Chapter 4. Basic Soil Fertility

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Table of Contents

Plant nutrition 55
What is an essential element? 55
Categories of essential elements 56
Functions of essential elements in plants 57
Nutrient deficiency symptoms 59
Caution regarding visual diagnosis 59
Terminology used to describe deficiency symptoms 60
Mobility and specific deficiency symptoms 60
Nutrient uptake by crops 63
Element uptake 63
Soil properties that influence nutrient availability 65
Influence of CEC and base saturation on fertilizer management 65
Ion mobility in soils 65
Effect of pH on nutrient availability 66
Liming 68
Introduction 68
Effect of pH/liming on crop yields 68
Benefits of liming 69
Determining lime requirements 69
Selecting a liming material 70
Frequency of lime applications 71
Applying lime 71
Nitrogen 71
The nitrogen cycle 71
Nitrogen fixation 72
Residual N from legume cover crops 73
Forms of soil nitrogen 75
Carbon to nitrogen ratios (C:N) 75
Nitrification 77
Phosphorus 78
The phosphorus cycle 78
Phosphorus availability and mobility 79
Phosphorus transport to surface waters 82
Potassium 82
The potassium cycle 82
Potassium availability and mobility 83

Timing and placement of K fertilizer 84
Secondary plant nutrients 85
Introduction 85
Calcium and magnesium 85
Sulfur 85
Micronutrients 87
Introduction 87
Determining micronutrient needs 88
Forms in the soil 88
Micronutrient soil-plant relationships 88
Boron 89
Copper 89
Iron 90
Manganese 90
Molybdenum 91
Zinc 91
Chlorine 92
References cited 93

Plant nutrition

What is an essential element?

An *essential mineral element* is one that is required for normal plant growth and reproduction. With the exception of carbon (C) and oxygen (O), which are supplied from the atmosphere, the essential elements are obtained from the soil. The amount of each element required by the plant varies; however, all essential elements are equally important in terms of plant physiological processes and plant growth.

The exact number of elements that should be considered "essential" to plant growth is a matter of some debate. For example, cobalt, which is required for N fixation in legumes, is not considered to be an essential element by some researchers. Table 4.1 lists 18 elements that are considered essential by many scientists. Other elements that are sometimes listed as essential are sodium (Na), silicon (Si), and vanadium (V).

Table 4.1. Eighteen essential elements for plant growth, and the chemical forms most commonly taken up by plants.

Element	Symbol	Form Absorbed by Plants
Carbon	C	CO_2
Hydrogen	H	H^+, OH^-, H_2O
Oxygen	O	O_2
Nitrogen	N	NH_4^+, NO_3^-
Phosphorus	P	HPO_4^{2-}, $H_2PO_4^-$
Potassium	K	K^+
Calcium	Ca	Ca^{2+}
Magnesium	Mg	Mg^{2+}
Sulfur	S	SO_4^{2-}
Iron	Fe	Fe^{2+}, Fe^{3+}
Manganese	Mn	Mn^{2+}, Mn^{4+}
Boron	B	H_3BO_3, BO_3^-, $B_40_7^{2-}$
Zinc	Zn	Zn^{2+}
Copper	Cu	Cu^{2+}
Molybdenum	Mo	MoO_4^{2-}
Chlorine	Cl	Cl^-
Cobalt	Co	Co^{2+}
Nickel	Ni	Ni^{2+}

Categories of essential elements

Essential elements can be grouped into four categories based on their origin or the relative amount a plant needs in order to develop properly (Table 4.2).

Non-mineral essential elements are derived from the air and water. *Primary* essential elements are most often applied in commercial fertilizers or in manures. *Secondary* elements are normally applied as soil amendments or are components of fertilizers that carry primary nutrients. Non-mineral, primary and secondary elements are also referred to as *macronutrients* since they are required in relatively large amounts by plants.

Micronutrients are required in very small, or *trace*, amounts by plants. Although micronutrients are required by plants in very small quantities, they are equally essential to plant growth.

Table 4.2. Essential elements, their relative uptake, and sources where they are obtained by plants.

