the center of the atom, comprising the nucleus, while electrons orbit the nucleus. Atoms have no net charge, so there are an equal number of protons and electrons, which is the atomic number. The number of neutrons varies, and is determined by subtracting the atomic number from the mass number (the atomic weight rounded up to the nearest whole number). The atomic weight for each element is given on the periodic table.

2. Compounds, molecules, and atomic bonds

   Atoms combine to form molecules. A collection of like molecules that consist of two or more different kinds of elements is called a compound. Molecules are represented by using the symbols of the elements with subscripts to tell how many there are of each. For example, water is represented as H_2O, which means it has two hydrogen atoms and one oxygen atom.

   One way that different atoms can join together is by sharing electrons. This is a type of chemical bond or atomic bond.

3. Ions

   When there is an imbalance in the number of protons and electrons of an atom, the resulting atom or molecule is called an ion. Ions are commonly formed, for example, when a compound dissolves in water. A cation is a positively charged ion (missing electrons) and an anion is a negatively charged ion (has surplus electrons). The example below shows calcium carbonate (on the left) when it dissolves in water (on the right). The superscript numbers indicate the number of missing (+) or surplus (-) ions. If no number is given and there is just a + or - then there is an imbalance of only one (1) electron.

   $CaCO_3 \rightleftarrows Ca^2 + CO_3^{2-}$

   Where:

   $CaCO_3$ = Calcium Carbonate
   Ca^{2+} = Calcium (cation)
   CO_3^{2-} = Carbonate (anion)

A molecule in solution is usually in equilibrium with its constituent ions. In other words, some molecules are breaking into ions while other ions are recombining to form molecules.

4. Elements needed by plants
   a) From water and air

      Carbon (C), Hydrogen (H), Oxygen (O)

   b) From soil

      Nitrogen (N), Phosphorus (P), Sulfur (S), Potassium (K), Calcium (Ca), Magnesium (Mg), Copper (Cu), Iron (Fe), Manganese (Mn), Zinc (Zn), Boron (B), Molybdenum (Mo), Cobalt (Co), Chlorine (Cl)

5. Chemical reactions

   Chemical reactions occur when atoms are rearranged to form new molecules or compounds. For example, carbon dioxide and water can combine to form a sugar (as in photosynthesis). This reaction is written out like this:

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

   (Note that since energy is required to make the reaction happen, this energy is released when the sugars are broken down. This energy-releasing equation is called respiration and is what happens in our bodies—and in some form in all organisms—all the time.)

   Redox reactions are paired oxidation and reduction reactions that are very common and important in nature. Oxidation occurs when an element or molecule loses an electron, and reduction occurs when another element or molecule gains the electron. The electron donor is said to be oxidized and the electron acceptor is reduced. The "ox" in redox is used because it was first studied in aerobic environments, with oxygen as the element that accepts the electrons (and thus increases in quantity in the new molecule).

   A common redox reaction occurs in the soil when ammonia is added: In the presence of oxygen, ammonia (NH_3) is oxidized to form nitric acid (HNO_3, which now contains oxygen) and water

   $$NH_3 + 2O_2 \rightarrow HNO_3 + H_2O$$

   (ammonia + oxygen → nitric acid + water)

6. Adsorption vs. absorption

   Adsorption and absorption are two similar soil science terms with almost opposite meanings

   Adsorption means to be held onto the outside of something. In soils this refers to how ions are held to the outer surfaces of mineral and organic particles.

   Absorption means to be taken up into something, such as water being taken up by a sponge or nutrients being taken into plant roots

   Picture a life raft at sea: Absorbed would be the people in the life raft, adsorbed would be the people hanging to the outside of the life raft

7. Organic vs. organic

   Organic is another term with multiple meanings. To the chemist, organic refers to many kinds of compounds containing carbon, which may be natural or synthetic (human-made). Many of the synthetic pesticides used are "organic" by this definition.

   Organic also refers to agricultural practices based on maintaining soil fertility through organic matter. Such systems do not use synthetic organic chemicals. When growers or food processors abide by a particular set of U.S. Department of Agriculture regulations and their practices are confirmed for that site by a certifying agency, they legally may market their food as "organic."

B. Soil Colloids

1. Definition

   Colloid: A particle, either mineral or organic, with a diameter of 0.1 to 0.001 µm. Because of their small size, colloids go into suspension in a solution—they float around for great lengths of time without settling out. Clay particles and soil organic matter are common examples of soil colloids.

2. Importance

   Colloids have properties that are important in soil chemistry. For example, because of their small size they have a high relative surface area that has a charge, so they can adsorb cations. This is key for Cation Exchange Capacity (see CEC, below), but also for maintaining the structure of the soil (binding particles together) and for its water-holding capacity (higher concentration of colloids means greater ability to hold water).

C. Soil Solution

1. Definition

   Water in the soil is referred to as the soil solution because it contains dissolved materials (cations and ions) as well as suspended colloids of clay and organic matter

   While plants tend to get their nutrients from the soil solution, the solution does not contain sufficient nutrients at any one time to last the life of the plant. Usually these nutrients are replenished from the pool of exchangeable nutrients (those that are adsorbed onto colloids; see CEC, below). Still more nutrients are held in what is called the stable pool (bound up in solid form as minerals or organic matter).

D. Cation Exchange Capacity (CEC) and Base Saturation

1. CEC

   a) Definition

      CEC is a measure of the ability of the soil to adsorb cations. Plants are primarily able to take up the ionic form of nutrients via their roots. Many of these nutrients are taken up as cations (remember, these are positive ions). Most soils have at least some ability to hold onto cations at negatively charged sites, called exchange sites, on soil particles. **(Demonstration: Use magnets to demonstrate attraction of positive to negative.)** The cations are held loosely to the edges (adsorbed) such that they can be easily replaced with similarly charged cations. The total amount of the cations that the soil can hold adsorb is the cation exchange capacity (CEC).

   b) Measurement: CEC is measured as milliequivalents (meq) per 100g of soil or centimoles (cmol) per kg. These are actually two ways of expressing the same numbers.

   c) Factors influencing CEC

      i. Amount and type of clay

         Higher amounts of clay in the soil (relative to sand and silt; see more at Unit 2.1, Soil Physical Properties) mean higher CEC. Certain kinds of clay (smectites, montmorillonite) have higher CEC than others (such as kaolinite).

      ii. Amount of organic matter

         Higher amounts of organic matter in the soil mean higher CEC

      iii. pH-dependent CEC

         Clay minerals and organic matter have a CEC that varies with pH. As pH increases, so do the number of negative charges on the clay or organic matter particles, and thus so does the CEC.

2. Base saturation

a) Definitions

Base saturation refers to the percentage of CEC sites that are occupied with bases (usually Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) instead of ions that make the soil acidic (H+ or Al3+). Base saturation is often expressed as a percent.

The term *exchangeable bases* usually refers to the Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} adsorbed to CEC sites.

b) Significance

Soils with high base saturations are considered more fertile because many of the "bases" that contribute to it are plant nutrients. Usually the base saturation is 100 percent when the pH is above about 6.5. Since rainfall tends to leach bases out of the soil, areas with higher rainfall tend to have lower base saturations than areas with lower rainfall, unless the parent material is high in bases (such as limestone).

E. Anion Exchange Capacity (AEC)

1. Definition

   While positively-charged cations adsorb to negatively-charged sites, the opposite is true for negatively-charged anions: They adsorb to sites with a positive charge. This is anion exchange capacity, AEC. Nutrients that are usually supplied by anions are nitrogen (as NO_3), phosphorus (as HPO_4^{2-}), sulfur (as SO_4^{-}), chlorine (as Cl^{-}), boron (as $B_4O_7^{2-}$) and molybdenum (MoO_4-).

2. Measurement: Just like CEC (above), AEC is measured as milliequivalents (meq) per 100g of soil or centimoles (cmol) per kg.

3. pH-dependent AEC: Most clay particles only have negative exchange sites, so they have CEC in neutral and high pH conditions and sometimes AEC at low pH. Soil organic matter has both negative and positive exchange sites; it usually has CEC and may have AEC in very low pH (2 or lower) conditions. Most productive soils in the U.S. have pH well above the pH necessary for AEC, so this process plays a minor role in nutrient provision here. Highly weathered soils of the tropics are more likely to have AEC.

4. Nutrient leaching: Because there is generally little adsorption of anions, many (particularly nitrates) are easily leached down through the soil with rain or excess irrigation. This can lead to groundwater contamination, which can even happen in organic farming if the N is not well managed.

F. pH

1. What is pH?

   pH stands for "potential of hydrogen" and it is expressed as the negative of the log of the concentration of hydrogen (H^{+}) ions. It is given as a number between 0 and 14. (Pure water is neutral with a pH of around 7.) In acidic soils ($pH < 7$), H^{+} ions predominate. In alkaline soils ($pH > 7$), OH^{-} ions predominate. Soils with pH of 7 are neutral. **(Demonstrate different methods of measuring pH; see pH demonstration in Demonstrations.)**

▶ TABLE 2.11 | SOIL REACTION AND pH

REACTION	pH	REACTION	pH
Ultra acid	< 3.5	Neutral	6.6 – 7.3
Extremely acid	3.5 – 4.4	Slightly alkaline	7.4 – 7.8
Very strongly acid	4.5 – 5.0	Moderately alkaline	7.9 – 8.4
Strongly acid	5.1 – 5.5	Strongly alkaline	8.5 – 9.0
Moderately acid	5.6 – 6.0	Very strongly alkaline	> 9.0
Slightly acid	6.1 – 6.5		

2. Effect of pH on nutrient availability and uptake (see ◀ Figure 2.8, Nutrient Availability at Different pH Values)

   Although pH does not directly affect plants, it does affect the availability of different nutrients to plants. As we've seen in the CEC and AEC sections above, nutrients need to be dissolved in the soil solution before they can be accessed by plants. The soil pH changes whether a nutrient is dissolved in the soil solution or forms other less-soluble compounds (e.g., calcium compounds in high pH soils with high calcium carbonate concentrations), or if dissolved is then susceptible to leaching (e.g., nitrate).

