10 The Soil and its Environment

Soil is the earth's skin. The pedosphere, which includes agricultural soil discussed in this section, is a complex mix of physical, biological, and chemical properties that are integrated into a base on which we grow our crops. Good soil takes years to develop yet it can be destroyed in a matter of minutes with improper management. While too many people refer to the soil as 'dirt', it is far from being something we need to remove with soap and water. Soil is part of our intricate life support system, and itself is a complex natural body supporting a host of biological diversity we rarely see. Soil is a major recycling system filtering water and providing support for several of the major biogeochemical cycles on the planet (carbon, nitrogen, phosphorus, and sulfur) (Or *et al.*, 2011). Rather than focus on many of the topics already covered in most soil texts, this chapter will focus on nutrients and their cycles, fertilizers and their uses, and mulches. Soil basics will be reviewed and the reader is directed to a good soil text such as the one by Brady and Weil (2007) for greater detail in areas of interest.

Soil Basics

Soil is the outermost layer of the earth's surface supporting crop growth. Most of the minerals needed for plant growth are absorbed by plants from the water in soil, called the soil solution. Characteristics of a particular soil and its solution depend on the parent mineral or organic matter material from which it was derived and the actions of macro- and microorganisms and the environment on them over time. In general, the soil is a 50:50 mixture of solids and pore space. The solid portion is mostly mineral (~90%) with some organic matter (~10%). Peat or muck soils may contain from 20 to nearly 100% of their solid component as organic matter. The pore space is occupied by varying percentages of air and water depending on current conditions.

Soil horizons

When considering soils for agricultural production, soil horizons are often discussed. Soil horizons are layers of soil running parallel to the surface. Each layer varies in thickness from less than a centimeter to many meters, depending on location. In some soils the horizons are easily distinguished while in others they flow one into the next. The topmost horizon, the A horizon, includes the mulch (topmost layer including plant debris, decaying organic litter, etc.) and the plow layer (under the mulch). Living organisms such as plant roots, fungi, bacteria, worms, nematodes, insects, and small animals are abundant in this layer of a healthy soil. In not-so-healthy soils, the biology of this layer may be severely compromised. The B horizon is located just below the A horizon and is often called the subsoil. It has characteristics of both the B and the C horizon. The C horizon is the parent material of mineral soils and lies below the B horizon and is usually the deepest layer.

Soil texture

Soil texture describes the relative proportion of particles of various sizes that make up the solid portion of a soil. The largest particles are sand (0.05–2.00 mm diameter), followed by silt (0.002–0.05 mm), and clay (<0.002 mm). Gravel is often part of many mineral soils. A particular soil is classified into one of 12 soil textural classes developed by the USDA (Brown, 2003) and can be determined using the USDA soil texture triangle or obtained from a soil test report (Fig. 10.1). Organic soils are those soils containing a significant amount of plant and animal remains in the process of decay. These soils are classified as mucks or peats, mucks being more highly decomposed than peats. In soils that have a substantial amount of fragments of coarse parent material, such as stones or

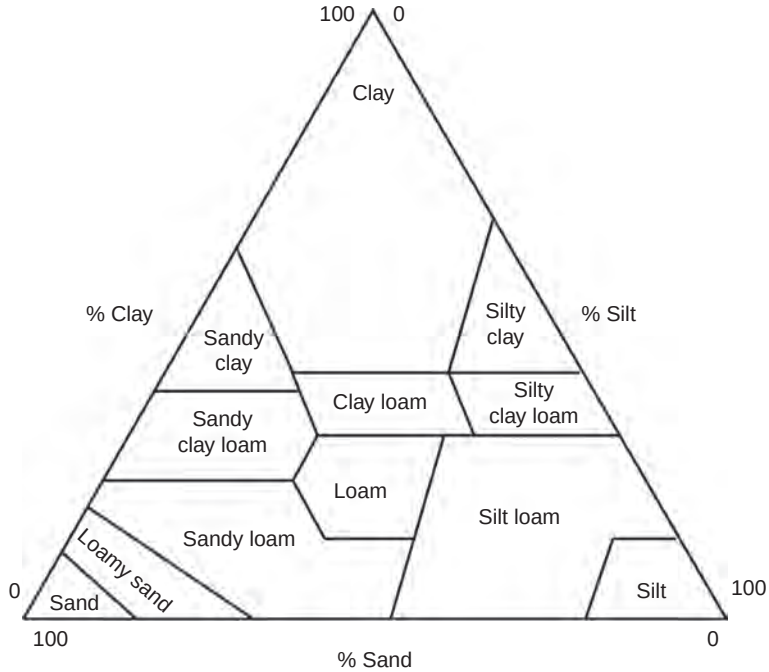


Fig. 10.1. Generalized soil texture triangle with soil texture names based on component percentages.

gravel, their presence is recognized by prefixing a textural class name with an appropriate adjective, such as 'gravelly, sandy loam'.

Soil texture has a profound influence on soil fertility, capacity to retain fertilizers, cation exchange and buffering capacity, and soil permeability and drainage. As the relative amount of clay and silt increase, these soil properties are increasingly affected. Clay- and silt-based soils tend to be more fertile with higher cation exchange and buffer capacities than sandy soils. They also retain more water than sandy soils, but may also be poorly drained if clay or silt amounts are excessive.

Soil structure

While texture refers to the proportions of the different sized solid particles in a soil, soil structure refers to their aggregation or lack thereof. Aggregation in the soil results from physical and chemical processes and takes time to achieve. Good soil structure takes a long time to develop but can be destroyed in a matter of minutes. Working the soil when it is wet is the number one way to ruin a soil's structure. Overworking soil when it is not wet is the other major activity that will destroy soil structure. Organic matter binds the sand, silt and clay particles together, thus the addition of organic matter to soils can improve their structure significantly, especially when the soil is originally low in organic matter. In extremely sandy soil, organic matter may not improve soil structure since the soil lacks structure to begin with. Soil structure combined with soil texture gives a soil its physical properties conducive to plant growth. These properties include water holding and drainage along with nutrient characteristics. It is much easier to correct nutrient deficiencies in a soil than to quickly improve a soil's structure.

Soil bulk density

Soil particle density is the mass of solid particle per unit volume and is generally around 2.6 g/cm^3. Soil bulk density is the mass of dry soil per unit volume, and unlike particle density, it takes into account pore spaces in the soil that are due to the soil's structure. Thus soil bulk density varies with structure while particle density does not.

Well-aggregated soil has a lower bulk density than poorly structured soil. When soil bulk densities are too high, root penetration and water infiltration is reduced resulting in poor plant growth. Bulk densities generally range from 1.0 to 1.8 g/cm^3 in well-aggregated soil.

Soil color

Soil color, especially subsoil color, can reveal good information concerning long-time water drainage of the soil. Well-drained soils often have reddish-brown subsoil while the subsoil of poorly drained soil is often mottled and gray. Soils with fair drainage often have pale yellow subsoils. Surface soil color varies tremendously with parent material and amount of organic matter.

Soil organisms

Most soils are teaming with life. Besides plant roots, there are many small to microscopic organisms living at and beneath the soil's surface that have a tremendous influence on plant productivity. The distribution and activity of soil organisms is related to food supply, temperature, soil pH, moisture availability, tillage practices, and the use of pesticides.

Arthropods

Arthropods are animals that have an exoskeleton such as insects, crustaceans, and arachnids. Arthropods in the soil shred organic matter, stimulate microbe activity, and recycle nutrients. Some arthropods such as millipedes and termites are shredders, chewing up dead plant material. Herbivores in the soil like mole crickets feed on live plant roots. Both shredders and herbivores can become a pest if their population gets too high. Finally, predator arthropods such as spiders and centipedes feed on other arthropods, helping to control their population, or feed on fungi and bacteria.

Bacteria

Bacteria are single-celled, microscopic organisms that are important in nutrient recycling, causing or suppressing diseases, and removal of toxins from polluted soils. Bacteria are often categorized as pathogens, decomposers, mutualists, or chemoautotrophs. Pathogens cause disease and decomposers break down organic matter in the soil. Mutualists such as *Rhizobium*, live in symbiosis with plants such as beans, clover, and alfalfa, providing nitrogen to the plant and receiving carbohydrates in return. Chemoautotrophs are bacteria that can utilize nitrogen, sulfur, or iron compounds for energy. They are often used to clean up pesticide or oil spills from a soil.

Earthworms

While not a required component, earthworms often indicate a healthy soil. Earthworms help aerate the soil by their burrowing action creating macropores in the soil that enhance root growth, gas exchange, and water infiltration. They are the primary consumer of organic matter in a soil and as such are responsible for decomposing plant materials and recycling nutrients. Earthworm populations and their activity in the soil is enhanced with organic matter and reduced with cultivation and pesticide use. Earthworm casts improve soil structure by enhancing soil aggregation and are a rich source of nutrients, especially nitrogen. The nitrogen content of earthworm casts is directly related to the nitrogen content of the organic matter consumed, with casts containing approximately 70% of the nitrogen in the consumed organic matter.

Nematodes

Nematodes are microscopic, non-segmented worms that live in the soil. Some feed on bacteria, fungi, and algae in the soil while others are plant or animal parasites. Nematodes help recycle nutrients in the soil and can either suppress or cause plant disease, depending on their feeding habit. Predator nematodes tend to suppress disease by ingesting disease-causing organisms. Those that feed on plant roots often transmit viruses that can cause disease.

Soil fungi

Fungi are abundant in most soils. They can be single celled like yeast or multi-cellular with an elaborate network of hyphae. They are important in nutrient recycling, decomposition of organic matter and can either cause or suppress plant diseases. An important group of fungi important in nutrient acquisition from the soil are the mychorrizae.

Soil protozoa

Protozoa, mobile single-celled organisms that are larger than bacteria, are important for nutrient recycling and regulating soil bacteria populations. Protozoa often release nitrogen that can be used by plants while feeding on bacteria or other protozoa. Protozoa are most abundant and active near plant roots.

Soil Chemistry

Much of the chemical activity in a soil is associated with humus and clay particles. Clay is a natural mineral constituent of the parent material while humus is derived from decomposed organic matter. Both types of particles are characterized by an extremely large surface area to weight ratio and the presence of electrical charges on their surfaces to which ions and water molecules are attracted. Humus and clay exist in the colloidal state, a suspension of fine particles in water. On a weight basis, humus colloids hold more water and nutrients compared with clay colloids, but there is usually much more clay in a soil compared with humus. Thus clay often has more of an impact on nutrient and water holding capacities of a soil than humus.

The two major types of clay found in most soils are: (i) montmorillonite; and (ii) kaolinite. Montmorillonitic clay is less weathered than kaolinitic clay. Montmorillonite particles are composed of three layers, two of silica and one of alumina (the crystalline form of aluminum). These sheets are not held together very tightly, and as such tend to expand or contract as they become wet or dry. Soils high in this type of clay tend to be difficult to manage, often being very sticky when wet, and hard and cracked when dry. Montmorillonite soils have a higher cation exchange and water holding capacity compared with kaolinite soils. Kaolinite clay is highly weathered and is composed of two layers, one of silica and one of alumina. The two layers are held together more tightly than montmorillonite and therefore do not expand or contract as much when wetted or dried. They are also easier to manage.