MACRONUTRIENTS			**MICRONUTRIENTS**
Non-Mineral	***Primary***	***Secondary***	
Mostly from air and water	*Mostly from soils*	*Mostly from soils*	*Mostly from soils*
Carbon	Nitrogen	Calcium	Iron
Hydrogen	Phosphorus	Magnesium	Manganese
Oxygen	Potassium	Sulfur	Boron
			Zinc
			Copper
			Molybdenum
			Chlorine
			Cobalt
			Nickel

Functions of essential elements in plants

Essential Element	Function In Plant
Carbon, Hydrogen, & Oxygen	• Directly involved in photosynthesis, which accounts for most of plant growth: $6\ CO_2 + 12\ H_2O \rightarrow 6\ O_2 + 6\ (CH_2O) + 6\ H_2O$
Nitrogen	• Found in chlorophyll, nucleic acids, and amino acids. • Component of protein and enzymes, which control almost all biological processes.
Phosphorus	• Typically concentrated in the seeds of many plants as phytin. • Important for plant development including: – development of a healthy root system – normal seed development – uniform crop maturation – photosynthesis, respiration, cell division, and other processes – Essential component of Adenosine Triphosphate (ATP), which is directly responsible for energy transfer reactions in the plant. • Essential component of DNA and RNA, and phospholipids, which play critical roles in cell membranes.
Potassium	• Found in ionic form in the cell, rather than incorporated in structure of organic compounds. • Responsible for: – regulation of water usage in plants – disease resistance – stem strength • Involved in: – photosynthesis – drought tolerance – improved winter-hardiness – protein synthesis • Linked to improvement of overall crop quality, including handling and storage quality.
Calcium	• Essential for cell elongation and division. • Specifically required for: – root and leaf development – function and cell membranes – formation of cell wall compounds • Involved in the activation of several plant enzymes.

Essential Element	Function In Plant
Magnesium	• Primary component of chlorophyll and is therefore actively involved in photosynthesis. • Structural component of ribosomes, which are required for protein synthesis. • Involved in phosphate metabolism, respiration, and the activation of several enzyme systems.
Sulfur	• Required for the synthesis of the sulfur-containing amino acids *cystine*, *cysteine*, and *methionin*e, which are essential for protein formation. • Involved with: – development of enzymes and vitamins – promotion of nodulation for N fixation by legumes – seed production chlorophyll formation – formation of several organic compounds that give characteristic odors to garlic, mustard, and onion.
Boron	• Essential for: – germination of pollen grains and growth of pollen tubes – seed and cell wall formation – development and growth of new cells in meristematic tissue • Forms sugar/borate complexes associated with the translocation of sugars, starches, N, and P. • Important in protein synthesis.
Copper	• Necessary for chlorophyll formation. • Catalyzes several enzymes.
Iron	• Serves as a catalyst in chlorophyll synthesis. • Involved in many oxidation-reduction reactions during respiration and photosynthesis.
Manganese	• Functions primarily as a part of the enzyme systems in plants. • Serves as a catalyst in chlorophyll synthesis along with iron. • Activates several important metabolic reactions (enzymes). • Plays a direct role in photosynthesis.
Zinc	• Aids in the synthesis of plant growth compounds and enzyme systems. • Essential for promoting certain metabolic/enzymatic reactions. • Necessary for the production of chlorophyll, carbohydrates, and growth hormones.

Essential Element	Function In Plant
Molybdenum	• Required for the synthesis and activity of nitrate reductase; the enzyme system that reduces NO_3^- to NH_4^+ in the plant. • Essential in the process of symbiotic N fixation by *Rhizobia* bacteria in legume root nodules.
Chlorine	• Involved in: – energy reactions in the plant – breakdown of water – regulation of stomata guard cells – maintenance of turgor and rate of water loss – plant response to moisture stress and resistance to some diseases – Activates several enzyme systems. • Serves as a counter ion in the transport of several cations in the plant.
Cobalt	• Essential in the process of symbiotic N fixation by *Rhizobia* bacteria in legume root nodules. • Has not been proven to be essential for the growth of all higher plants.
Nickel	• Component of the urease enzyme. • Essential for plants supplied with urea and for those in which ureides are important in N metabolism.