3. pH and soil microbes

   Soil microbes have reduced activity in low pH soils. This can cause them to take much longer to release necessary nutrients, such as N, P, and S, from organic matter.

G. Acidity

1. Definitions

   Acidity refers to the condition of the soil when the exchange sites on soil colloids (collectively called the *exchange complex*) are dominated by hydrogen (H^+) and aluminum (Al^+) ions. As described above, these soils have pH <7.

2. Distribution of acid soils

   Acidic soils usually occur where rainfall leaches the cations out of the soil over time. In the U.S. there is a fairly strong correlation between precipitation and pH, with soils receiving more than about 30 inches of annual precipitation having a pH < 6. (See map on page 163 of *Start with the Soil*.)

3. Problems associated with acidity

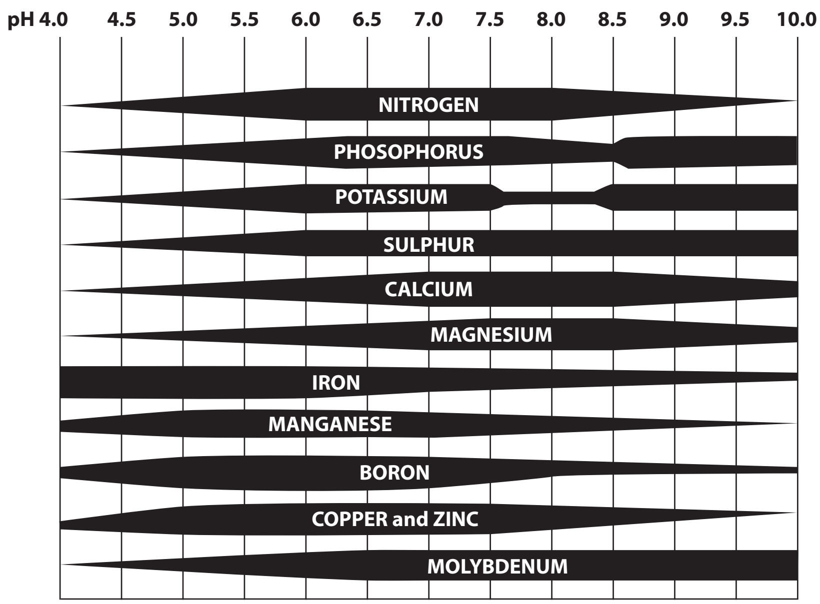
   Aluminum toxicity: Aluminum becomes more available when pH is pH <6 and especially <4.75, and can be toxic to plants.

   Manganese toxicity: This may occur in soil that are high in Mn and that have a pH < 5.

4. Acid soils and liming

   Lime (calcium carbonate) is added to acid soils to raise the pH (see Unit 1.11, Reading and Interpreting Soil Test Reports). Calcium (Ca^{2+}) replaces hydrogen and aluminum on the exchange sites. For a good reference on liming, see the Soil Quality – Agronomy Technical Note Number 8 (listed in Resources). **(See Acid Demonstration in Demonstrations.)**

◀ **FIGURE 2.8** | NUTRIENT AVAILABILITY AT DIFFERENT pH VALUES. MAXIMUM AVAILABILITY IS INDICATED BY WIDEST PART OF BAR.



H. Alkaline, Saline, and Sodic Soils

1. Overview

   Alkalinity and acidity: Soils that vary from a neutral pH have varying degrees of alkalinity (pH > 7) or acidity (pH < 7). The mean soil pH in the U.S. is around 6.4.

   Salinity: Soils that have excess soluble salts in the soil solution have varying degrees of salinity

   Sodicity: Soils that specifically have excess sodium in the soil solution are called sodic

2. Alkalinity

   Soils in arid and semi-arid areas can lack enough rainfall to leach cations, especially calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+), from the soil. These cations bind many of the CEC sites, blocking hydrogen (H^+) ions from binding and making the soil alkaline. This can also happen if irrigating with water high in calcium bicarbonate or magnesium bicarbonate.

3. Salinity

   A soil containing sufficient soluble salts (these salts include Mg^{2+}, Na^+, Ca^{2+}, chloride (Cl^-), sulfate
   (SO_4^{2-}), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). Saline soils mainly occur in dry areas, again, where there is not enough precipitation to leach the salts from the soil, so the salts build up over time. In order for there to be salts in the soil, there must be a source for them. Some come from former ocean floors that were under ancient seas but are now exposed. Some parent material (rocks from which the soil was formed) also may release salts, such as carbonate from limestone or sodium from feldspar. **(See Salt Crust Example and Conductivity Demonstration in Demonstrations.)**

   Some salts are toxic to plants and others bind so tightly to water that the plants cannot access it. In addition, it can be difficult for non-saline water to infiltrate saline soils, so it may be necessary to add gypsum to the water to aid infiltration.

4. Sodicity

   A soil containing sufficient exchangeable sodium to adversely affect crop production and soil structure under most conditions of soil and plant types. Many saline soils are also sodic, although not necessarily. Sodium is toxic to plants. It also causes soil particles to disperse (separate), which causes cracking and sealing of the soil surface, leading to poor soil structure and decreased water intake.

   Sodic soils can be reclaimed with a two-step process. First the sodium is flushed from CEC sites by adding amendments high in calcium (such as lime, gypsum, or dolomite) or by adding sulfur followed by lime. (The sulfur is converted to sulfuric acid by microbial activity. The sulfuric acid then reacts with lime to free calcium.) In either case, the Ca^{2+} ions replace the Na^{+} cations, freeing the Na^{+} in the soil solution. The second step is to leach out the sodium ions by irrigating in excess of what the plant needs.

5. Quantitative definitions

   Specifically, alkaline, saline, and sodic soils are defined as such:

   a) Alkaline soil: Has a pH of > 8.5 or with an exchangeable sodium percentage (ESP, that is, the percent of the CEC occupied just by sodium) greater than 15%. Soils at this ESP contain sufficient sodium to interfere with the growth of most crop plants.
   b) Saline soil: Soil salinity is determined by measuring the electrical conductivity (EC) of a saturated paste of soil: if the EC is greater than 4 dS/m (decisiemens per meter), the soil is classified as saline. However this is a rough range: salt-sensitive plants can be affected at half this EC and highly tolerant plants can handle up to about twice this EC.
   c) Sodic soil: A soil in which the ESP is at least 15%.The amount of sodium in the soil may also be expressed by the Sodium Adsorption Ratio (SAR), which reflects the degree to which the CEC sites in the soil are occupied by sodium instead of other cations. A soil with a SAR greater than 13 is considered sodic. An ESP of 15% is roughly equivalent to a SAR of 13.
   d) Saline-sodic soil: A soil containing both high soluble salts in general and high sufficient exchangeable sodium in particular. The ESP is at least 15%, the EC of the soil solution is >4 dS/m , and the pH is usually < 8.5.

I. Soil as a Medium for Plant Growth

1. Nutrient uptake processes

   (This section is adapted from material produced by the University of Saskatchewan)

   Imagine you are a tiny creature trying to move around in the soil. You are surrounded by millions of pores of all sizes and shapes, shaped and blocked by particles of organic matter and minerals. The surfaces of these particles are chemically active, adsorbing ions and organic molecules all around you. You start to learn your way around, but your microenvironment changes with each wet-and-dry cycle and freeze-and-thaw cycle. Sometimes it's not a physical process but a biological one that rearranges the structure of your little world, like a burrowing animal that tunnels through. In short, you live in a constantly changing soil ecosystem that has numerous barriers to the movement of organisms and chemicals.

   In terms of soil fertility we are particularly interested in the physical component of the soil ecosystem. For a nutrient to be available for the plant to take up it must meet two criteria: 1) it must be in the proper chemical form to pass the root membrane; and 2) it must be available at the root surface.