Cation exchange capacity (CEC)

Clay and humus particles are negatively charged. With large surface areas, they both have a tremendous number of negative electrical sites on each particle, each site capable of attracting and holding particles with a positive charge (i.e. cations). These cations may be held to the soil particle surface or exchanged with another cation into the soil solution, hence the term CEC ('cation exchange capacity'). Once in the soil solution, the cation may be absorbed by a plant or it may combine with a negatively charged ion and leach out of the soil.

The CEC of a soil is important for understanding its nutrient holding capability. Soils with a high percentage of clay or organic matter have a high CEC and therefore can adsorb and retain applied fertilizers easily. Sandy soils have a much lower CEC and therefore cannot adsorb applied nutrients as easily and are subject to leaching. How tightly a cation is held to a soil particle is related to the CEC of the particle as well as the nature of the cation. Smaller cations or cations that contain less water tend to be held more tightly than larger or drier cations. Divalent cations are held more tightly than monovalent cations.

The CEC of a soil is expressed in milliequivalents (mEq); 1 mEq is 1 mg of hydrogen or the amount of any other cation that will displace it. Sand may have a CEC as low as 2 while clay may have a value as high as 150. Soil milliequivalents are expressed on the basis of a 100 g of dried soil. One milliequivalent is equal to 10 parts hydrogen per 1 million parts soil, or about 22 kg hydrogen/ha soil, 17 cm deep (20 lbs/acre, 6.67 in deep). This standard allows easy conversion of milliequivalents of other elements to kilograms per hectare, kg/ha (pounds per acre, lbs/acre). To determine kilograms per hectare (pounds per acre) for any other element, first determine the element's equivalent weight then multiply by 22.4 (20). The equivalent weight is equal to the element's atomic weight divided by its valence. For example, calcium has an atomic weight of 40 and a valence of 2, thus its equivalent weight is 40/2 or 20. Thus 1 mEq of calcium is equal to 20 × 22.4 or 448 kg/ha (20 × 20 = 400 lbs/acre).

Since laboratory estimation of a soil's CEC is time consuming and laborious, CEC is often estimated from soil test results for hydrogen, calcium, potassium, and magnesium. Divide the kilograms per hectare (or pounds per acre) for each component as reported on the soil test results by its corresponding milliequivalent weight (20 for hydrogen, 400 for calcium, 240 for magnesium, and 780 for potassium) then add the four values. This is the estimate of the soil's CEC. For example, suppose the test results for were H = 48, Ca = 780, Mg = 115, and K = 247. The estimated CEC for that soil would be [(48/20) + (780/400) + (115/240) + (247/780)] = 5.14.

Percentage base saturation

The percentage base saturation gives a reasonable idea of soil pH and fertility. The higher the percentage base saturation, the higher the pH and fertility. The percentage base saturation is calculated as the proportion of the total CEC accounted for by calcium, magnesium, and potassium. In our example, the base saturation would be (1.9 + 0.5 + 0.3)/5.14 = 53%.

Ions that are absorbed by plants from the soil solution are quickly replaced by a similar ion, if available, from the ions adsorbed to soil or humus particles. The capacity of a soil to replenish ions, particularly cations, from the soil solids to the soil solution is often called a soil's buffering capacity. This is different than a soil's pH buffering capacity, which is the soil's capacity to resist changes in pH. Soils with a high CEC have the potential to have a high buffering capacity if they are well fertilized.

Anion adsorption

Anion adsorption isn't as important as cation adsorption from a horticultural standpoint. Anion adsorption is regulated by soil pH and is only significant at a pH lower than that which would support plant growth. Common soil anions include chloride, phosphate, nitrate, and sulfate. Phosphates and sulfates are adsorbed more strongly than chlorides and nitrates. Occasionally adsorption of phosphate ions may be significant enough to cause concerns regarding availability for plant use. Most anions are lost from the soil by leaching.

pH

Soil pH greatly affects nutrient availability in the soil and is therefore of concern to horticulturists. Soils with a low pH are called acidic soils while those with a high pH are called basic or alkaline soils. But what does this mean? Recall from basic chemistry that an acid is a substance that releases hydrogen (H^+) ions while a base is a substance that releases hydroxyl (OH^-) ions. The strength of the acid or base is its tendency to release either hydrogen or hydroxyl ions when dissolved in water. Thus substances in soil water can contribute acidic or basic properties to the soil making the soil itself either acid, alkaline, or neutral.

A reasonable generality is that the more hydrogen ions held by a soil in relation to the number of basic ions (Ca^{2+}, Mg^{2+}, K^+) the more acidic the soil. Soils become more acidic as basic ions are replaced from the soil particles by hydrogen ions due to absorption by plants or leaching from the soil. Soils formed in area with high annual rainfall tend to have acidic soils. In addition, rain helps acidify soils. Carbon dioxide in the air combines with rainwater to form a weak acid, carbonic acid. In the soil solution, carbonic acid ionizes into hydrogen ions and bicarbonate ions, and the hydrogen ions replace calcium ions held by soil particles. The released calcium ions combine with the bicarbonate ions forming calcium bicarbonate, which is soluble in water and leaches out of the soil. Many fertilizers, especially those fertilizers that release ammonium, contribute to soil acidity. As ammonium is converted to nitrate via nitrification, hydrogen ions are released, acidifying the soil. Certain crops such as soybeans (*Glycine max*), alfalfa (*Medicago sativa*), and clover (*Trifolium* spp.) absorb more cations compared with anions while concomitantly releasing hydrogen ions to maintain an electrochemical balance within their roots, acidifying the soil.

Soil acidity is measured by its pH, a measure of the concentration of hydrogen ions in solution. Values near 1 indicate excessive acidity while values near 14 indicate excessive alkalinity. A value of 7 is neutral. The pH scale is logarithmic, meaning that a pH of 5 is ten times more acidic than a pH of 6 and 100 times as acidic as a pH of 7. Most crops grow best in a slightly acidic soil with a pH ranging from about 5.8 to 6.5. Of course there are exceptions, such as blueberry (*Vaccinium* spp.) and azalea (*Rhododendron*) which grow best at a soil pH near 5.0–5.5 and alfalfa (*M. sativa*), clover (*Trifolium* spp.) or sugarbeet (*Beta vulgaris*) that grow best in soils with a pH of 6.5–7.0. Another measurement called the buffer pH is an important indicator of the potential acidity of a soil. It is often included in a soil test report as BpH. The BpH measurement is used in calculating the amount of lime needed to increase the pH of the soil, if necessary.

Liming to correct pH

Many horticultural soils need liming to increase their pH. Raising the soil pH makes essential nutrients available for plant use and also prevents elements such as aluminum and manganese from reaching toxic levels. In addition, liming adds calcium (and magnesium if the lime is dolomitic) to the soil.

Materials used for liming contain calcium and/or magnesium in specific forms that neutralize soil acidity. The main differences among the materials available for liming are the costs of the material and the rapidity in which they raise pH. The faster acting materials cost more. Just because a material contains calcium or magnesium does not mean that it will change the soil pH. Gypsum (calcium sulfate) contains significant calcium, yet does not alter soil pH. When calcium sulfate is added to water, calcium hydroxide and sulfuric acid are produced and these two substances neutralize each other, thus there is no change in soil pH. When calcium carbonate (calcitic limestone) is added to the soil, it dissolves to form a weak acid (carbonic acid) and a strong base (calcium hydroxide). The hydroxide ionizes to calcium and hydroxyl ions and the cations replace hydrogen ions on the soil particle to neutralize the soil acidity.

Ground limestone is either calcitic (calcium carbonate) or dolomitic (calcium carbonate and magnesium carbonate). In some areas, limestone must contain at least 6% magnesium to be labeled 'dolomitic'. The effectiveness of either type of limestone in raising the soil pH depends on its purity and fineness of grinding. Hydrated lime, also called slaked or builder's lime, is calcium hydroxide. It is quick acting, but powdery and somewhat hard to handle. It is also more effective in neutralizing pH than ground limestone since it only takes 75% as much hydrated lime as ground limestone to neutralize the same soil situation.

The quality of any liming material is determined by its purity and particle size. Purity is expressed as calcium carbonate equivalents (CCE) or the neutralizing capacity of the material as compared to pure calcium carbonate. A high CCE is useless if the particle size is too large. Thus the two components must be considered together. Sometimes limestone is pelletized with clay to improve ease of handling, and when it is used, should be allowed to react with rain before incorporating into the soil.

When applying lime, sufficient time must be provided for the material to work prior to establishing a crop. This will depend on the form of liming material, its fineness, and the crop. A ballpark figure of 3–6 months prior to planting should allow sufficient time for the pH increase to occur. Even lime applied just prior to planting can be beneficial for raising extremely low pHs if the lime is finely ground and well incorporated. Liming material should be well incorporated into the topsoil after application if possible. With perennial crops or no-till scenarios, incorporation is not possible, thus it is even more important to use the most finely ground materials available and to apply it on a regular basis.

Excessive alkalinity

Some soils are naturally alkaline. Other soils are made alkaline by irrigation water that may be high in calcium or magnesium carbonate. Similarly, irrigation water may be high in sodium, further exacerbating the problem. Elemental sulfur is used to reduce soil pH in these situations. When the sulfur is applied to the soil, it combines with water in the presence of specific microorganisms to form sulfuric acid. This process may take from 3 to 6 weeks, depending on weather, soil conditions, and how fine the sulfur is ground.

Aluminum sulfate should not be used to lower soil pH. It contains aluminum, which at low pH (which is the direction you are aiming at with its application) may be in sufficient quantities to be toxic.

Soil salinity

Soil salinity and the problems it causes were covered in Chapter 6 of this volume.

Soil Testing

In order to make intelligent decisions concerning soil management, growers must know some basic attributes of their soil. This is what a soil test provides: a snapshot of the general condition of a soil including, but not limited to, its texture, sodium content, pH, and fertility levels. There are many commercial laboratories that specialize in soil testing including many labs at agricultural universities, and the tests they routinely perform vary. Before embarking on a soil testing venture, make sure you have evaluated your needs so that the appropriate tests are performed. You don't want to skip an important test and you don't need to pay for tests that you don't need.

Soil sampling

A good soil test begins with a good sample that represents the soil in question. If several soil types are involved in the management program, separate

samples should be taken and separate tests should be performed for each soil. The soil test is meant to estimate the entire soil, thus a good sample is crucial for effectively interpreting results and implementing recommendations. Remember, less than a tablespoon full of soil is used in the test which might represent a field of many hectares. Most growers now rely on site specific management which involves precise regulation of soil management of 2–3 acre parcels of land, rather than entire fields. Thus a field of 30 acres may now be managed as ten 3 acre sites rather than a 30 acre field. Site size depends on variability within the field. Greater variability requires smaller sites.

Soil samples are taken to estimate how well a particular site will support a specific crop, not to measure the nutrients in a particular parcel of land. Samples should be drawn with this goal in mind while taking into consideration the variability present in the field. Think of the sample of soil you send to the lab as a set of subsamples gathered from each field being tested. Labs will provide a specific set of sampling criteria that should be followed concerning collection of subsamples. Subsamples are normally drawn from a depth of 17 cm. Shallow samples will over-estimate the fertility of the field while samples deeper than recommended will probably underestimate cropping capacity of the soil. Samples should also be taken in an organized and documented pattern, taking care not to sample directly where banded fertilizer applications may have been made.