Nutrient deficiency symptoms

Caution regarding visual diagnosis

Visual diagnosis of plant deficiencies can be very risky. There may be more than one deficiency symptom expressed, which can make diagnosis difficult. **Both soil and tissue samples should be collected, analyzed, and interpreted before any recommendations are made concerning application of fertilizer.**

Terminology used to describe deficiency symptoms

Term	Definition
Chlorosis	Yellowing or lighter shade of green
Necrosis	Browning or dying of plant tissue
Interveinal	Between the leaf veins
Meristem	The growing point of a plant
Internode	Distance of the stem between the leaves
Mobile	A mobile element is one that is able to *translocate*, or move, from one part of the plant to another depending on its need. Mobile elements generally move from older (lower) plant parts to the plant's site of most active growth (*meristem*).

Mobility and specific deficiency symptoms

Essential Element	Mobility	Deficiency Symptoms and Occurrence
Nitrogen	Mobile within plants: lower leaves show chlorosis first.	• Stunted, slow growing, chlorotic plants. • Reduced yield. • Plants more susceptible to weather stress and disease. • Some crops may mature earlier.
Phosphorus	Mobile within plants: lower leaves show deficiency first.	• Over-all stunted plant and a poorly developed root system. • Can cause purple or reddish color associated with the accumulation of sugars. • Difficult to detect in field.
Potassium	Mobile within plants: lower leaves show deficiency first.	• Commonly causes scorching or firing along leaf margins. • Deficient plants grow slowly, have poorly-developed root systems, weak stalks; lodging is common. • Seed and fruit are small and shriveled. • Plants possess low resistance to disease. • Deficiencies most common on acid sandy soils and soils that have received large applications of Ca and/or Mg.

Essential Element	Mobility	Deficiency Symptoms and Occurrence
Calcium	Not mobile within plants: upper leaves and the growing point show deficiency symptoms first.	• Poor root growth: Ca deficient roots often turn black and rot. • Failure of terminal buds of shoots and apical tips of roots to develop, causing plant growth to cease. • Most often occurs on very acid soils where Ca levels are low. • Other deficiency effects such as high acidity usually limit growth before Ca deficiency apparent.
Magnesium	Mobile within plants: lower leaves show deficiency first.	• Leaves show a yellowish, bronze or reddish color while leaf veins remain green.
Sulfur	Somewhat mobile within plants but upper leaves tend to show deficiency first.	• Chlorosis of the longer leaves. • If deficiency is severe, entire plant can be chlorotic and stunted. • Symptoms resemble those of N deficiency; can lead to incorrect diagnoses.
Boron	Not mobile within plants: upper leaves and the growing point show deficiency symptoms first.	• Reduced leaf size and deformation of new leaves. • Interveinal chlorosis if deficiency is severe. • May cause distorted branches and stems. • Related to flower and or fruit abortion, poor grain fill, and stunted growth. • May occur on very acid, sandy-textured soils or alkaline soils.
Copper	Not mobile within plants: upper leaves and the growing point show deficiency symptoms first.	• Reduced leaf size. • Uniformly pale yellow leaves. • Leaves may lack turgor and may develop a bluish-green cast, become chlorotic and curl. • Flower production fails to take place. • Organic soils are most likely to be Cu deficient.

Essential Element	Mobility	Deficiency Symptoms and Occurrence
Iron	Not mobile within plants: upper leaves show deficiency symptoms first.	• Interveinal chlorosis that progresses over the entire leaf. With severe deficiencies, leaves turn entirely white. • Factors contributing to Fe deficiency include imbalance with other metals, excessive soil P levels, high soil pH, wet, and cold soils.
Manganese	Not mobile within plants: upper leaves show deficiency symptoms first.	• Interveinal chlorosis. • Appearance of brownish-black specks. • Occurs most often on high organic matter soils and soils with neutral to alkaline pH with low native Mn content.
Zinc	Not mobile within plants: upper leaves and the growing point show deficiency symptoms first.	• Shortened internodes between new leaves. • Death of meristematic tissue. • Deformed new leaves. • Interveinal chlorosis. • Occurs most often on alkaline (high pH) soils or soils with high available P levels.
Molybdenum	Not mobile within plants: upper leaves show deficiency symptoms first.	• Interveinal chlorosis. • Wilting. • Marginal necrosis of upper leaves. • Occurs principally on very acid soils, since Mo becomes less available with low pH.
Chlorine	Mobile within plant, but deficiency symptoms usually appear on the upper leaves first.	• Chlorosis in upper leaves. • Overall wilting of the plants. • Deficiencies may occur in well drained soils under high rainfall conditions.
Cobalt	Used by symbiotic N-fixing bacteria in root nodules of legumes and other plants.	• Causes N deficiency: chlorotic leaves and stunted plants. • Occurs in areas with soils deficient in native Co.