   Nutrients move through the soil to plant roots in three ways:

   - root interception
   - mass flow
   - diffusion

Each nutrient will have one or more of these methods of movement depending on its chemical form (including how strongly they are adsorbed by mineral and organic matter particles) and soil physical and chemical conditions (including the concentration of the nutrient in the soil)

a) **Root interception**

Plant roots are constantly expanding (opening up blocked pores as they do so), growing from areas of depleted nutrients (e.g., because of prior plant uptake) to regions where nutrients are more concentrated

Although many plants, such as cereals and other grasses, have a very extensive root system, they contact less than 5% of the soil volume. The root interception mechanism is very valuable, however, because root growth can extend the root into areas where mass flow and diffusion then take over. For example, a root could grow within a few millimeters of some soil phosphorus hot spot. Although the root does not technically bump into the nutrient and intercept it, the root is close enough for diffusion to occur and the phosphorus to move into it (see below). In some cases, the presence of mychorrhizal fungi increases the nutrient-absorption capacity of root systems (see Unit 2.3, Soil Biology and Ecology). Root interception allows for uptake of some calcium, magnesium, zinc, and manganese.

b) **Mass Flow**

Growing plants are continually taking up water from the soil profile, a process driven by transpiration (loss of water from the plant via stomata on the leaves). Dissolved in the soil water are soluble nutrients. These nutrients are transported along with the water to the root surface. Nutrients, such as nitrogen as nitrate and sulfur as sulfate, that are held very weakly by soil particles readily move along with the water. But nutrients, such as phosphorus as orthophosphate, that are strongly adsorbed to the soil particles are not able to reach roots by mass flow. Mass flow allows for the uptake of most of a plant's nitrogen, calcium, magnesium, sulfur, copper, boron, manganese and molybdenum.

c) **Diffusion**

Diffusion is the movement of ions along a gradient from a high concentration to a lower concentration, until the ions are evenly distributed. For example, imagine you have a tank of water with a removable barrier in the middle. On one side of the barrier you pour ink, while the other side stays pure water. If you remove the barrier very slowly you will see the ink and water mix as the molecules move from an area of high concentration (the inky side) to an area of low concentration (the pure water side). Similarly, nutrients move from areas of high concentration in the soil solution to areas of lower concentration. This is a very slow process, but it is the dominant mechanism of movement for phosphorus and potassium, which are strongly adsorbed on the soils and present in low concentrations in the soil solution.

Lecture 2: Plant Nutrient Requirements & Nutrient Cycles

A. Plant Nutrient Requirements

1. Introduction

   a) Nutrient balance

   Although it is easier to consider one nutrient at a time, it is important to think of plant needs holistically. Supplying one nutrient while ignoring other plant needs, including other nutrients and environmental factors such as temperature, water, and light, may have little benefit or even be detrimental to the crop.

   Justus von Liebig (1803–1873) analyzed plant samples and proposed a law of the minimum. This law states that plant growth is proportional to the amount available of the most limiting plant nutrient. For example, if I supply nitrogen sufficient to produce 70 bushels of wheat per acre but only supply enough phosphorus for 50 bushels per acre, then I will get only 50 bushels per acre (providing everything else is sufficient). This concept has since been expanded to include not only nutrients but also environmental factors.

   As important as Liebig's contributions are, they do not address the situation holistically. In the above example, for instance, nitrogen that is applied in excess of what the crop will consume is in danger of being leached into the groundwater, where it will become a pollutant (see Unit 1.6, Irrigation–Principles and Practices). Also, applying too much of any one nutrient can be injurious. For example, if too much nitrogen is supplied to tomatoes relative to the amount of phosphorus supplied, you may end up with vigorous plants that don't produce any fruit.

   One advantage of organic farming and gardening is that natural and organic soil amendments, unlike many synthetic ones, frequently supply many nutrients at once, including micronutrients

   b) Feed the plant or feed the soil

   One of the main distinctions of organic farming and gardening is its emphasis on feeding the soil rather than on feeding the plant (which most contemporary agricultural practices do). The crux of this idea is that healthy soil produces healthy, productive plants. However, we still need to keep in mind the nutrient needs of the plant, because the plant may need some nutrient that the soil is perfectly content to do without.

   The reason for this is that most soils are well suited to supply the needs of the native vegetation. While a soil may have no problem supporting coastal chaparral or a deciduous forest, it may be ill suited for growing a healthy field of lettuce or a corn crop.

   c) Macronutrients and micronutrients

   Plant nutrients are divided into two categories. Macronutrients are those that make up the greatest proportion of the plant and so are needed in large quantities. These are nitrogen, phosphorus, potassium, sulfur, calcium, and magnesium. Micronutrients are needed in small quantities, but are no less important; however, deficiencies of these are less likely to occur. Micronutrients include boron, copper, iron, manganese, molybdenum, zinc, chlorine, and cobolt.

   d) Nutrient cycling

   The amount of each chemical element in the world (with some exceptions) is fixed. Consequently, if we remove all of one element from a location, it's not going to be available there anymore unless it is replaced. This is a very important consideration in soil chemistry and plant nutrition. While some nutrients cycle within the farm, returning to the soil via manure or compost, other nutrients leave the farm, e.g., when crops are taken to market. The nutrients in these crops need to be replaced in the soil. In this sense, farming and gardening are little more than moving nutrients around.

Some details of different nutrient cycles will be discussed further below (see the sections on the individual nutrients)

e) Mobility of nutrients within the plant

Some nutrients are mobile within plants; others remain where they are. This affects how nutrient-deficiency symptoms appear. Nutrients that are mobile can move from older leaves to the sites of new growth, especially if those nutrients are in short supply. Consequently, when these nutrients are lacking, symptoms first appear in the older (lower and inner) leaves. Mobile nutrients include nitrogen, potassium, phosphorus, magnesium, molybdenum, and zinc.

Nutrients that are immobile cannot be translocated to young, new growth. As a result, deficiency symptoms first appear in younger (upper and outer) tissues. Nutrients that are immobile include sulfur, calcium, iron, manganese, boron, and copper.

2. Carbon, hydrogen, and oxygen

a) Plants and animals are primarily made up of carbon, hydrogen, and oxygen. Plants obtain carbon and oxygen from the air (as CO_2 and O_2) and hydrogen and oxygen from water (H_2O). With the help of light energy, they recombine these three elements into carbohydrates. This happens in the leaves of plants during photosynthesis:

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

b) Carbon, hydrogen, and oxygen also combine to form hydrocarbons, the long molecular chains that make up fats, and the same three elements combine with nitrogen to form the main structure of proteins. Overall, these three elements are key components of the large organic molecules that comprise all living beings. The carbon cycle, as depicted in ◀ Figure 2.9, the Carbon Cycle, describes the movement of carbon as it is recycled and reused by animals, plants, and microbes.

c) Carbon also plays a key role in global climate change, as increased levels of CO_2 and CH_4 (methane) in the atmosphere (along with water vapor and a few other gases) reflect infrared radiation to the earth, overall increasing the average surface temperature. Ecologists and soil scientists have been examining the potential for building up soil organic matter as a way to sequester C, removing it from the atmosphere and maintaining it in the soil. How large a role this could play in mitigating C emissions from human activity is being debated.

3. Nitrogen (N)

a) Physiological role in plant development

Plants take up nitrogen either as the ammonium ion (NH_4^+) or nitrate (NO_3^-). Most organic compounds in plants contain nitrogen, including amino acids, nucleic acids, many enzymes and energy transfer materials such as chlorophyll, ADP, and ATP. N is necessary for the production of sugars such as is found in sweet ripe fruit. Growing plants must have N to form new cells, so it is essential for plants.

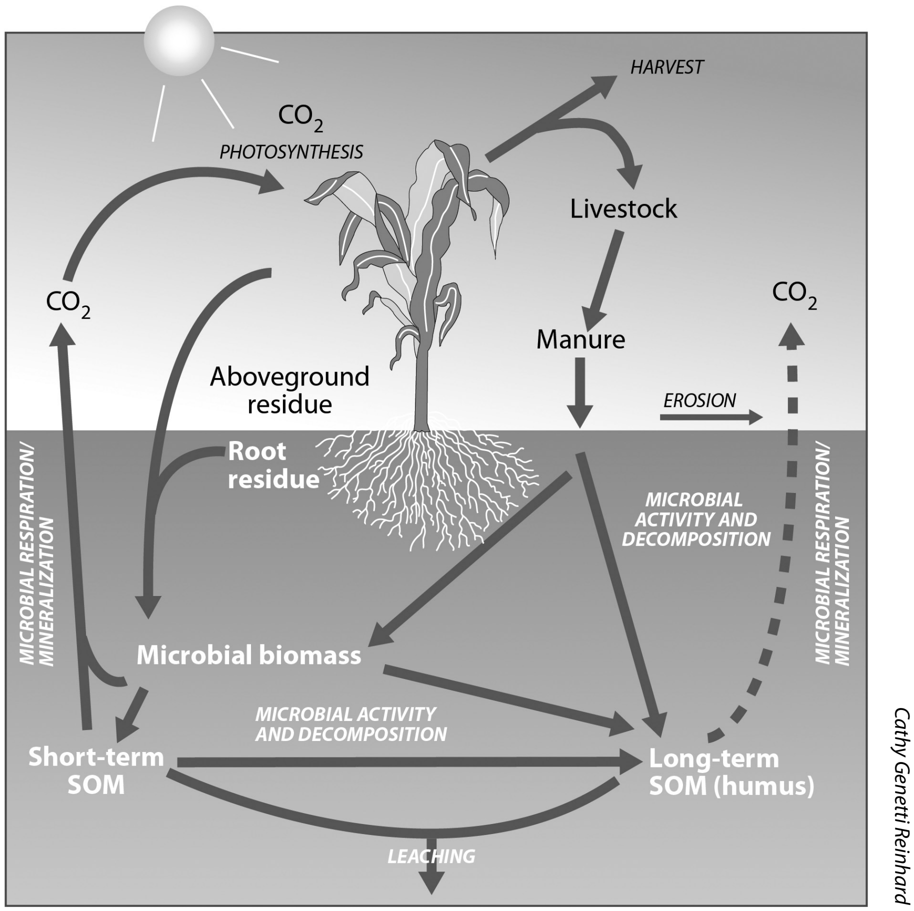
b) Soil nutrient imbalances

Nitrogen deficiency symptoms in plants include:

i. Slow growth, stunted plants

ii. Yellow-green color (chlorosis)