Stainless steel or chrome-plated sampling tubes or augers should be used and subsamples transferred to clean plastic buckets for mixing. Avoid galvanized or rubber buckets. Samples should be taken around the same time each year but at least 30 days after liming, sulfur, or fertilizer application. Always remove any surface debris before sampling and sample at a consistent recommended depth. Each sample should be made up of 10–15 subsamples, thoroughly mixed in a plastic bucket. Follow the lab's specific instructions for packaging and shipping your samples, making sure you have included the appropriate paperwork and fees.

Calibrating and interpreting soil test results

Soil test results must be calibrated to the crop they are intended to support. Calibration studies are performed by professionals over many years on many soil types. The testing lab normally performs the calibration for you, and this is why they request cropping information on forms submitted with your samples (Fig. 10.2). It is best to look at recommendations as suggestions for optimizing production. Improved crop performance may occur if recommendations are followed but there is no guarantee. The best yield responses are obtained when soil tests reveal a soil that is 'far away' from optimum and recommendations are followed closely. But remember soil fertility is only one part of the production equation.

Soil Fertility

Even though plants are autotrophs that synthesize their own food through photosynthesis, they have a requirement for obtaining certain nutrients, mostly ions, from an external source such as the soil or growing medium in the case of hydroponics (Fig. 10.3).

Plants require 17 essential mineral elements which are divided into macronutrients and micronutrients based on quantities needed for normal growth and development. The macronutrients include carbon, hydrogen, oxygen, nitrogen, potassium, phosphorus, calcium, magnesium, and sulfur. The micronutrients include iron, chlorine, copper, manganese, zinc, nickel, molybdenum, and boron.

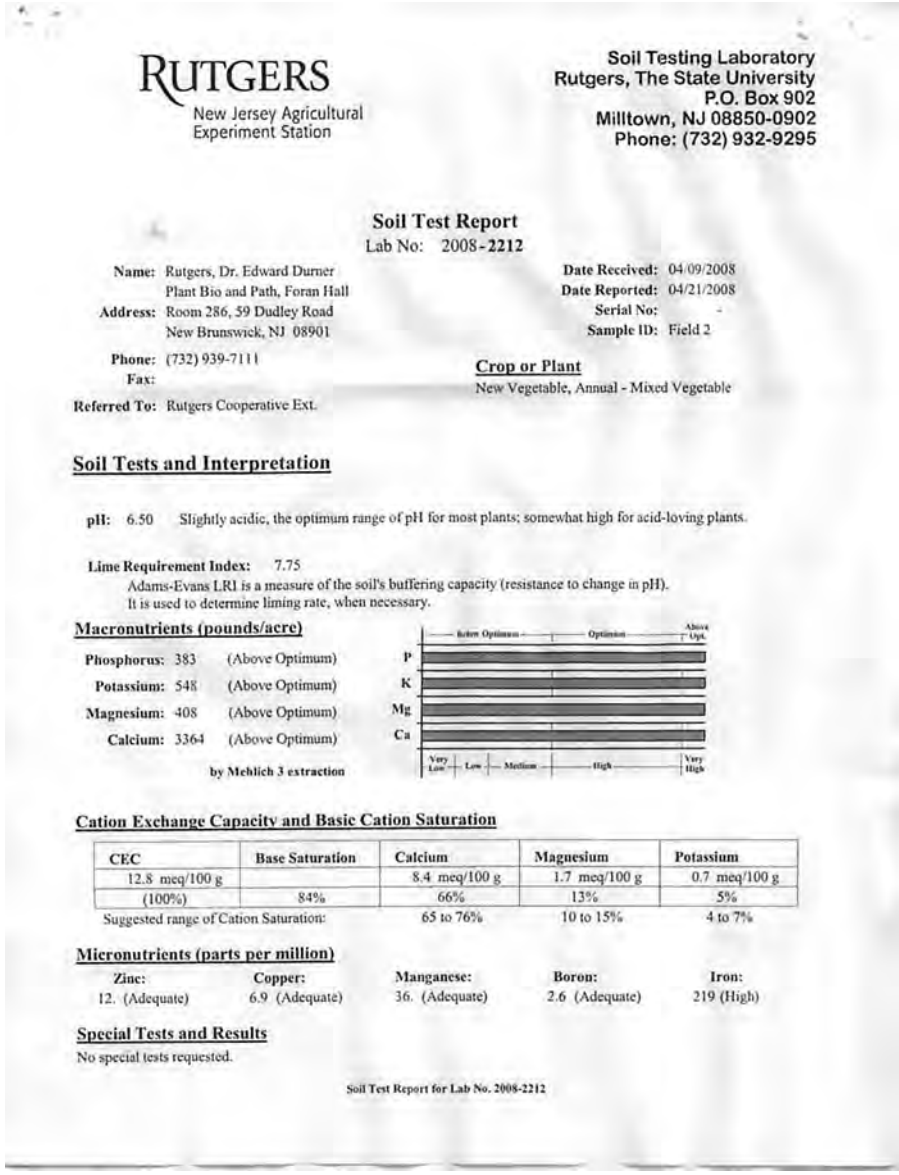
Macronutrients are often categorized as either primary or secondary. The primary nutrients include nitrogen (N), phosphorus (P), and potassium (K). They are called primary because they are usually lacking from the soil because plants use such large amounts of them. Soils almost always require supplemental N, P, and K for crop production. The secondary nutrients are calcium (Ca), magnesium (Mg), and sulfur (S). They are called secondary because one or more of them are often present and available in sufficient quantities such that fertilization with them is not required.

In this section, the major roles each nutrient plays in plant growth and development will be explored along with fertilizer sources for each nutrient, as well as a brief description of excess and deficiency symptoms.

Macronutrients

Carbon, hydrogen, and oxygen

Carbon, hydrogen, and oxygen together make up about 98% of a plant's fresh weight. These



RUTGERS
New Jersey Agricultural Experiment Station

Soil Testing Laboratory
Rutgers, The State University
P.O. Box 902
Milltown, NJ 08850-0902
Phone: (732) 932-9295

Soil Test Report
Lab No: 2008-**2212**

Name: Rutgers, Dr. Edward Durner
Plant Bio and Path, Foran Hall
Address: Room 286, 59 Dudley Road
New Brunswick, NJ 08901
Phone: (732) 939-7111
Fax:
Referred To: Rutgers Cooperative Ext.

Date Received: 04/09/2008
Date Reported: 04/21/2008
Serial No: -
Sample ID: Field 2

Crop or Plant
New Vegetable, Annual - Mixed Vegetable

Soil Tests and Interpretation

pH: 6.50 Slightly acidic, the optimum range of pH for most plants; somewhat high for acid-loving plants.

Lime Requirement Index: 7.75
Adams-Evans LRI is a measure of the soil's buffering capacity (resistance to change in pH).
It is used to determine liming rate, when necessary.

Macronutrients (pounds/acre)

Phosphorus: 383 (Above Optimum)
Potassium: 548 (Above Optimum)
Magnesium: 408 (Above Optimum)
Calcium: 3364 (Above Optimum)
by Mehlich 3 extraction

Cation Exchange Capacity and Basic Cation Saturation

CEC	Base Saturation	Calcium	Magnesium	Potassium
12.8 meq/100 g		8.4 meq/100 g	1.7 meq/100 g	0.7 meq/100 g
(100%)	84%	66%	13%	5%
Suggested range of Cation Saturation:		65 to 76%	10 to 15%	4 to 7%

Micronutrients (parts per million)

Zinc:	Copper:	Manganese:	Boron:	Iron:
12. (Adequate)	6.9 (Adequate)	36. (Adequate)	2.6 (Adequate)	219 (High)

Special Tests and Results
No special tests requested.

Soil Test Report for Lab No. 2008-2212

Fig. 10.2. Soil test results for a field used for mixed organic vegetable production.

elements are obtained from the atmosphere and soil as carbon dioxide and water. They are major components in many molecules involved in plant growth but since they are obtained from non-mineral sources, they are not normally covered in discussions of mineral nutrients. They were included here for completeness in our listing of plant essential elements.

Nitrogen

After carbon, hydrogen and oxygen, nitrogen is the most abundant element in plant tissues. In some species it can account for up to 4% of a plant's fresh weight. Even though plants are surrounded by an atmosphere that is 78% nitrogen, it is inert nitrogen gas (N_2) that is not directly available to

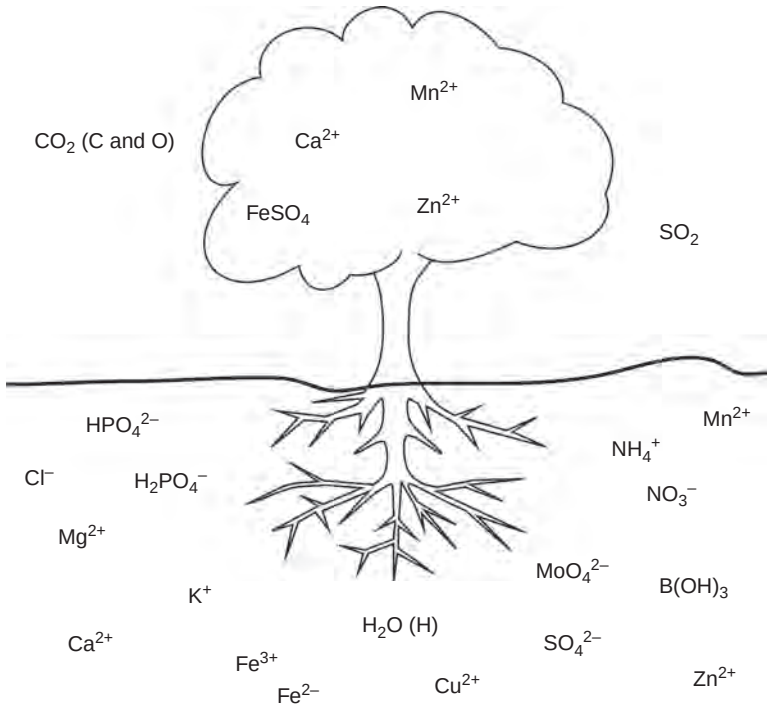


Fig. 10.3. Forms of nutrients absorbed by plants.

plants for growth and development. Nitrogen deficiency is the most common plant nutrient deficiency worldwide. With insufficient nitrogen, plants are weak, spindly, and unproductive.

Nitrogen is a key element of proteins which include the thousands of enzymes that facilitate life. Proteins are also key structural components in plant tissue. It is a major component of chlorophyll, and under deficiency conditions, chlorophyll production is reduced and leaves take on a chlorotic, yellow color. Nitrogen is a mobile element, meaning that once incorporated into plant tissues it can be remobilized if necessary and move to actively growing tissue. Since it is mobile, older leaves first show signs of nitrogen deficiency. Nitrogen is part of the ATP molecule, important in the metabolic energy balance of plants, and is also a part of nucleic acids, the genetic code for life.

Nitrogen in the soil exists as nitrogen in organic compounds, ammonium (NH_4^+) and nitrate (NO_3^-). Most soil nitrogen (95–99%) is present as nitrogen in organic matter such as plant and animal residue or microbes such as bacteria. This nitrogen is not available to plants, but a small portion of it can be converted to usable forms by microbes. A very small fraction of organic soil nitrogen may also be in a soluble form such as urea, which may be available for plant use. Most soil nitrogen available to plants is in an inorganic form, either NH_4^+ or NO_3^-. Since NH_4^+ is a cation, it binds to negatively charged soil particles such as clay or humus. On the other hand, NO_3^- is an anion and remains in the soil solution or precipitates out as a soluble salt under dry conditions. Being soluble, NO_3^- is easily leached from the soil and at times is leached at rates high enough to cause concerns about groundwater pollution.

Plants can absorb nitrogen as either NH_4^+ or NO_3^-, however, since most of the soluble inorganic nitrogen in a soil is in the NO_3^- form, most nitrogen is taken up as NO_3^-. Once absorbed, NO_3^- is converted to NH_4^+ then assimilated into biomolecules.

Nitrogen in the soil comes from two major sources: (i) fertilizer; and (ii) naturally occurring nitrogen. Naturally occurring nitrogen comes from either the nitrogen in minerals of the soil or the atmosphere. Very small quantities of nitrogen are slowly released as mineral and organic matter components of the soil breakdown. Most of the naturally occurring nitrogen in the soil comes from

the atmosphere through either of two mechanisms: (i) conversion of nitrogen (N_2) to nitrate (NO_3^-) by lightning in thunderstorms; or (ii) fixation by microbes in the soil. Nitrate produced during a thunderstorm dissolves in rainwater and is deposited in the soil. This process normally accounts for only 22 kg N/ha and the exact amount depends on the number of thunderstorms occurring in any year.

BIOLOGICAL NITROGEN FIXATION Nitrogen fixation by microorganisms is a much more important source of nitrogen for plant growth. This process called biological nitrogen fixation is accomplished by free-living organisms in the soil or by organisms living symbiotically with certain species such as legumes. Organisms that fix nitrogen utilize atmospheric nitrogen to synthesize nitrogenous compounds for their own growth and development. When they die and decompose, the nitrogen is released into the soil for use by other organisms, including plants. Since biological nitrogen fixation requires substantial amounts of energy, free-living nitrogen-fixing organisms such as *Azotobacter* fix minimal amounts of nitrogen each year because food sources for the energy required for fixation are often scarce. Symbiotic organisms such as strains of *Rhizobium* fix significantly more nitrogen. Rhizobia are bacteria that infect the roots of certain plants, mainly legumes, and form small nodules with a complex anatomy and biochemistry that allows them to live in symbiosis with the host plant (Fig. 10.4). The bacteria obtain carbohydrates from the host plant and, when the bacteria fix more nitrogen than they need, it is passed onto the host plant. In addition, when the host plant dies, nitrogen from dying Rhizobia is released to the soil for use by a future crop. Most of the fixed nitrogen is actually removed in the harvested crop. In fact, the field residue of legume plants remaining after harvest usually contains no more nitrogen than non-leguminous residue. Plants may relinquish 20–30% of their carbohydrates to *Rhizobium* over the growing season in exchange for as much as 225 kg or more N/ha/year.

The symbiotic relationship for nitrogen fixation is a complex one. *Rhizobium* bacteria invade cortical cells in legume roots where they quickly begin to multiply. The infection site begins to swell, forming the classic nodule seen on many legume roots. Young nodules do not fix nitrogen and are usually white or gray inside. Older nodules that are fixing nitrogen are pink or reddish colored. The reddish color is caused by leghemoglobin, a compound that regulates oxygen movement to the bacteria in the nodule. Nodules on perennial legumes such as alfalfa (*M. sativa*) are often fingerlike in shape and often look like a hand – a central mass with protruding fingers. These nodules are long lived and may fix nitrogen for the entire growing season. There are generally 10–50 nodules per plant, centered on the tap root. Nodules on annual legumes such as peas (*Pisum* spp.), beans (*Phaseolus* spp.), or peanuts (*Arachis hypogaea*) are short lived and about the size of a pea. They are constantly being replaced throughout the growing season. When pods of the host plant begin to fill, nitrogen fixation ceases, since carbohydrates are diverted from the nodules to the filling pods. Beans generally have less than 100 nodules per plant, soybeans may have several hundred, and peanuts may have well over 1000 nodules per plant.

Fig. 10.4. Nodules of *Rhizobium* on roots of green bean (*Phaseolus vulgaris*).

Healthy nodules will be pink or red during the growing season, indicating good nitrogen fixation. If nodules are white or gray, it means that they are not fixing nitrogen. Lack of nitrogen fixation may be due to: (i) a poor *Rhizobium* strain; (ii) poor

plant nutrition, especially phosphorus, potassium, zinc, iron, molybedenum, or cobalt; (iii) pod filling; or (iv) plant stress. Stress could include insects, disease, heat, or drought. If the stress is alleviated, productivity can often be improved and nitrogen fixation enhanced.

Some legumes fix nitrogen more effectively than others. Common beans (*Phaseolus* spp.) are poor nitrogen fixers, fixing less than 56 kg N/ha/year. Maximum productivity often requires a fertilizer supplement of 33–56 kg N/year. If beans are not well nodulated, productivity may remain low even with supplemental fertilization. The nodules somehow help the plants utilize nitrogen more efficiently. Peanuts (*A. hypogaea*), cowpeas (*Vigna* spp.), soybeans (*G. max*), and fava beans (*Vicia faba*) are good nitrogen fixers, fixing up to 280 kg N/ha/year. Maximum productivity with these crops requires no supplemental nitrogen fertilization, though a very small amount of nitrogen (11–16 kg/ha) may be supplied to seedlings prior to the onset of fixation. Too much supplemental nitrogen at this stage will inhibit fixation. Perennial and forage legumes such as alfalfa (*M. sativa*), clover (*Trifolium* spp.), and vetch (*Vicia* spp.) may fix as much as 280–560 kg N/ha/year and are not normally fertilized with supplementary nitrogen. Immediately after cutting, a small amount of nitrogen may be applied to supplement the lack of fixation while the plant re-establishes a photosynthesizing surface.

Adequate nitrogen fixation depends on an adequate supply of an appropriate and efficient *Rhizobium* strain. While *Rhizobium* is present in most soils, it may not be present in sufficient quantities or present as the appropriate strain for the crop being grown. Since inoculation is inexpensive ($1–5/ha), it is often a good idea to inoculate seed with an appropriate strain prior to planting. This is particularly true if: (i) the land has never been in cultivation; (ii) the legume you are planting has never been grown in the intended field; or (iii) it hasn't been grown there for more than 5 years. If the legume is not new, but you don't know how well-nodulated previous crops have been, it is wise to inoculate. There is no need to inoculate if the legume was recently grown on the same land and nodulation and nitrogen fixation appeared adequate. Once established, *Rhizobium* will persist in the soil for several years, thus there is no advantage to yearly inoculation of legume crops in fields where the well-nodulated legume is routinely grown. Once a particular strain of *Rhizobium* is established, it is hard to get another strain to establish itself if you decide to change crops. This is because the established strain is usually more competitive for the nodulation sites on the roots.

Inoculants are available as powders, granules, liquids, and on pre-inoculated seeds. Powders are the most common and reliable form of inoculant. They are black or tan, contain 1 billion *Rhizobium*/g and are stuck on the seed before planting. Granular inoculants are two to three times as expensive as powders and contain the same concentration of bacteria as powders. The larger particle size allows it to flow through an insecticide or fertilizer applicator and no mixing with seed is required. Granules are useful for pesticide-coated seed or seed with crops with a fragile seedcoat (e.g. peanut, *A. hypogaea*) which would be easily damaged by mixing. Liquids are easier to handle than powders, but be especially careful regarding expiration date and handling, especially temperature, as improper handling can kill the bacteria in the inoculant. Pre-inoculated seed is only worth the extra cost if seed are freshly inoculated and quickly planted. *Rhizobium* won't survive long when exposed to air, heat, cold, or light.

Inoculants must be handled correctly to be effective. *Rhizobium* is living and very sensitive to heat, desiccation, and light. Many inoculant failures can be traced to improper handling. They should be stored in a cool, dry place away from heat. Some pesticide and fertilizer coatings can kill the bacteria if the inoculant is applied directly to the seed. Check the inoculant's label for: (i) the type of legume it is intended for; (ii) the quantity of seed or acreage the inoculant will cover; and (iii) its expiration date. The inoculant must match the crop. If conditions are particularly hot or dry, double the recommended amount of inoculum. Never buy inoculant that has been stored in a fertilizer or pesticide warehouse. When inoculating the crop, follow label instructions, don't leave inoculants in the hot sun, and store leftovers appropriately. Use a sticker with powders, either a commercial one or a homemade one consisting of 266 ml sugar to 946 ml water. Don't use too much sticker and be as gentle as possible with seeds. Plant inoculated seeds immediately and don't expose treated seed to sunlight.

THE NITROGEN CYCLE The complex transformations of nitrogen in the soil are collectively called the nitrogen cycle. Most of the transformations are

carried out by microorganisms, thus they occur at very slow rates in cool or cold soils. As soil temperature increases, transformation rates also increase. The main focus of the nitrogen cycle is the interconversion of organic and inorganic nitrogen in the soil. As microorganisms grow, they absorb NH_4^+ and NO_3^- from the soil's inorganic nitrogen pool and incorporate it into their cells, becoming part of the organic nitrogen pool. This process is called immobilization. When these organisms die and decompose, NH_4^+ is released back into the inorganic nitrogen pool. This process is called mineralization. Mineralization also occurs when an organism decomposes organic matter in the soil and releases excess NH_4^+ into the inorganic soil nitrogen pool. How much inorganic nitrogen is available from the soil for plant uptake often depends on the balance between mineralization and immobilization that is occurring. Ammonium ions (NH_4^+) that are not quickly immobilized or absorbed by plant roots are quickly converted into NO_3^- in a two-step process called nitrification. In the first step, the bacteria *Nitrosomonas* converts NH_4^+ to nitrite (NO_2^-). Another bacteria, *Nitrobacter*, then converts the NO_2^- to NO_3^-. These two conversions usually occur at a rapid rate, thus much of the nitrogen in the inorganic soil pool is in the NO_3^- form. Nitrate is an anion and is easily leached from the soil. If soils become waterlogged and the oxygen supply in the soil is reduced, some bacteria convert NO_3^- to nitrous oxides and N_2, releasing oxygen for their respiration. The nitrous oxides and N_2 are not available for plant use and both are volatile and easily lost from the soil. This process is called denitrification. Significant losses of soil nitrogen can occur due to denitrification if soils are warm and remain saturated for more than a few days. Soils may also lose limited amounts of nitrogen through the volatilization of ammonia (NH_3), which readily forms from NH_4^+, particularly in alkaline soils. Nitrogen is also removed from the cycle in harvested crops.

Commercial nitrogen fertilizers

ORGANIC SOURCES Organic sources of nitrogen such as cover crops, compost, blood meal, feather meal, alfalfa meal, etc., rely on mineralization to release their nitrogen for plant use. A cover crop of alfalfa or clover can provide up to 224 kg N/ha/year, and about half of it will be mineralized during decomposition immediately following incorporation (Sarrantonio, 1994). This might be enough to supply the entire amount of nitrogen needed by the crop. However, cover crops require a long-term land commitment. For growers who cannot commit enough land to cover cropping and/or need to supplement nitrogen from an organic source, the process can be a bit difficult. The main problems with most organic sources of nitrogen is that they: (i) are expensive ($1–50/kg N); (ii) have a low nitrogen content; and (iii) the nitrogen in them is very slowly available to the plant.