FIGURE 2.9 | THE CARBON CYCLE (ADAPTED FROM MICHIGAN STATE UNIVERSITY EXTENSION BULLETIN E-2646)



iii. Firing (burnt look) of tips and margins of leaves beginning with more mature leaves
iv. Low protein content of crops

c) Symptoms of nitrogen excess include:
i. Dark green, succulent, vegetative growth at the expense of seed production in grain crops, the expense of fruit production in tomatoes and some tree crops, and the expense of sugar content in beets
ii. Watery potatoes
iii. Frost damage if there is too much succulent growth when frost hits
iv. Weakened stems (lodging)
v. Delayed flowering or fruiting
vi. Boron or copper deficiency due to inhibited uptake of these nutrients

d) Forms of nitrogen in the soil
Nitrogen occurs in the soil in various forms:
i. Nitrogen gas in the soil air (N_2)
ii. Nitrate (NO_3^-)
iii. Nitrite (NO_2^-)
iv. Ammonium (NH_4^+)
v. Ammonia (NH_3)—a gaseous, transitory form
vi. In various other forms as part of complex organic molecules

These forms are the main components of the nitrogen cycle (see ◀ Figure 2.10, the Nitrogen Cycle, page 2-66)

e) Nitrogen fixation

  i. Nitrogen gas makes up about 78% of the atmosphere. It is a very stable form of nitrogen, but it is unavailable to plants. However, certain bacteria are able to transform N_2 gas into nitrate. This is called biological nitrogen fixation (as opposed to industrial nitrogen fixation carried out by chemical factories, which use large amounts of energy to "fix" the N_2 gas into ammonium). During biological N fixation, microbes form symbiotic relationships with plants: the microbes provide N to the plants and the plants provide sugars from photosynthesis to the microbes.

  ii. The main N-fixing bacteria in agricultural systems are from the genus *Rhizobium*, and are associated with plants of the bean family (Leguminosae). Bacteria in the genus *Frankia* and some species of free-living or lichen-forming cyanobacteria also are able to fix N, but are generally less important in agroecosystems.

  iii. In some cases, there may not be sufficient natural populations of *Rhizobia* to form symbioses in a high proportion of the crop, or the *Rhizobia* species present in the soil may not be the right species for the crop you are planting. In these cases it may be necessary to inoculate the seed with a commercial inoculant when the crop is planted. Some seeds come pre-inoculated, while others need to be mixed with an inoculant prior to planting.

  iv. Inoculating legume seed does not mean that it will not be necessary to supply additional N to the crop. The crop and the *Rhizobia* themselves need N to get started. Also, *Rhizobia* need sufficient phosphorus, iron, molybdenum, and cobalt.

▶ **TABLE 2.12** | COMPARISON OF NITROGEN FIXATION SOURCES.
VALUES ARE IN MILLIONS OF METRIC TONS PER YEAR ON A GLOBAL BASIS (APPROXIMATE VALUES)

NON BIOLOGICAL		**BIOLOGICAL**	
Industrial	~50	Agricultural land	~90
Combustion	~20	Forest and other land	~50
Lightning	~10	Seas	~35
TOTAL	~80		~175

f) Ammonification and nitrification

Ammonification is the release of ammonium ions from decomposing organic matter. This process is also called N mineralization, as it changes the unavailable organic forms of N into plant-usable forms. Many microbes are capable of doing this, so an environment that is favorable to microbial growth makes for fairly rapid ammonification. The ammonium that is produced is held in the soil solution, adsorbed onto CEC sites, or taken up by plants.

Nitrification is a two-stage process in which ammonium is transformed into nitrate. This, too, depends on microbial activity: *Nitrosomas* spp. oxidize ammonium to nitrite and *Nitrobacter* spp. oxidize nitrite to nitrate.

g) Denitrification

N can be lost from wet soils where anaerobic conditions occur. Under these conditions some bacteria get their oxygen from nitrate rather than oxygen gas, releasing N_2 gas back into the atmosphere. This process is called denitrification. Though N can be lost from the soil ecosystem this way, denitrification can be a very useful function where excess concentrations of nitrate occur in the soil.

To minimize denitrification, soil should have good structure and thus good aeration and drainage, a pH near neutral, and residues incorporated in the upper few inches of the soil where there is more oxygen. Note that due to microhabitats and conditions in the soil, even well- drained soils may have areas that become anaerobic at some times.

h) Immobilization

N is unavailable to plants (immobilized) when it is in the organic form. Usually, rates of mineralization in the soil are higher than rates of immobilization. However, if organic matter added to the soil has less than 1.5% N, soil microbes will rapidly take up the available N, so that the rate of immobilization will temporarily exceed the rate of mineralization. This temporarily decreases the amount of N available to plants.

i) Losses of N through leaching and volatilization

N is one of the nutrients most easily lost from the soil. Ammonia is easily volatilized, so organic matter left on the soil surface will rapidly lose total N. Volatilization increases with warmer temperatures.

N as nitrate is easily leached, moving down through the soil profile with precipitation or high levels of irrigation. This is a loss to the crop because of a decrease in the pool of plant-available N, as well as a problem for ground and surface water, where excess N generally has negative ecosystem effects. Leaching occurs most in sandier soils, exposed soils (i.e., without crops to take up the N), and in soils low in organic matter.

j) Supplying nitrogen to the soil

There are many ways that N can be supplied to the soil. These include green manures (N-fixing cover crops), crop rotation with leguminous crops, and amendments. Amendments that supply high quantities of N include animal manures, guano, cottonseed meal, bone meal, hoof and horn meal, bloodmeal, and fish emulsion.

Care must be taken when using amendments high in ammonia, such as fresh poultry manure. Ammonia is a strong base that can "burn" plants. However, its use over an extended period of time will acidify the soil as bacteria oxidize the ammonia to form nitric acid.

CARBON-NITROGEN RATIOS

Microbial action can either mineralize or immobilize nitrogen. The main factor in determining which will happen is the carbon to nitrogen (C:N) ratio. Microbes use carbon (from organic matter) for growth as well as for energy. The nitrogen entering their bodies needs to be in a fixed ratio to the amount of carbon. The critical range of the C:N ratio is ~22:1 to 25:1. Ratios higher than this (i.e., more than 25:1) will cause N to be immobilized. Lower ratios will lead to available NH4+ or NO3- as organic matter decomposes. Most plant residues have C:N rations of 20:1-100:1; the bodies of microorganisms have a C:N ratio of 4:1 to 9:1. Usually soil OM stabilizes with a C:N ratio somewhere between 8:1 to 15:1.

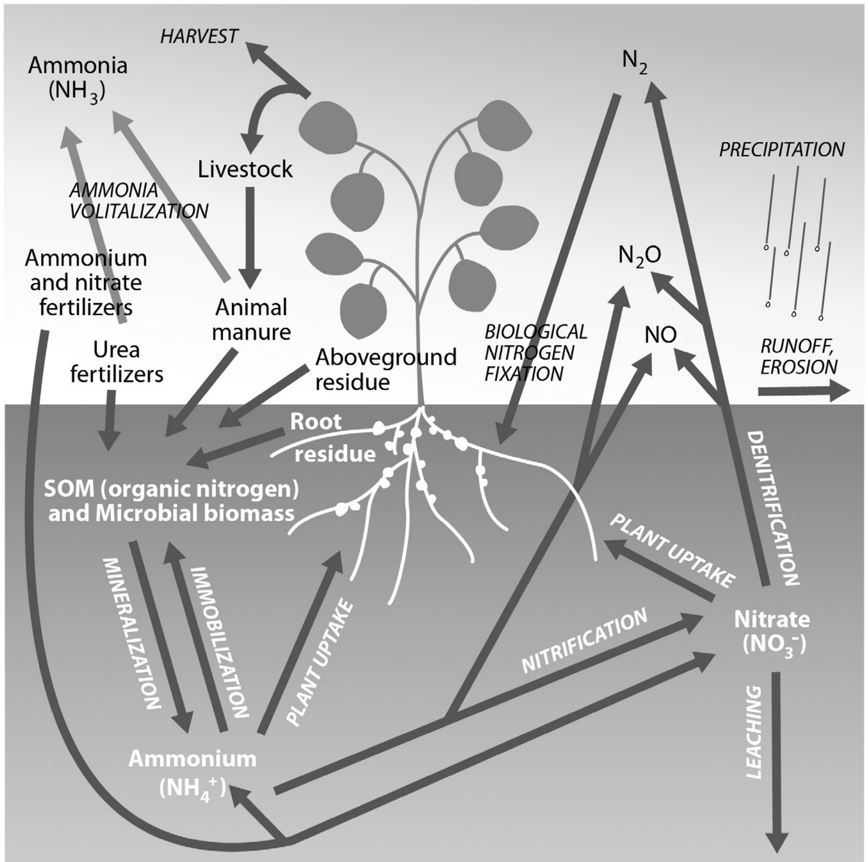
NITRATE TOXICITY

When infants consume nitrate, it is converted to nitrite in the anaerobic conditions in the gut. This nitrite gets absorbed into hemoglobin molecules, which reduces their oxygen-carrying capacity, and can cause "blue-baby syndrome" (see Supplement 4, Nitrate Contamination of Groundwater, in Unit 1.5, Irrigation—Principles and Practices). In humans, nitrate can also react with amino acids to form nitrosamines, which are carcinogenic.