Compost or manure can be added as a source of nitrogen. It is important to understand the principles behind using composts and manures for fertilization. Both manures and composts also supply other nutrients and they must be considered in decision making. Many types of composts and manures are available for field application. It is important to know: (i) what type of compost or manure you are using; (ii) if it is fresh or aged; and (iii) its nutrient content. Average nutrient contents for various composts and manures are available in any good reference, including Rosen and Bierman (2005). If possible, it is a good idea to have a sample of the product you are going to use tested. In addition, many products may not be derived from organic sources.

Composted manure is better to use than fresh manure for several reasons. Fresh manure is high in soluble nitrogen and salt build up, or losses from leaching, could occur with over-application. Fresh manure also may contain many viable weed seeds and may also contain pathogens such as *Escherichia coli*. If fresh manure is used, it should be applied at least 4 months prior to harvest. High temperatures generated in composting will kill most weed seed and pathogens. On the negative side, compost is usually more expensive than fresh manure and may reduce the amount of available nitrogen. In fact, nearly all of the nitrogen in compost is in the organic form which is not available to plants for uptake until it is mineralized by microorgansims in the soil. In addition, all of the nitrogen in compost may not be available to plants even after mineralization due to denitrification, volatilization, and leaching. Finally, only a part of the total nitrogen in compost is available to the plants in the year of application.

In general, 45–75% of the organic nitrogen in fresh manure is available the year of application while only to 14–30% is available from compost. Fresh manure should be incorporated immediately

into the soil after application to avoid losses from volatilization of ammonia. The C:N ratio of the manure or compost should also be considered as a C:N ratio of 25:1 or greater will greatly reduce the nitrogen immediately available to plants.

Unlike most conventional nitrogen fertilizers, organic sources such as compost and manure provide a residual supply of nutrients that must be accounted for in subsequent years of application. A general rule of thumb is that in the second and third years following application, 50 and 25%, respectively, of the organic nitrogen mineralized during the first cropping season will be available to the crop. Some manures and composts are especially high in phosphorus which can build to excessive levels. Routine soil and plant tissue tests should be performed to monitor nutrient levels over time.

In any fertilizer management scheme, whether organic or conventional, the first step is to determine crop needs. This information is readily available from reference books. For example, a general figure for the nitrogen requirement of mixed vegetables in the North-east USA is 125 lbs N/acre (140 kg/ha) (Maynard and Hochmuth, 1997). This figure will vary slightly with specific crop, soil and climate conditions, but it is a good reference point. The next step is to figure out how much nitrogen will be supplied by decomposing organic matter (not from the cover crop) in the soil. The organic matter content is often reported in soil test results. A rule of thumb is that 11 kg N/ha are released for every 1% organic matter, up to 4% (Grubinger, 2011). Assuming a soil with 3% organic matter, 33 kg N/ha would be available for plant growth; 107 kg N/ha are still needed, and we'll assume that a cover crop was not incorporated (not a very good organic practice!).

To determine the amount of compost or manure needed, the nutrient content of the material should be determined with testing or estimated from a table such as the one in Rosen and Bierman (2005). Most often since nitrogen is the nutrient most deficient, application rates are based on nitrogen needs rather than phosphorous (P) or potassium (K). The available nitrogen from your source is calculated as:

$$\text{Available N} = [(\text{Total N} - \text{Ammonium N}) \times (\text{Fraction of organic N released}) + \text{Ammonium N}]$$

Where total N and ammonium N are from a test result or estimated from a reference table and fraction of N released is from a reference table.

As an example suppose we are using fresh dairy manure with bedding which will be incorporated immediately after application. It has an estimated that the total N content is 4.5 kg/t and the ammonium N is 2.5 kg/t with the fraction of N released is 25%.

$$\text{Available N} = [(4.5 - 2.5) \times (0.25) + 2.5]$$

$$\text{Available N} = 3 \text{ kg/t}$$

In our example we still needed 107 kg N/ha, which means we need 107/3 or approximately 36 t/ha.

You should next determine the amount of P and K supplied by the manure to establish whether or not supplemental fertilizers are required for either. The P_2O_5 and K_2O content of the manure is obtained via test results or estimated and availability is generally 80% for P_2O_5 and 90% for K_2O.

For our example, estimated P_2O_5 content is 2 kg/t and K_2O is 5 kg/t, but only 80% and 90%, respectively, is available:

$$\text{Available P} = (2 \times 0.8) = 1.6 \text{ kg/t}$$

$$\text{Available K} = (5 \times 0.9) = 4.5 \text{ kg/t}$$

If we are applying 36 t/ha to satisfy the nitrogen requirements, we are applying 57.6 kg P_2O_5/ha and 162 kg K_2O/ha. Whether or not these amounts are sufficient depends on soil test results and recommended application rates for the two nutrients.

The same general procedure can be followed for calculating application rates for other organic nutrient sources. Other organic sources of nitrogen include but are not limited to: legume hay, grass hay, alfalfa meal, soybean meal, cottonseed meal, crab meal, fish meal, and feather meal.

CONVENTIONAL SOURCES Most commercial nitrogen fertilizers for conventional agriculture are manufactured from ammonia. Anhydrous ammonia (NH_3) is 82% nitrogen and is a gas at room temperature. It is stored and transported as a liquid under pressure that is injected several inches below the soil surface where it dissolves in water and forms ammonium (NH_4^+). Ammonia is manufactured using the Haber process, developed in the early 1900s. Gaseous H_2 and N_2 are combined under high temperature and pressure to produce ammonia. Manufacturing ammonia is an energy-intensive process not only for the production of ammonia itself, but for the production of the H_2 and N_2 that are used in the process.

Ammonium nitrate (NH_4NO_3) contains approximately 34% nitrogen. It is usually used as a solid and may be applied directly or in combination with other materials to create a custom-blended fertilizer. When ammonia is oxidized in air, nitric acid is produced. If the nitric acid is neutralized with more ammonia, a solution of ammonium nitrate (83%) in water (17%) is produced, which is then concentrated and sprayed into air forming small crystals of ammonium nitrate called prills. The prills are sized and sorted for sale.

Urea, $CO(NH_2)_2$, contains 46% nitrogen and is used as a solid or liquid. It is the most important solid nitrogen fertilizer worldwide (Eckert, 2011). When urea is applied to the soil, it is converted to ammonium carbonate by an enzyme called urease. Ammonium carbonate is unstable and breaks down into carbon dioxide and ammonia. If the ammonia does not dissolve in the soil water, it quickly volatilizes resulting in significant nitrogen losses to the atmosphere. This is a major problem with using urea as a nitrogen source, particularly in warm and humid climates. Mixtures of urea and ammonium nitrate are often dissolved in water to produce solutions with 19–32% nitrogen. The solution is then injected or applied as a banded side dressing, as overplant applications can cause severe tissue burning. Urea is manufactured from ammonia and carbon dioxide under heat and pressure.

Ammonium phosphates are manufactured from ammonia and phosphoric acid into many different formulations which include mono-ammonium phosphate (MAP), diammonium phosphate (DAP), and a few ammonium polyphosphates. They are mostly used as phosphorus fertilizers with the added benefit of supplying nitrogen.

A number of nitrate salts are available as nitrogen fertilizers. They include sodium nitrate (NaNO3, 16% nitrogen), calcium nitrate (Ca(NO3)2, 15.5% nitrogen), and potassium nitrate (KNO3, 14% nitrogen). They are expensive and contain relatively low amounts of nitrogen, thus other sources are often used.

Many slow-release forms of nitrogen are available and are particularly well suited to container production and turfgrass management. These products release nitrogen at low levels, slowly over time at a predictable rate. Compounds such as magnesium ammonium phosphate, ureaformaldehyde and isobutylidene diurea have very low nitrogen solubility in water. In addition the ureaformaldehyde and isobutylidene diurea rely on microbial degradation for nitrogen release. Other compounds, urea for example, can be coated with a polymer, wax or sulfur thereby slowing the release of nitrogen into the soil.

Phosphorus

Phosphorus is an important element in nucleic acids, particularly in the chemical bonds associated with them. Phosphorus is also important in energy metabolism: it is part of the ATP molecule. The bonds between phosphorus atoms hold the energy in ATP so vital for all metabolic processes. Cell membranes also contain a significant amount of phosphorus in the form of phospholipids. At the whole plant level, phosphorus stimulates: (i) root development; (ii) increased stem strength; (iii) improved flowering; (iv) better seed production; (v) uniform and early crop production; (vi) increased disease resistance; and (vii) more efficient nitrogen fixation in leguminous plants (Griffith, 2011).

After nitrogen, phosphorus is the nutrient most limiting plant growth (Schachtman *et al.*, 1998). Phosphorus deficiency can often be difficult to detect and by the time a deficiency is detected, it is too late to remedy the problem with a fertilizer application. One symptom that often appears is a darkened, purplish-red coloration of leaves due to an accumulation of carbohydrates that enhances anthocyanin production. Phosphorus is mobile, thus deficiency symptoms appear in older leaves first.

Soil phosphorus content depends on: (i) parent material; (ii) degree of weathering; (iii) climate; (iv) previous crop production; and (v) fertilization. Organic forms of phosphorus come from manure, plant residue, compost, and microorganisms. From 20 to 80% of the phosphorus in soil is organic in the form of phytic acid (inositol hexaphosphate) (Richardson, 1994). Inorganic phosphorus occurs in the soil in over 170 forms (Holford, 1997). Some of the major forms of soil phosphorus are apatite, the source of all phosphorus, iron, and aluminum phosphates. Phosphorus is not very soluble in the soil and the average agricultural hectare contains less than 1 kg of available, soluble phosphorus. As phosphorus is removed from the soil by plants, it is quickly replaced (Griffith, 2011). Plants with extensive root systems are often more efficient at obtaining phosphorus from the soil (Lynch, 1995). Mycorrhizae are extremely important in plant phosphorus uptake because their hyphae effectively increase the surface area of the root system

(Smith and Read, 1997). Adding soluble phosphorus to the soil does not increase the amount of phosphorus available to plants as it is quickly fixed into insoluble forms. More than 80% of the phosphorus in a soil is unavailable to plants (Holford, 1997). Phosphorus is not very soluble and moves very little in the soil, around 10^{-12}–10^{-15}/m^2/s (Schachtman *et al.*, 1998). It is not prone to leaching. Losses of phosphorus from the soil occur by crop removal and erosion.

In acidic soils phosphorus precipitates as iron and aluminum phosphates while in alkaline soils, it precipitates as slightly soluble calcium phosphate. Plants absorb $H_2PO_4^-$ ions more readily than HPO_4^{2-} ions and the former are favored by a soil pH between 6.0 and 7.0. When supplementary phosphorus and nitrogen are both needed, more phosphorus is absorbed by plants when applied as ammonium phosphate compared with other forms. High organic matter favors phosphorus availability to plants. The organic matter can chelate iron ions and make them unavailable for forming insoluble iron phosphates. Soils high in clay fix large amounts of phosphorus. To maximize the phosphorus available to plants, phosphorus-containing fertilizers should be applied just before it is needed by the crop. In addition, banding is recommended compared with broadcast applications. Cool, wet soils decrease oxygen in the soil which reduces the capacity of plants to absorb phosphorus.

Most responses to phosphorus application occur when soil tests indicate a low phosphorus level in the soil. With the increase in conservation tillage worldwide, response to phosphorus application even when soil tests indicate high soil phosphorus have been reported (Griffith, 2011). The reason for this 'new' response to phosphorus application is that conservation tillage results in lower soil temperatures and higher soil moisture levels especially at planting. These two factors often render phosphorus unavailable to plants, thus supplemental phosphorus enhances crop performance.

Given that phosphorus concentrations in the cytoplasm may be 1000 times greater than soil concentrations of phosphorus, plant root cells have specialized active-transport-uptake mechanisms for phosphorus. Energy is required to move phosphorus against a concentration gradient and against the negative electrical membrane potential of the cell membrane. Phosphorus is co-transported with one or more protons. Cells can import phosphorus in either of two forms, $H_2PO_4^-$ or HPO_4^{2-}, but phosphorus is mostly absorbed in the monovalent form (Ullrich-Eberius *et al.*, 1984; Furihata *et al.*, 1992). Once in the cell, phosphorus concentration in the cytoplasm is fairly constant while the vacuolar concentration varies considerably depending on soil phosphorus availability. When soil supplies are limited, the vacuole serves as a phosphorus reserve for the cell. Within the plant, phosphorus moves in the xylem primarily as inorganic phosphorus, and in the phloem as organic phosphorus. Movement in the phloem is usually a remobilization of phosphorus from older leaves to younger leaves during times of phosphorus deficiency.

While plant roots absorb phosphorus directly from the soil, in more than 90% of land plants, a symbiotic association between plant roots and mycorrhizal fungi exists (Smith and Read, 1997). There are two forms of mycorrhizae, ectomycorrhizae and endomycorrhizae, with vesicular arbuscular mycorrhizae the most widespread form in the plant kingdom. Vesicular arbuscular mycorrhizae are fungi that penetrate cortical cells of the root and eventually form structures called vesicles. Plants supply the fungus with carbohydrates while the fungus supplies the plant with phosphorus. Increased phosphorus uptake by mycorrhizal plants may be due to increased surface area of the effective root system due to fungal hyphae extensions into the soil and the ability of mycorrhizal fungi to more effectively scavenge for phosphorus in the soil compared with other soil organisms. Mycorrhizae may also be able to absorb organic forms of phosphorus that plants cannot from the soil. When soils are adequate in phosphorus, the degree of mycorrhizal colonization of roots is often limited. Specific signals from the plant rather than phosphorus concentration in the soil appear to regulate the degree of colonization (Tawaraya *et al.*, 1996).

SOURCES OF PHOSPHORUS Rock phosphate is mined from the earth and finely ground for application to the soil. It has very little phosphorus available for plant use, thus it is not used as a fertilizer very often (Rehm *et al.*, 2010). Rather, it is used to manufacture phosphoric acid, an ingredient for other manufactured forms of phosphorus. DAP, $(NH_4)_2HPO_4$, which is 18% nitrogen and 46% P_2O_5, is manufactured by reacting ammonia with phosphoric acid. When applied to the soil, it causes a temporary increase in pH as one molecule of ammonia is released. As the product continues to

break down, it has an acidifying effect on the soil. Another product of reacting ammonia with phosphoric acid is MAP, $NH_4H_2PO_4$. It contains 11% nitrogen and 52% P_2O_5. Bone meal, 22% P_2O_5, is a slow-release organic source of phosphorus.

Potassium

Plants absorb potassium as a cation, K^+. Potassium is not a structural part of plant tissues nor is it an element in metabolic compounds. Rather, it is an element which is essential for regulation of many processes within the plant. It is crucial in regulating: (i) photosynthesis; (ii) photosynthate translocation; (iii) protein synthesis; (iv) opening and closing of stomata; and (v) the activation of at least 60 enzymes (Thompson, 2011).

Potassium is mobile therefore deficiency symptoms appear in older tissue first. A common symptom of potassium deficiency is severe chlorosis of leaf margins which may be followed by premature defoliation of the plant.

While potassium comprises about 2.4% of the earth's crust, from 90 to 98% of the total potassium in the soil is not available to plants (Thompson, 2011). Only about 0.1–2% of the total potassium in the soil is in the available form, K^+. When soil K^+ is high, plants may suffer a magnesium deficiency and vice versa.

Potassium is mined from sylvinite, sylvite, and langbeinite. While it does not exist in the plant or soil in this form, potassium content is expressed as a percentage K_2O. Sylvinite is mostly potassium chloride (KCl) and sodium chloride (NaCl), containing 20–30% K_2O. Sylvite is mostly potassium chloride with 60–62% K_2O. Langbeinite is mostly potassium sulfate (K_2SO_4) and magnesium sulfate ($MgSO_4$) containing 22% K_2O, 11% magnesium, and 22% sulfur.

Potassium chloride is also called muriate of potash and accounts for most of the potassium used in fertilizers. Potassium sulfate, also called sulfate of potash, is often used as a potassium source in chloride-sensitive crops such as tobacco (*Nicotiana* spp.), fruit crops, and some vegetables (Thompson, 2011). It accounts for about 2–6% of the potassium used in fertilizers. Mined langbeinite is often called double sulfate of potash and is a good source of potassium, magnesium, and sulfur. Potassium nitrate (KNO_3) supplies both nitrogen (13%) and potassium (44% K_2O).

Sulfur

Sulfur is absorbed as the sulfate anion (SO_4^{2-}) by plant roots and may be absorbed to a lesser degree as sulfur dioxide (SO_2) by leaves. Sulfur is an important component of cysteine and methionine, two sulfur-containing amino acids. It is also important for efficient nitrogen fixation by legumes and for conversion of nitrates to amino acids. The pungent flavor of *Brassica* and *Allium* species is due to sulfur-containing compounds. The very sweet and mild onions such as 'Vidalia' or 'Maui Sweets' are grown on soils with very low sulfur content to minimize the production of pungent sulfur compounds.

Most of the sulfur in soil is tied up in organic matter and is not available for plant use until it is converted into the sulfate (SO_4^{2-}) by bacteria in a process similar to mineralization of nitrogen. Sulfate is soluble and negatively charged, thus it tends to be leached from the soil much like nitrate. Sulfates can move upwards in the soil via capillary action as water is drawn to the surface with evaporation. Soil tests and crop calibrations for sulfur are difficult due to this mobility.

Sulfur deficiency is often confused with nitrogen deficiency since both are first noticed as chlorosis of leaves with a general stunting of growth. Sulfur is immobile, thus as symptom intensity increases, chlorosis appears on younger leaves; nitrogen symptoms occur on older leaves. Since soil tests for sulfur are unreliable, plant tissue analysis provides a better measure of deficiency. Tissue concentration of sulfur should be between 0.2 and 0.5 %. The total nitrogen to total sulfur ratio should lie between 7:1 and 15:1. Values greater than 15:1 may indicate a sulfur deficiency.

If irrigation water contains 5 ppm or more of sulfur, sulfur deficiency is highly unlikely. If elemental sulfur is applied to improve sulfur fertility, it must be converted to sulfate by bacteria before the plant can utilize it. This can take from 3 to 6 weeks, depending on moisture and temperature conditions in the soil. Other sulfur-containing fertilizers can also be used, most of them with sulfur in the form of sulfates. Ammonium sulfate, $(NH_4)_2SO_4$, contains 21% nitrogen and 24% sulfur. It is a good source of both sulfur and nitrogen, however, it does significantly lower the soil pH. Approximately 15 kg of lime must be used per kilogram of nitrogen applied to neutralize the acid formed. Gypsum, or calcium sulfate, $CaSO_4$, is a ready source of calcium and sulfur with the added benefit that it

does not alter the soil pH. Sulfur-coated urea has 11% sulfur and is a good source of slow-release nitrogen.

Calcium

Calcium is absorbed by plants as the cation Ca^{2+}. It is important in cell wall structure and also an important messenger ion in the plant.

In the soil Ca^{2+} is adsorbed to soil particles and released into solution. If soils are properly limed, calcium deficiency should not be a problem for most crops. However, a number of horticulturally important crops suffer from calcium-related problems. Blossom end rot in tomatoes (*Solanum lycopersicum*) is due to insufficient calcium transport to young fruit, even when sufficient levels of calcium are present in the soil. Similarly cork spot and bitter pit of apple (*Malus domestica*) is due to insufficient calcium in the fruit, not the soil. When deficiencies do occur, they are observed in younger tissues as calcium is immobile in the plant. A classic symptom is marginal necrosis of young leaves.

The best source of calcium is calcitic limestone, provided during good soil pH management. If magnesium is also deficient, dolomitic limestone is a good choice, providing both magnesium and calcium while increasing the pH. If calcium is needed and there is no need to increase the pH, calcium sulfate (gypsum) is a good choice.

Magnesium

Magnesium is absorbed as a cation, Mg^{2+}, and is essential for photosynthesis. The center of each chlorophyll molecule is a magnesium atom. Magnesium is also important in phosphorus translocation, cell division, protein formation, and is an important activator of enzymes.

Magnesium availability to plants is dependent on soil pH. At a low soil pH (<5.8), magnesium availability decreases due to interactions with hydrogen ions and aluminum ions. At higher pH levels (>7.4), interference from calcium may reduce magnesium uptake by plants. If soil test readings are below 25–50 ppm, supplemental magnesium is warranted. A rule of thumb based on the CEC of a soil test is with a CEC higher than 5 mEq/100 g, it is desirable to maintain a soil Ca:Mg ratio of about 10:1 (Snyder and Thompson, 2011).

Magnesium is mobile and deficiency symptoms appear in older leaves first. Interveinal chlorosis begins near the tips or margins of the leaves and progressively moves inwards towards the central axis of the leaf. Leaves often become brittle and curl upwards. Tips and margins may turn reddish purple with a severe deficiency. In general plants require about 0.2% tissue magnesium. Some crops that require significantly more magnesium than usual include forage legumes and grasses, cotton (*Gossypium* spp.), oil palm (*Elaeis* spp.), corn (*Zea mays*), potatoes (*Solanum tuberosum*), citrus (*Citrus* spp.), sugarbeet (*B. vulgaris*), soybeans (*Glycine max*), celery (*Apium graveolens*), and tobacco (*Nicotiana* spp.).

A popular source of magnesium is dolomitic lime, containing 6–12% magnesium depending on source. It contains magnesium as magnesium carbonate which is quite insoluble in water so it is only slowly available for plant uptake. More finely ground lime makes more of the magnesium and calcium available more quickly than less finely ground product. When dolomitic lime is used, another form of more readily available magnesium should be used as well.

Sulfate of magnesium potash, also known as K-Mag and also a good source of potassium and sulfur, is 10–11% water-soluble magnesium which is readily available to crops. It is one of the most economical forms of magnesium available (Snyder and Thompson, 2011). Magnesium sulfate, more commonly known as Epsom salts, contains about 10% soluble magnesium and can be used as a foliar spray. It is quite expensive. Commercially available sources of less refined magnesium sulfate contain 16–18% magnesium, but it is not completely water soluble so it cannot be used as a foliar spray. It is useful as a soil application.