PHOSPHORUS AND WATER QUALITY

When soil is lost through erosion, it carries any P that is adsorbed to it. When the P enters freshwater lakes and streams it acts as a fertilizer, causing an excess growth of plants and algae. When the plants and algae die, they are consumed by microbial decomposers, which respire as their populations grow, and use up dissolved O_2 in the water. This decreases the amount of O_2 available for fish, invertebrates, and plants, in some cases creating "dead zones."

FIGURE 2.10 | THE NITROGEN CYCLE (ADAPTED FROM MICHIGAN STATE UNIVERSITY EXTENSION BULLETIN E-2646)



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4. Phosphorus (P)
   a) Physiological role in plant development

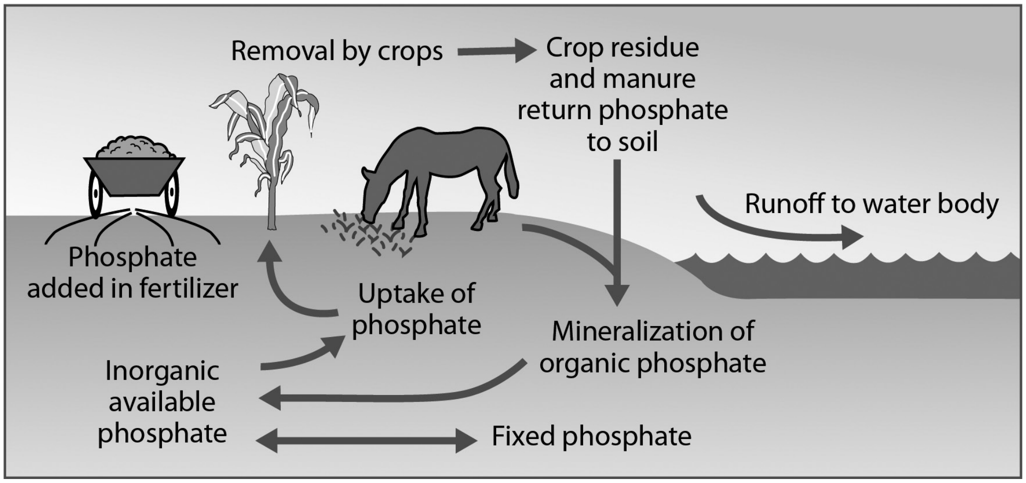
      P is present in all living cells, including as nucleic acids (DNA and RNA), as part of phospholipid cell membranes, and as molecules for energy storage and transfer (ATP). P also stimulates early growth and root formation, hastens bloom time, and promotes seed production and size. It is used in protein synthesis and is found in legume nodules.
   b) Soil nutrient imbalances

      P must be balanced with N both in the plant and in the soil. In the soil, P and N compete to be taken up. Because N is highly mobile and P is one of the least mobile nutrients, excessive N availability can cause a P deficiency, even if there is enough P in the soil for the crop.

      Phosphorus deficiency symptoms in plants include:

      i. Slow growth, stunting
      ii. Purplish coloration on foliage of some plants
      iii. Dark green coloration with tips of leaves dying
      iv. Delayed maturity
      v. Poor grain, fruit, or seed development

◀ **FIGURE 2.11** | THE PHOSPHORUS CYCLE (ADAPTED FROM WWW.EXTENSION.UMN.EDU/DISTRIBUTION/CROPSYSTEMS/)



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c) The phosphorus cycle (see ◀ Figure 2.11, the Phosphorus Cycle)

Phosphorus is not easily leached from the soil because it is adsorbed tightly to soil particles. Consequently, the main losses of P from agroecosystems are either by removal of crops (e.g., for sale and use off-farm) or by soil erosion. Most phosphate pollution of lakes and streams is from sediment that is high in P.

d) Phosphorus in soils and factors affecting its availability

i . Plants take up phosphorus as $H_2PO_4^-$, HPO_4^{2-}, or PO_4^{3-} depending on soil pH. $H_2PO_4^-$ is more available in very acid conditions while PO_4^{3-} is more available in very alkaline conditions. Maximum availability occurs between pH 6.5 and 7.2.

ii. Some soils will bind P in nearly irreversible forms. This "fixing" capacity of a soil is largely dependent on the amount and types of clay present in the soil. For example, clays made up of iron, aluminum, and manganese oxides have high P-fixing ability. These clays are commonly found in weathered soils (Oxisols and Ultisols) in warm humid climates and in soils affected by volcanic ash (Andisols). Usually these conditions are dealt with by adding enough P to the soil to satisfy its P-fixing ability.

iii. Phosphorus is highly immobile. Because roots only take up what is only a fraction of an inch away, if the P is not close to the root, it will not be available. Maintaining adequate moisture throughout the growing season facilitates P movement.

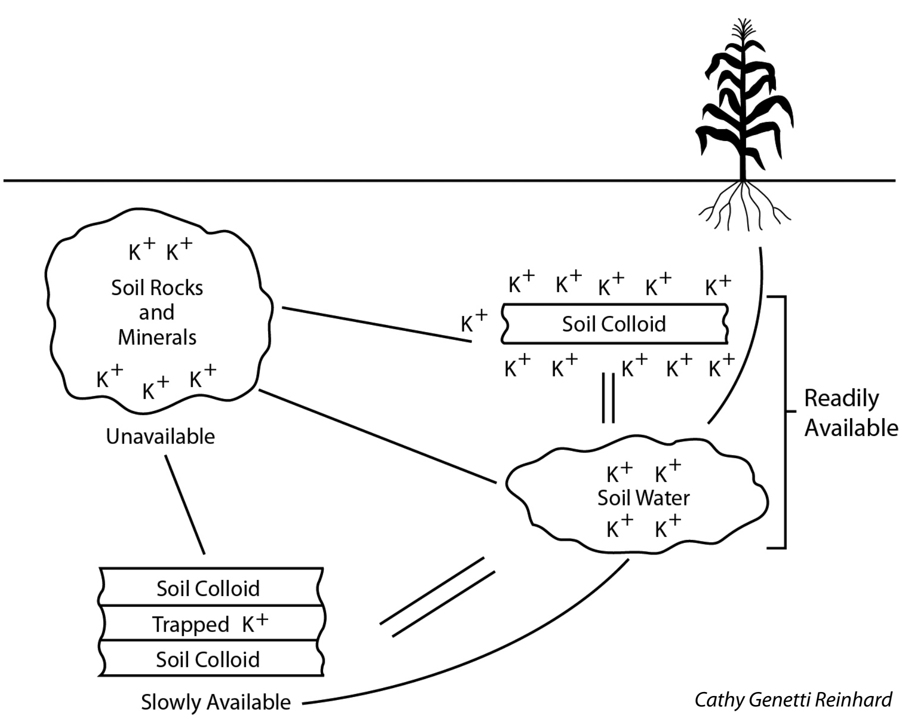
iv. P availability is also affected by temperature. In cool temperatures, plants may show P deficiencies even though there is enough present in the soil for the plant needs. As temperatures warm, deficiency symptoms may go away. Organic P tends to be more available than inorganic, so use of organic amendments, along with promoting biological activity, will make P more available.

e) Phosphorus in amendments

The best source of P to use in the garden is "recycled," from compost and manures. Compost and manures are fairly low in P content but their organic form of P may be more available than from some other sources. Organic amendments should have a pH between 6.5 and 6.8 to maximize availability. Another option is bone meal (finely ground bones from slaughterhouses), which is high in P but requires a soil pH of less than 7 for it to slowly be converted in the soil solution into a plant-available form. Rock phosphate (sold in hard and soft, or "colloidal," forms) is another option for providing P. However, the product is mined and also needs a soil pH less than 7 for it to become plant-available.

5. Potassium (K)
   a) Physiological role in plant development
      Potassium plays a role in several key processes in plants:
      i. Regulating the rate of photosynthesis (by activating enzymes used in photosynthesis and by helping in the production of the energy storage molecule ATP)
      ii. Opening and closing stomata (openings on leaves) to allow CO_2 in and O_2 out and to regulate water loss
      iii. Transporting sugars within plants, again by its role in ATP production
      iv. Starch formation, by activating the enzyme responsible for this process
      v. Plant growth, by helping to produce proteins (the building blocks) and enzymes that regulate growth
   b) Soil nutrient imbalances
      i. Potassium deficiency symptoms in plants include:
         - Slow growth
         - Tip and marginal "burn" starting on more mature leaves and progressing toward the top of the plant
         - Weak stalks, plants lodge (fall over) easily
         - Small fruit or shriveled fruit and seeds
         - Reduced disease and pest resistance
         - Increased sensitivity to drought, frost, and salts
         - White or yellow spots develop along the edges of clover leaves; in severe cases these join to give a scorched appearance
      ii. Excess potassium can cause:
         - Magnesium deficiency
         - Calcium deficiency in acid soils
   c) The potassium cycle (see ◀ Figure 2.12, the Potassium Cycle)

◀ **FIGURE 2.12** | THE POTASSIUM CYCLE



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   d) Potassium in soils: Factors affecting its availability
      Plants take up potassium in the form of potassium ions (K^+) from CEC sites or the soil solution. Because K dissolves readily, it is highly mobile in the soil; however, it can get trapped on CEC sites in between the layers inside clay particles.
      Potassium is present in some rocks, such as granite, so soils formed from these rocks have a large supply of K. Even though a soil test may not show much K at one point in time, it is usually released in sufficient quantities for plant growth. This is the case for many soils in the Sierra Nevada and southern California.

e) Potassium in amendments

Sources of K include wood ashes, granite dust, seaweed, greensand, and langbeinite (also called sulfate of potash-magnesia or Sul-Po-Mag). Greensand and langbeinite are mined, non-renewable resources. Granite dust is also non-renewable, but granite occurs in such huge quantities over extensive areas that it will be available for a long time. In neutral or alkaline soils, wood ashes may increase the soil pH to undesirable levels.

Potassium in organic residues tends to be more highly available than that supplied by inorganic sources. So even though the total quantity of potassium supplied by these residues may be less, it may be more effective. If organic residues are regularly returned to the soil, K is not likely to be deficient.

6. Other macronutrients: Calcium, magnesium, sulfur

a) Calcium (Ca)

Calcium is an essential part of cell wall structure and must be present for the formation of new cells throughout the plant. Calcium also helps control movement into and out of cells, including by reacting with waste products to precipitate them or to render them harmless to the plant.

Calcium is not mobile in plants. Young tissue is affected first when there is a deficiency. Deficiency symptoms in plants include:

i. Death of growing points, including on the root tips and shoot or leaf tips
ii. Abnormal dark green appearance of foliage
iii. Premature shedding of blossoms and buds
iv. Weakened stems because cell membranes lose permeability and disintegrate
v. Blossom-end rot of tomatoes
vi. Short, thick, bulbous roots

Plants take up Ca as an ion (Ca^{2+}). Calcium is normally so abundant that it usually only needs to be added to very acidic soils where lime is required. However, excessive irrigation can leach Ca from the soil enough to cause deficiency symptoms in plants. Excess Ca can lead to a deficiency of Mg or K.

Sources of Ca include plant residues, poultry manure, wood ashes, seashells, lobster shells, legume hay, limestone, and gypsum.

b) Magnesium (Mg)

Magnesium is the central atom of chlorophyll molecules, so it is required for photosynthesis. It also helps activate key enzymes for converting CO_2 gas into carbohydrates, as well as many plant enzymes required in growth processes. Magnesium also activates enzymes necessary for P transfer within plants.

Magnesium is mobile within plants and can be translocated from older tissue to younger tissue during conditions of deficiency. Symptoms of Mg deficiency include:

i. Chlorosis (yellowing) between the veins in older leaves; marginal yellowing with a green fir-tree shape along the big midrib of the leaf
ii. Upward curling of leaves along their margins
iii. Stunted growth
iv. Ripe fruit is not sweet

Plants take up Mg in its ionic form (Mg^{2+}). Magnesium is generally available throughout the dry-climate Western states but it is often more deficient than Ca. Like Ca, Mg is easily leached, and soils with low CEC have low Mg content. It is important to have a balance of Mg, K, and Ca ions so that no one of these elements dominates the CEC sites.

Sources of Mg include plant residues, fresh poultry manure, dolomitic limestone, and langbeinite (Sul-Po-Mag—see Section on K, above)

c) Sulfur (S) (see ◀ Figure 2.13, the Sulphur Cycle)

Sulfur is part of two amino acids (cysteine and methionine) that are incorporated into proteins. Sulfur is also essential for nodule formation by N-fixing bacteria on the roots of legumes. It is present in oil compounds that give plants such as garlic and onions their characteristic odor. (Vidalia onions, known for their sweetness, come from an area that has low S soils.)

Sulfur deficiency problems can occur if growers rely on fertilizers that are concentrated with other nutrients (e.g., N, P, and K) but are free of S. Symptoms of S deficiency in plants include:

i. Pale young leaves, light green to yellowish in color, sometimes with veins lighter than surrounding tissue. In some plants older tissue may be affected also.

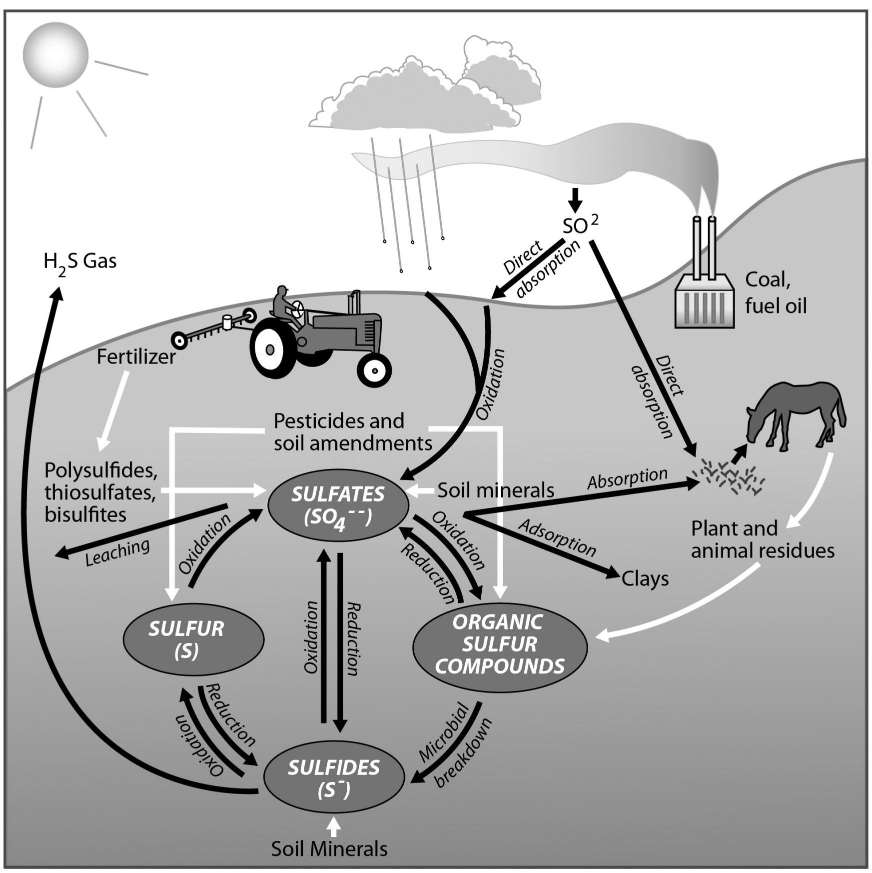
ii. Small and spindly plants

iii. Slow growth rate and delayed maturity

Plants take up S as the sulfate ion SO_4^{2-}. Sulfur is also sometimes absorbed from the air through leaves in industrial areas where S is in high concentration.

The use of organic residues in amounts to satisfy other nutrient requirements will usually provide sufficient sulfur. Other sources of sulfur include animal manures (S is usually well balanced with N), langbeinite (Sul-Po-Mag—see section above on P), gypsum, and pure S from natural sources (granular sulfur is preferred since sulfur dust is an explosion hazard).

◀ **FIGURE 2.13** | THE SULFUR CYCLE



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7. Micronutrients
    a) Introduction

    Micronutrients are those plant nutrients that are needed only in small quantities compared to other (macro-) nutrients. This, however, does not diminish their importance. The effects of micronutrients on plants are difficult to understand, partly because of their interrelationships with each other and with macronutrients and partly due to how the plants respond to micronutrients individually.

    The response of many plants to micronutrients is nearly an all or nothing affair. As long as the concentration of the micronutrients falls within a certain range, the response of the plant is the same, regardless of the exact concentration of the nutrient. If the concentration of the nutrient falls above this range, toxicity problems occur and if the concentration is below the range, the plants become deficient in the nutrient.

    Interrelationships of micronutrients and with macronutrients are many. For example, excess nitrate-N can lower pH and reduce Fe uptake. Phosphorous can form a precipitate with Fe, making the Fe unavailable for plant uptake. Iron, copper, manganese, and zinc cations can interfere with each other for plant uptake.

    Availability of micronutrients is highly dependent on soil pH and organic matter. At certain pH levels, micronutrients can bind to inorganic compounds and become unavailable. Organic matter can diminish the effect of pH, supplying micronutrients if their concentrations in the soil are low and binding them up if their concentrations are too high, reducing their toxicity.

    b) Boron ($B_4O_7^{2-}$)
        i. Boron is needed in plants for:
            - Synthesizing protein
            - Transporting starches and sugars
            - Regulating N and carbohydrate metabolism
            - Root growth
            - Fruit and seed formation
            - Water uptake and transport
            - Boron contributes more than any other micronutrient to the quality of produce.
        ii. Boron is non-mobile in plants and so a continuous supply is necessary at all growing points. Symptoms of boron deficiency include:
            - Death of terminal growth, causing lateral buds to develop and producing a "witches'-broom" effect
            - Thickened, curled, wilted, and chlorotic leaves
            - Soft or necrotic spots in fruit or tubers
            - Reduced flowering or improper pollination

    Boron is required in minute quantities by plants, but may be insufficient in some soils. Boron can also become toxic in amounts not much higher than that needed by plants. Boron toxicity is most frequently a problem in soils formed at the bottoms of enclosed basins in arid areas where groundwater evaporates upward through the soil, leaving salt concentrations near the surface (playas).

    c) Copper (Cu^{2+})

    Copper is a catalyst for respiration (combusting sugars for energy in plants) and an activator of several enzymes. It is important for carbohydrate and protein synthesis.