Micronutrients

Iron

Iron is absorbed by plants as the cations Fe^{3+} or Fe^{2+}, and is most available from slightly acidic soils. It is important in chlorophyll synthesis, thus a deficiency is easily recognized as chlorosis in younger leaves. If the deficiency is severe enough, leaves will turn nearly white before browning and dying. Iron deficiencies are exacerbated by high levels of zinc, phosphorus, and manganese in the soil. Iron is also important for the activity of many enzymes, especially those involved in energy transfer, nitrogen reduction and fixation, and lignin formation.

Iron is most effectively supplemented with foliar applications of a 3% solution of $FeSO_4$ at 187–374 l/ha (Mortvedt, 2011).

Boron

Boron is absorbed by plants as borate, $B(OH)_3$, and is important in cell wall formation, formation of vascular tissue, carbohydrate metabolism, flower formation, and in pollen formation and germination. Boron is immobile in the plant so deficiencies appear at the growing point, causing extreme rosette growth. Other symptoms of boron deficiency include poor fruit set due to poor pollination, hollow stems and fruits, brittle discolored leaves, and flower bud abscission.

Boron deficiencies are often found on acidic, sandy soils in regions with high rainfall and or low organic matter. Borate ions are soil mobile, thus leaching can occur. Recommended rates of application for boron are very low, from 1 to 2 kg/ha. Extreme care should be given to accurate application since the difference between adequate and toxic levels is very small.

Copper

Copper is absorbed by plants as Cu^{2+}. It is important in carbohydrate and nitrogen metabolism as well as lignin formation. Deficiency symptoms include stem and twig dieback, stunted growth, and chlorotic or pale green leaves leaves that easily wilt. Copper absorption decreases with increasing pH and phosphorus and iron in soils may inhibit copper uptake. Copper is often supplemented at the rate of 3–12 kg/ha of copper as copper sulfate or finely ground copper oxide and its effects may last for up to 8 years (Mortvedt, 2011). Careful monitoring of soil and plant tissue copper levels are needed to prevent copper toxicity.

Zinc

Zinc is absorbed by plants as Zn^{2+}. It is an essential cofactor for many enzyme systems, especially those involved in energy metabolism, protein synthesis and growth regulator activity. Zinc is plant immobile with deficiency symptoms appearing in young tissue. Symptoms include small leaves and a highly rosette shoot growth. Chlorotic banding in monocots and mottled leaves of some dicots are also characteristic symptoms of zinc deficiency. Delayed maturity is also caused by zinc deficiency.

Plant uptake of zinc decreases as soil pH increases and may be inhibited by high phosphorus and iron levels in the soil. Supplements of 1–12 kg zinc/ha are often recommended as foliar sprays or band applications of zinc sulfate. Zinc supplementation is residual for up to 5 years.

Molybdenum

Molybdenum is taken up by plants as MoO_4^{2-} and is mobile in the plant. It is involved in bacterial nitrogen fixation in legumes and is important in most enzyme systems. Both nitrogen and sulfur metabolism as well as pollen formation require molybdenum. Most plants never exhibit molybdenum deficiency. Legumes may exhibit molybdenum deficiency as a nitrogen deficiency, since the molybdenum deficiency is impacting nitrogen fixation by *Rhizobium*. In some vegetable crops, molybdenum deficiency causes irregular leaf blade formation called whiptail. Molybdenum uptake increases with increasing pH, thus liming to correct pH may correct a molybdenum deficiency.

Manganese

Manganese, absorbed as Mn^{2+}, is important in photosynthesis and nitrogen metabolism. Interveinal chlorosis is a classic symptom of manganese deficiency. Uptake decreases as pH increases and may be adversely affected by high iron in the soil. Annual banded applications of manganese as manganese sulfate or manganese oxide at 2–22 kg manganese/ha are often needed.

Chlorine

Chlorine is a non-mineral absorbed by plants as an anion, Cl^-. It is mobile within the plant and is important in the regulation of electrical charges throughout the plant and for stomatal functioning.

Chloride deficiencies in nature are extremely rare, but when deficient on sandy, wet soils, can be easily corrected with KCl.

Micronutrient fertilizers

Micronutrient supplements come in four forms: (i) inorganic products; (ii) synthetic chelates; (iii) natural organic complexes; or (iv) fritted glass

products. Inorganic sources are mostly oxides, carbonates or metallic salts such as nitrates, chlorides or sulfates. Synthetic chelates are compounds that effectively hold the micronutrient through covalent bonding and readily release it for plant uptake. Natural organic complexes are derived by reacting metallic salts with byproducts of the wood pulp industry forming a readily decomposed carrier for the micronutrient. Frits are small glass beads in which the micronutrients are embedded during manufacture. Their release depends on glass composition and frit size. Frits are normally used for maintenance of micronutrient levels rather than for correcting deficiencies.

Since application rates for micronutrient supplementation are normally very low, they are most often soil applied using granular or fluid NPK fertilizers as a carrier. The micronutrients can be incorporated during manufacturing, blended with NPK fertilizers to create a custom mix, coated onto granular fertilizers or mixed in with liquid fertilizers.

Foliar sprays are often used for correcting micronutrient deficiencies, especially iron and manganese. Application rates are much lower than for soil-applied amendments and uniform distribution is easily accomplished. Deficiency symptoms normally disappear within a few days of application if they were indeed due to a micronutrient deficiency, thus deficiencies can be corrected immediately during the growing season when first noticed.

Fertilizers and their use

Rates of application for any nutrient should be derived from either soil or tissue tests combined with specific crop requirements. Fertilizer application is an expensive and environmentally challenging endeavor, thus planning for applications is wise. Rates for nitrogen fertilization are probably the most difficult to determine as so many factors are involved in managing crop nitrogen. First, different yield objectives will lead to different nitrogen requirements. In addition, the amount of nitrogen required for application will depend on how much might be provided by the soil. This is governed by release of nitrogen from organic matter and crop residues as well as any residual nitrogen left from a previous crop. Previous cover cropping and compost or manure application must also be taken into consideration.

Fertilizers may be applied broadcast, banded with row crops, or applied foliarly. Placement and application should minimize potential injury to plants by fertilizer burning and maximize crop utilization of the nutrients applied. Broadcast fertilizers need to be incorporated into the soil while banded applications must be deep enough to prevent nitrogen losses, yet not so deep that the plant roots cannot absorb the nutrients.

If possible, fertilizers should be applied as close to the time of critical crop need as possible. For this reason, split applications, especially of nitrogen, are often made. However, split applications increase costs by requiring additional trips across the field. A good rule of thumb is to apply fertilizers within 30 days of planting or to actively growing crops.

Nitrate content of water supplies, particularly drinking water supplies, are of global concern. Ingestion of large amounts of nitrate by infants can lead to a potentially fatal condition called methemoglobinemia. This blood disorder leads to excessive production of methemoglobin, a form of hemoglobin that does not release the oxygen it is carrying to body tissues. Excessive fertilization with nitrate-containing fertilizers can potentially contaminate wells and groundwater.

Mulches

Mulches are an integral part of any horticultural production system. Mulches may be used year round depending on their purpose. The mulch may be as simple as plant debris on top of the soil, to applied compost or synthetic soil covers. No matter what form they take, mulches serve a host of common functions. All mulches: (i) conserve water; (ii) inhibit weed growth; (iii) prevent erosion; and (iv) influence soil temperature. The degree to which they accomplish these effects varies with mulching material. Organic mulches have the added benefit of adding organic matter to the soil as they decompose as well as providing nutrients. Living mulches such as white clover also provide nitrogen while contributing the other benefits of mulching. Winter mulches provide protection from widely fluctuating soil temperatures and plant desiccation by cold, dry winds.

Many different materials are used as mulches including, straw, compost, leaf mold, pine needles, newspapers, kraft paper, sawdust, biodegradable films made from starch, oxo-degradable mulches, landscape fabric, plastic mulch, and living mulches.

Organic mulches

Organic mulches are any material composed of organic matter used as a mulch in plant management. The term organic does not necessarily imply that the material is from an organically grown source. This is important for certified organic growers since many mulches composed of organic material are from conventional sources and may contain pesticides and fertilizers not approved in certified organic production.

Most organic mulches are environmentally friendly, renewable, biodegradable, and contribute to soil health with nutrients and humus. Organic mulches are also expensive. With any organic mulch, care must be exercised to ensure that enough supplemental nitrogen is supplied to the crop being mulched to compensate for nitrogen tied up in microorganisms that are breaking down the organic matter. Composted organic materials make better mulches than non-composted materials for this reason. Some composted mulches may tie up nitrogen as well, depending on the degree of decomposition of the compost material.

Biodegradable mulches

As an alternative to non-recycleable LDPE (low density polyethylene) plastic mulches, biopolymers made from polysaccharides and thermoplasticized, extruded starch films have been developed and used with varying degrees of success. These materials are biodegradeable in the soil by bacteria and fungi and are turned under after usually one crop (Moreno and Moreno, 2008).

An interesting alternative to biodegradeable films are biodegradeable materials such as sodium alginate, glucomannan, chitosan and cellulose that are sprayed directly onto the soil. When the water carrier of such materials evaporates, a thin mulch remains. The main drawback to these sprayed-on mulches is that they are still in the developmental stages so costs cannot be estimated and they often degrade too quickly once applied to the soil (Immirze *et al*., 2009).

Paper mulches, such as kraft paper and newspaper, are biodegradable. Ink type should be considered when recycling newspapers. Kraft paper may be impregnated with vegetable-oil-based resin made from soybean or linseed oil and citric acid (Shogren, 2000) which lengthens the time before degradation occurs and increases strength against weed penetration. Another advantage to impregnated paper is that they can be made from 100% recycled paper, natural or organic oils, and citric acid from corn sugar. It is reasonable to surmise that using brown kraft paper impregnated with polymerized oil would offer some degree of soil warming and moisture retention.

Oxo-degradeable mulches

Oxo-degradeable mulches are polyethylene-based plastic mulches with additives containing iron, nickel, cobalt, and manganese to cause accelerated degradation that is initiated by heat and light (Thomas *et al*., 2010). Manufacturers claim that the mulch will effectively disappear by the end of the growing season, thus eliminating the need for removal from the field. Oxidative degradation is induced by heat and light and results in the material fragmenting into very small pieces of mulch. These materials do not biodegrade quickly into harmless components (carbon dioxide and water) as often implied. The clear distinction between a material that undergoes oxidative degradation and one that is biodegradable is not often emphasized in marketing these products. Oxo-degradable plastics are not compostable.

Living mulches and cover crops

Cover crops and living mulches are two additional management tools for controlling weeds, erosion, and nutrient losses from cropland. A cover crop is any crop grown primarily to cover bare soil during times of the year when cash crops are not being grown. Cover crops are also those crops used to enrich soil with organic matter and nitrogen fixed by legumes during crop fallows or to rebuild soils depleted during normal crop production. Living mulches are species grown concurrently with the cash crop as a ground cover to provide all the benefits of a non-living mulch. Living mulches also act as a cover crop in that they return substantial amounts of organic matter and nutrients to the soil.