    Symptoms of copper deficiency include:
        i. Stunted growth
        ii. Dieback of terminal shoots in trees
        iii. Poor pigmentation

iv. Wilting and eventual death of leaf tips
v. Formation of gum pockets around central pith in oranges

Copper is fairly abundant and deficiencies rarely occur. It is found as impurities in the structures of clay particles and other soil compounds. As these materials weather the copper is released, and then adsorbed onto CEC sites, from where it may be taken up by plants or leached from the soil. Consequently, soils formed from highly weathered materials may be deficient in copper. However, since copper can be highly toxic at low levels, amendments should not be used except where the need for it has been established.

d) Iron (Fe^{2+}, Fe^{3+})

Iron plays several critical roles in plants. It is used in chlorophyll synthesis, during respiration, and as a constituent of some enzymes and proteins. It also activates nitrogen fixation.

Symptoms of Fe deficiency include:

i. Interveinal chlorosis—a yellowing of the leaves between the veins
ii. Twig dieback
iii. Death of entire limbs or plants

Plants require Fe in larger amounts than any other micronutrient. Iron is very abundant in the soil, but some of its forms are so insoluble that plants may suffer a deficiency in spite of its abundance (this would be like being stranded in the ocean yet being thirsty for want of fresh water). This is particularly true at pH levels above 7; where there is a high content of lime or manganese; or where there is poor aeration. Treatment may consist of adding iron in a form that won't be bound up in the soil or by lowering the soil pH.

e) Manganese (Mn^{2+})

Manganese is part of multiple enzymes and is a catalyst of other enzymes, and so is used in the metabolism of N and inorganic acids; for the formation of vitamins (carotene, riboflavin, and ascorbic acid); for the assimilation of CO_2 during photosynthesis; and in the breakdown of carbohydrates.

Symptoms of manganese deficiency include:

i. Interveinal chlorosis of young leaves, with a gradation of pale green coloration with darker color next to the veins. There is no sharp distinction between veins and interveinal areas as with iron deficiency.
ii. Development of gray specks, interveinal white or brown streaks, or interveinal brown spots

Similar to Fe, high pH (over 6.5) may make Mn unavailable, as can soils very high in organic matter (muck soils). High Mn levels may induce iron deficiency. Improving soil structure can improve Mn availability.

f) Molybdenum (MoO_4^{2-})

Molybdenum is necessary for nitrogen fixation and for converting nitrate-N taken up by plants into a form the plant can use to build amino acids and thus proteins. Because of this a Mo deficiency can cause an N deficiency in plants.

Symptoms of molybdenum deficiency include:

i. Stunting and lack of vigor (induced nitrogen deficiency)
ii. Marginal scorching and cupping or rolling of leaves
iii. "Whiptail" of cauliflower
iv. Yellow spotting of citrus

As with boron, molybdenum is needed only in minute quantities and is toxic at levels above what plants require. Molybdenum has been found in quantities sufficient to be toxic to livestock in forage grown in inland desert areas such as the San Joaquin Valley and Nevada. Molybdenum levels tend to be low in highly leached soils.

g) Zinc (Zn^{2+})

Zinc activates enzymes that run photosynthesis, helps regulate and combust carbohydrates, and is part of the synthesis of the plant hormone auxin. It is also key for seed and grain maturation and production.

Symptoms of zinc deficiency include:

i. Decrease in stem length and a rosetting of terminal leaves
ii. Reduced fruit bud formation
iii. Mottled leaves (interveinal chlorosis)
iv. Dieback of twigs after first year
v. Striping or banding on corn leaves

Soils formed from highly weathered materials may be deficient in Zn, while soils formed from igneous rocks tend to have higher levels of Zn. Warm soil temperatures improve Zn availability, as does a well-aerated soil. High levels of available P can cause Zn deficiency in plants.

h) Others

Other micronutrients that may be of importance are:

i. Cobalt (Co^{2+})

Cobalt has not yet been shown to be essential for plants, but is generally beneficial. However, it is essential in the symbiotic relationship between legumes and their associated Rhizobia bacteria.

ii. Chlorine (Cl^{-})

Chlorine is required for photosynthetic reactions in plants. However, the quantities needed are so small that deficiencies are rare and usually in places with high rainfall and sandy soils, where Cl anions would leach out.

iii. Silicon (Si)

While not an essential plant nutrient, Si gives plants mechanical strength and may help minimize water loss and increase disease resistance. Plant pathologists are especially interested in the potential for improving disease resistance.

Demonstrations: Soil Chemistry

DEMONSTRATION OVERVIEW

The following demonstrations provide visual representations and visual analogies for the concepts presented in Lecture 1. When possible, they should be integrated into the lectures.

MAGNET DEMONSTRATION

Lecture 1, D. 1

PURPOSE

To show how unlike charges attract and like charges repel

MATERIALS

- 2 bar magnets, preferably labeled

METHODS

Hold the negative ends of the magnets together, show how they repel, then hold the negative to the positive and show how they attract.

pH DEMONSTRATION

Lecture 1, F. 1

PURPOSE

To demonstrate different methods of measuring pH

MATERIALS

- pH meter
- Colorimetric pH test kit (I use the Hellige-Truog)

METHODS

Measure the pH of the soil sample using the different techniques. Compare the results. Explain why differences may occur.

ACID DEMONSTRATION

Lecture 1, G. 4

PURPOSE

To show how to test for the presence of carbonates in the soil

MATERIALS

- Soil sample with free carbonates, e.g., $CaCO^3$
- Dilute hydrochloric acid or vinegar

METHODS

Drop acid onto the soil to show how it effervesces. The effervescence is the release of CO_2 bubbles from the carbonates.

SALT CRUST EXAMPLE

Lecture 1, H. 3

PURPOSE

To show how high salt concentrations might look in the soil

MATERIALS

- Salt crust

METHODS

Pass around samples of salt-encrusted soil

CONDUCTIVITY DEMONSTRATION

Lecture 1, H. 3

PURPOSE

To demonstrate that saline soils conduct electricity

MATERIALS

- Saline soil sample
- Nonsaline soil sample
- Distilled water
- 2 beakers or jars
- Table salt
- Conductivity tester: Any kind of device that shows that electricity will pass through a saline soil but not a nonsaline soil will do. A device that combines a light bulb and a voltmeter is a good choice.

METHODS

1. Prepare the two samples (saline and nonsaline) by placing them into separate jars and mixing distilled water into each until a smooth paste is created.
2. Place the electrodes of the tester into the nonsaline sample. Notice that the light bulb does not light.
3. Remove the electrodes and rinse them with distilled water. Then place them into the saline soil. Notice that the light bulb lights.
4. Remove electrodes from samples and rinse them with distilled water. Place them back into the nonsaline sample. Stir in table salt until enough has been added to make the light bulb light up.

Note: The operation can be simplified by having four electrodes. Use alligator clips on the tester wires to connect them to the electrodes.

Assessment Questions

TRUE OR FALSE

1) The bulk of a plant is made up of minerals extracted from the soil.

   True False

2) Clay soils can hold more nutrients than sandy soils.

   True False

3) The main source of nitrogen in the soil is rocks.

   True False

4) Phosphorus becomes a pollutant when it is leached into the groundwater.

   True False

5) Alkaline soils are predominant in the arid western states.

   True False

MULTIPLE CHOICE

1) Which one of the following refers to the nutrient-holding ability of the soil?
   a. Alkalinity
   b. Cation Exchange Capacity
   c. Available Water Capacity
   d. Nutrient Loading

2) Leaching of bases out of a soil causes the soil to become
   a. Alkaline
   b. Acid

3) Salinity problems are most likely to occur in
   a. Dry environments
   b. Upper New York state
   c. Tropical rainforests
   d. Humid areas

4) Which of the following is NOT a plant nutrient?
   a. Nitrogen
   b. Copper
   c. Aluminum
   d. Potassium

5) Nutrients needed in large quantities by plants are called
   a. Meganutrients
   b. Micronutrients
   c. Macronutrients
   d. High end nutrients

6) Certain plant nutrients are called micronutrients because
   a. They are too small to see with the naked eye
   b. They are not all that important to the plant
   c. They are only needed in small quantities

7) Which one of the following plant nutrients comes from the air?
   a. Carbon
   b. Potassium
   c. Hydrogen
   d. Copper

8) Which of the following affects nutrient availability? (circle all correct responses)
   a. pH
   b. Soil organic matter content
   c. Texture
   d. Soil moisture

9) An ion with a positive charge is called a(n)
   a. Cation
   b. Anion
   c. Onion
   d. Positron

10) Clay particles tend to have a
   a. Positive charge
   b. No charge
   c. Negative charge

ASSESSMENT

1) How can knowledge of the climate of an area help you make an initial assessment of soil fertility?

2) Your plants are showing signs of iron deficiency. You check the soil pH and it is 8.0. What would most likely be the best way to eliminate the iron deficiency and why?

3) You know that the air around you is full of nitrogen, yet your garden regularly shows signs that it could use a little of it. How can you harness some of the nitrogen for your garden?

4) Is adding a large quantity of nitrogen-rich amendments to your garden before you plant necessarily a good thing to do? Why or why not?

5) What is the most important thing you can do to a mineral soil in order to ensure an adequate supply of and maximum availability of plant nutrients?

Assessment Questions Key

TRUE OR FALSE

1) The bulk of a plant is made up of minerals extracted from the soil.
   True **False**

2) Clay soils can hold more nutrients than sandy soils.
   True *False*

3) The main source of nitrogen in the soil is rocks.
   True **False**

4) Phosphorus becomes a pollutant when it is leached into the groundwater.
   True **False**

5) Alkaline soils are predominant in the arid western states.
   True *False*

MULTIPLE CHOICE

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   - *a. Alkalinity*
   - **b. Cation Exchange Capacity**
   - *c. Available Water Capacity*
   - *d. Nutrient Loading*

2) Leaching of bases out of a soil causes the soil to become
   - *a. Alkaline*
   - **b. Acid**

3) Salinity problems are most likely to occur in
   - **a. Dry environments**
   - *b. Upper New York state*
   - *c. Tropical rainforests*
   - *d. Humid areas*

4) Which of the following is NOT a plant nutrient?
   - *a. Nitrogen*
   - *b. Copper*
   - **c. Aluminum**
   - *d. Potassium*

5) Nutrients needed in large quantities by plants are called
   - *a. Meganutrients*
   - *b. Micronutrients*
   - **c. Macronutrients**
   - *d. High end nutrients*

6) Certain plant nutrients are called micronutrients because
   - *a. They are too small to see with the naked eye*
   - *b. They are not all that important to the plant*
   - **c. They are only needed in small quantities**

7) Which one of the following plant nutrients comes from the air?
   - **a. Carbon**
   - *b. Potassium*
   - *c. Hydrogen*
   - *d. Copper*

8) Which of the following affects nutrient availability? (circle all correct responses)
   - **a. pH**
   - **b. Soil organic matter content**
   - **c. Texture**
   - **d. Soil moisture**

9) An ion with a positive charge is called a(n)
   - **a. Cation**
   - *b. Anion*
   - *c. Onion*
   - *d. Positron*

10) Clay particles tend to have a
   a. *Positive charge*
   b. *No charge*
   c. **<u>Negative charge</u>**

ASSESSMENT

1) How can knowledge of the climate of an area help you make an initial assessment of soil fertility?
   - *Humid areas tend be more heavily leached, have lower pH and lower fertility*
   - *Dry areas tend to have higher base saturation, higher pH, more fertile*
   - *Warm areas tend to have more highly weathered soils as compared to cooler ones, lower relative fertility*

2) Your plants are showing signs of iron deficiency. You check the soil pH and it is 8.0. What would most likely be the best way to eliminate the iron deficiency and why?
   - *Lower the pH so that the iron in the soil can become more available (usually done by adding sulfur or acid organic materials). If iron supplements are used they, too, will be unavailable due to the high pH unless chelated forms of iron are used.*

3) You know that the air around you is full of nitrogen, yet your garden regularly shows signs that it could use a little of it. How can you harness some of the nitrogen for your garden?
   - *Nitrogen-fixing green manures*
   - *Intercrop with nitrogen-fixing plants*

4) Is adding a large quantity of nitrogen-rich amendments to your garden before you plant necessarily a good thing to do? Why or why not?

   No.
   - *Large amounts of nitrogen without plants to take it up can lead to losses by leaching (polluting groundwater) or volatilization (polluting air)*
   - *Too much nitrogen can burn seedlings*
   - *An imbalance of nitrogen with respect to other nutrients is unhealthy for the plants*

5) What is the most important thing you can do to a mineral soil in order to ensure an adequate supply of and maximum availability of plant nutrients?

   Maintain high levels of organic matter and foster biological activity

Organic matter helps by
   - *Buffers micronutrients, keeping them from becoming toxic or imbalanced*
   - *Chelates certain micronutrients to keep them available to plants*
   - *Increases cation exchange capacity*
   - *Supplies certain nutrients such as nitrogen, phosphorus, and sulfur*
   - *Improves physical condition of soil (air and water relationships enhanced), which helps to ensure maximum availability of nutrients*
   - *Buffers the effect of high or low pH*

Biological activity helps by
   - *Breaking down certain compounds to release nutrients*
   - *Breaking down organic matter*
   - *Some micro-organisms are involved with nitrogen fixation*
   - *Organisms can help move otherwise immobile nutrients through the soil*

Resources

PRINT RESOURCES

Brady, Nyle C., and Ray R. Weil. 2008. *The Nature and Property of Soils, 14th Edition*. Upper Saddle River, New Jersey: Prentice-Hall, Inc.

A good general soils text, used for introductory soils classes at universities. great for those who want to "go deeper" into the origins, classifications, and workings of soil.

California Fertilizer Association. 1997. *Western Fertilizer Handbook, 2nd Edition*. Danville, IL: The Interstate Printers & Publishers, Inc.

This book contains general information about soils and more detailed information about plant nutrients and fertilizers. Some parts may be difficult to understand. Emphasis is on inorganic fertilizers.

Foth, Henry D. 1990. *Fundamentals of Soil Science, 8th Edition*. New York: John Wiley & Sons.

Gershuny, Grace. 1993. *Start with the Soil*. Emmaus, PA: Rodale Press.

A general book on soils and soil management geared toward organic gardeners. Easy to read and understand.

Hanson, Blaire, Stephen R. Grattan, and Alan Fulton. 1999. *Agricultural Salinity and Drainage*. Publication 3375. UC Irrigation Program. Oakland, CA: University of California Division of Agriculture and Natural Resources.

An indispensable reference for anyone farming in an area where salinity might be a problem.

Parnes, Robert. 1990. *Fertile Soil: A Grower's Guide to Organic and Inorganic Fertilizers*. Davis, CA: agAccess.

Probably the best reference here on plant nutrients, with good coverage of organic amendments. Some useful reference charts in the appendices.

Stell, Elizabeth P. 1998. *Secrets to Great Soil*. Pownal, VT: Storey Communications, Inc.

An easy to read primer on soils, composting, and basic gardening techniques. Lots of diagrams.

Troeh, F. R., and L. M. Thompson. 2005. *Soils and Soil Fertility, 6th Edition*. Ames, IA: Wiley-Blackwell.

A general soils text used in introductory soils classes.

WEB-BASED RESOURCES

LIMING (PH)

Liming to Improve Soil Quality in Acid Soils – Agronomy Technical Note No. 8. USDA.

www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_019229.pdf

SALINITY

Saline and Sodic Soils

www.ag.ndsu.edu/langdonrec/soil-health/saline-sodic-soils/view

CARBON

C sequestration potential

www.strauscom.com/rodale-whitepaper/

NITROGEN

www.extension.umn.edu/agriculure/nutrient-management/nitrogen/understanding-nitrogen-in-soils

PHOSPHORUS

www.extension.umn.edu/agriculture/nutrient-management/phosphorus/the-nature-of-phosphorus/

www.extension.umn.edu/agriculture/nutrient-management/phosphorus/understanding-phosphorus-fertilizers/

www.ess.uci.edu/~reeburgh/fig4.html

www.sera17.ext.vt.edu/SERA_17_Publications.htm

POTASSIUM

www.ipipotash.org

www.extension.umn.edu/agriculture/nutrient-management/potassium/

SULFUR

www.extension.umn.edu/agriculture/nutrient-management/secondary-macronutrients/

www.soils.wisc.edu/extension/pubs/A2525.pdf

CALCIUM

soils.usda.gov/sqi/files/08d3.pdf

www.soils.wisc.edu/extension/pubs/A2523.pdf

www.psu.edu/ur/NEWS/news/liming.html

BASE CATION SATURATION RATIO

www.extension.umn.edu/agriculture/nutrient-management/soil-and-plant-sampling/soil-cation-ratios/

NUTRIENT CYCLING & SOIL FERTILITY

www.extension.umn.edu/distribution/horticulture/m1193.html#nutp

MISCELLANEOUS NUTRIENTS

eap.mcgill.ca/MagRack/COG/COGHandbook/COGHandbook_1_3.htm

www2.hawaii.edu/~nvhue/sustain_ag/sustag895.html

DEFICIENCY SYMPTOMS

extension.arizona.edu/sites/extension.arizona.edu/files/pubs/az1106.pdf

INSTITUTIONS

Cooperative Extension Service or Farm Advisors Office

Staff from these agencies will be aware of crop nutrient needs and problems in your area. They can assist you with nutrient deficiency symptoms and known plant nutrition problems in your area.

Soil and Plant Tissue Labs

These labs can test your soil or crop for deficiencies. Some websites containing listings of laboratories:

attra.ncat.org/attra-pub/soil_testing/

gardeningproductsreview.com/resources/soil-testing-for-the-home-gardener/state-state-list-soil-testing-labs-cooperative-extension-offices/

www.al-labs-west.com/

www.clemson.edu/agsrvlb/sera6/changes/accompli.htm