Winter cover crops are sown in late summer or early fall to grow through the winter or grow during the fall, go dormant during the winter months, and if hardy enough, resume growth in the spring. Before planting the spring crop, the cover is turned under or killed. A common winter cover crop is winter rye (*Secale cereale*). Winter hardy legumes such as alfalfa (*M. sativa*), hairy vetch (*Vicia villosa*), red clover (*Trifolium pratense*), white clover

(*Trifolium repens*), and sweet clover (*Melilotus* spp.) also make excellent cover crops, adding nitrogen to soils low in nitrogen. Some legumes may actually remove nitrogen from the soil if it is available, rather than fix it (Kaspar *et al.*, 2008). Brassicas such as oilseed and forage radish and mustards make good winter covers that suppress nematodes, diseases, and some weeds (Kasper *et al.*, 2008).

Living mulches are companion cover crops planted either before or with the main crop and left as a living cover during the growing season (Hughes and Sweet, 1979; Hartwig and Ammon, 2002). They are often perennial and remain in the field for many years or may be annuals or perennials that must be replanted regularly. The main problem with living mulches is that they tend to compete with the cash crop for water and nutrients. Living mulches have been used for years in vineyards and orchards and are being tested for adaptation to row crops. In orchards and vineyards, the living mulch is often some distance away from the vine or tree to reduce the competition for water and nutrients but maintain the benefits of a mulch in the row middles.

In order to be suitable as a living mulch, a species must possess a number of desirable attributes. For example it should be: (i) able to establish rapidly and have good wear tolerance; (ii) tolerant of drought and low fertility; and (iii) able to enhance crop yield and quality with minimal costs (William, 1987). Grasses and legumes are the primary species considered for living mulches. Suppression of the living mulch growth during production of the cash crop is the main difficulty with using a living mulch. Mulches are suppressed with reduced herbicide rates, mowing, rototilling, and animal grazing of living mulch sod middles in tree fruit orchards. Even with mulch suppression, the cash crop yield is often reduced compared with yield under other mulching or clean cultivation systems. In addition, living mulches often reduce soil temperatures and may harbor insect or disease pests (Paine and Harrison, 1993).

Landscape fabric mulches

Landscape fabric mulches, also called geotextiles, are typically manufactured from polypropylene or polyester, are long lasting but expensive and non-degradable. They are woven, perforated or spun-bonded sheets used extensively as an underlay for landscaping projects around trees and shrubs which utilize some form of mulch as an overlay. Pebbles or gravel are the best overlay as organic mulches degrade and form a layer of soil-like debris in which weeds can grow. Polyester fabrics last longer than those made from polypropylene.

Landscape fabrics are porous, thus air and water easily pass through to the soil, yet they prevent weeds from pushing through the fabric. They are usually pinned to the soil with plastic or metal fasteners and in general, will last up to 5 years. It is often easier to position fabrics around plants after planting rather than to try and plant through the fabric, especially with larger specimens.

Plastic mulches

Plastic mulches are very common, especially in row crop production of flowers, vegetables, and fruit. They are used to: (i) reduce weed growth; (ii) conserve moisture; (iii) reduce wind and water erosion; (iv) prevent leaching of valuable nutrients; and (v) diminish the development of plant diseases from soil-borne organisms. Plastic mulches also alter the soil and plant microclimate much more than other mulch types. In general, plastic mulches warm the soil leading to earlier maturing spring crops and extended harvests of fall crops. Plastic mulched crops are often harvested 7–14 days earlier than non-mulched soils, the product is often cleaner and yield is often two to three times higher, especially in sweet corn (*Z. mays*), eggplant (*Solanum melongena*), tomatoes (*Solanum lycopersicum*), muskmelons (*Cucumis melo*), peppers (*Capsicum annuum*), cucumbers (*Cucumis sativus*), summer squash (*Cucurbita* spp.), okra (*Abelmoschus esculentus*), and watermelon (*Citrullus lanatus*) (Lamont, 1993). When combined with drip irrigation, water savings of 45% can be realized using plastic mulch compared with bare soil. Most weeds will not grow under black plastic mulch. Nutgrass (*Cyperus rotundus*) is an exception: it easily punctures plastic due to the energy derived from food stores in its tubers (Fig. 10.5).

Linear low-density polyethylene black mulches are mostly used due to their: (i) high durability; (ii) resistance to chemicals; (iii) reasonable ease of use; and (iv) widespread availability (Lamont, 1993). Most plastic mulch is 1.25 mil thick (1 mil is one-thousanth of an inch, equivalent to 0.031 mm; it is a common description for plastic mulch thickness) and 48 inches (122 cm) wide and comes in rolls

Fig. 10.5. Nutgrass (*Cyperus rotundus*) puncturing black plastic mulch.

2400 ft (731 m) long. The plastic is usually smooth or embossed with a diamond-shaped pattern to reduce expansion and contraction which loosens the mulch from the soil, decreasing its effectiveness. Recently, colored mulches with different light-reflecting properties that alter plant growth, often enhance productivity and crop quality, and discourage insect pests have been introduced (Lamont, 1993). Plastic mulches also provide the opportunity to double or triple crop the land using only one application of mulch.

The negative side of plastic mulches is their environmental impact (Fig. 10.6). Most plastic mulch is not recycled, and unfortunately, some growers simply leave the plastic in the field and incorporate the material into the soil or burn it. New 'plastics' made from biopolymers of polysaccharides from corn (*Z. mays*), potato (*S. tuberosum*) or rice (*Oryza* spp.) are degraded by bacteria and fungi in the soil into carbon dioxide, methane, water, and biomass.

Decisions on which mulch to use are based on: (i) the crop; (ii) the season of production (spring, summer or fall); (iii) single or multiple cropping; and (iv) pest management considerations. The standard colors of mulch used today are black, clear, and white-on-black. Red, green, blue, and silver mulches are used to a lesser extent. They are crop specific and more expensive than the standard colors (Orzolek and Lamont, 2011).

The selection of black, white-on-black (henceforth white), or clear depends on how a grower wants to impact the temperature microclimate around the crop and the soil. Black mulch is an opaque black body absorber and radiator. This means it absorbs most UV, visible and infrared radiation and re-radiates the absorbed energy as thermal or long-wave infrared radiation. Most of the absorbed energy is lost to the atmosphere through radiation and convection. Good soil-to-mulch contact improves heat transfer from the mulch to the soil. Daytime soil temperatures are generally 2–3°C higher under black plastic mulch compared with bare soil.

Clear plastic mulch absorbs little radiation but transmits up to 95% of the incoming radiation, depending on thickness and opacity. In addition, the surface of the mulch next to the soil is usually covered in water droplets which are transparent to incoming short-wave radiation but opaque to outgoing long-wave infrared radiation. Thus much of the heat that would normally be lost to the atmosphere from a bare soil is trapped under the clear mulch. Daytime soil temperatures under clear mulch can be 3–8°C higher under clear plastic mulch, depending on the depth in the soil, compared with bare soil. The disadvantage of clear mulches is that they require fumigation, solarisation, or a fumigant to control weeds.

White or silver reflecting mulches result in a slight decrease in soil temperature of about 1 or 2°C. Most of the light intercepted by these mulches is reflected back into the plant canopy. Some white mulches require additional weed control measures. Some blue- and red-colored mulches can raise soil temperatures dramatically, as much as 18°C.

A group of mulches called photoselective mulches are available that transmit infrared radiation and absorb photosynthetically active radiation (PAR), which provides somewhat of a compromise between clear and black mulches in terms of soil temperatures. Photoselective mulches increase soil temperatures like clear mulches but do not have their weed problem. These mulches are usually blue- green or brown in color. They are more expensive than either black or clear mulch.

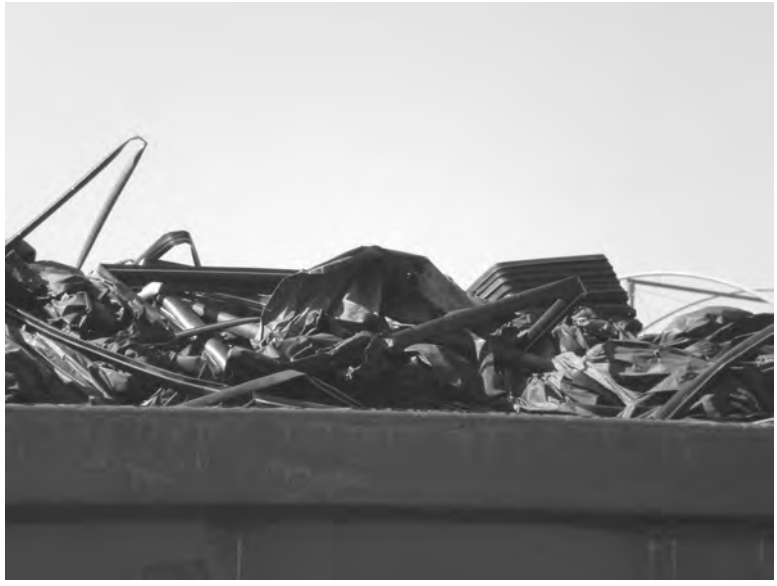


Fig. 10.6. Dumpster (large rubbish receptacle) containing non-recyclable agricultural plastics used in vegetable production. Waste includes plastic mulch, greenhouse plug trays, germination flats, and trickle tape.

Plant growth is also affected by phytochrome- or temperature-mediated foliar responses induced by mulch color. Clear mulch reflects nearly twice as much PAR than black mulch or bare soil, since the black mulch and soil absorb much of the PAR. The reflected PAR leads to larger plants with higher yields.

Red and black mulches similarly raise soil temperatures. Higher and earlier yields of certain plants, for example peppers (*C. annuum*) and tomatoes (*S. lycopersicum*), on plants of smaller stature are often observed with red mulches compared with black. Both mulches reflect similar amounts of PAR, but the red mulch reflects substantially more red than far-red light. More red light than far-red light tips the P_r:P_{fr} ratio in favor of P_{fr}, leading to smaller plants with higher yields. Other colors under investigation for their radiation-absorbing and reflecting properties include blue, green, yellow, orange, and gray.

Mulch color can also influence insect activity around the crop. Yellow, red, and blue mulches tend to attract certain insects while silver mulches repel them, especially aphids (Orzolek and Lamont, 2011).

Some general recommendations for mulch color selection for specific vegetable crops typically grown on plastic mulch were made by Orzolek and Lamont (2011). Keep in mind that results will vary, especially in locations significantly further south than Pennsylvania, USA, so be sure to consult local recommendations. When growing conditions were less than ideal, tomatoes (*S. lycopersicum*) produced significantly more fruit and exhibited fewer symptoms of early blight when grown on red mulch compared with black. When growing conditions were ideal, no differences were detected. Peppers (*C. annuum*) produced significantly more fruit when grown on silver mulch compared with black. Eggplant (*S. melongena*) responded with increased production to red mulch, especially when grown under stressful conditions. Muskmelon (*C. melo*) responded to green infrared-transmitting or dark blue mulch with a third more fruit than when grown with black mulch. Cucumber (*C. sativus*) and summer squash (*Cucurbita pepo*) responded to dark blue mulch with a 30% and 20% increase in marketable yield, respectively.