Essential Element	Mobility	Deficiency Symptoms and Occurrence
Nickel	Mobile within plants.	• Symptoms and occurrence are not well documented but may include chlorosis and necrosis in young leaves and failure to produce viable seeds.

Note: Information given above on nutrient mobility and deficiency symptoms is condensed. For more information, or for information on deficiency symptoms for a specific crop, please see Bennett, 1993; Horst, 1995; Jones, 1998; PPI, 2003, or your state's Cooperative Extension Service publications.

Nutrient uptake by crops

Element uptake

The amount of nine different elements taken up by selected crops is shown in Tables 4.3a through 4.3c.

Table 4.3a. Nutrient removal by selected hay crops.

Crop	Yield	N	P	K	Ca	Mg	S	Cu	Mn	Zn
		---------- pounds per acre ----------								
Alfalfa	6 tons	350	40	300	160	40	44	0.10	0.64	0.62
Bluegrass	2 tons	60	12	55	16	7	5	0.02	0.30	0.08
Coastal Bermuda-grass	8 tons	400	45	310	48	32	32	0.02	0.64	0.48
Fescue	3.5 tons	135	18	160	--	13	20	--	--	--
Orchard Grass	6 tons	300	50	320	--	25	35	--	--	--
Red Clover	2.5 tons	100	13	90	69	17	7	0.04	0.54	0.36
Soybean	2 tons	90	12	40	40	18	10	0.04	0.46	0.15
Timothy	4 tons	150	24	190	18	6	5	0.03	0.31	0.20

Table 4.3b. Nutrient removal by selected field crops.

Crop	Yield	N	P	K	Ca	Mg	S	Cu	Mn	Zn
		---------- pounds per acre ----------								
Barley (grain)	60 bu	65	14	24	2	6	8	0.04	0.03	0.08
Barley (straw)	2 tons	30	10	80	8	2	4	0.01	0.32	0.05
Corn (grain)	200 bu	150	40	40	6	18	15	0.08	0.10	0.18
Corn (stover)	6 tons	110	12	160	16	36	16	0.05	1.50	0.30
Cotton (seed+lint)	1.3 tons	63	25	31	4	7	5	0.18	0.33	0.96
Cotton (stalk+leaf)	1.5 tons	57	16	72	56	16	15	0.05	0.06	0.75
Oats (grain)	80 bu	60	10	15	2	4	6	0.03	0.12	0.05
Oats (straw)	2 tons	35	8	90	8	12	9	0.03	--	0.29
Peanuts (nuts)	2 tons	140	22	35	6	5	10	0.04	0.30	0.25
Peanuts (vines)	2.5 tons	100	17	150	88	20	11	0.12	0.15	--
Rye (grain)	30 bu	35	10	10	2	3	7	0.02	0.22	0.03
Rye (straw)	1.5 tons	15	8	25	8	2	3	0.01	0.14	0.07
Soybean (grain)	50 bu	188	41	74	19	10	23	0.05	0.06	0.05
Soybean (stover)	3 tons	89	16	74	30	9	12	--	--	--
Wheat (grain)	60 bu	70	20	25	2	10	4	0.04	0.10	0.16
Wheat (straw)	2.5 tons	45	5	65	8	12	15	0.01	0.16	0.05
Tobacco (burley)	2 tons	145	14	150	--	18	24	--	--	--
Tobacco (flue cured)	1.5 tons	85	15	155	75	15	12	0.03	0.55	0.07

Table 4.3c. Nutrient removal by selected fruit and vegetable crops.

Crop	Yield	N	P	K	Ca	Mg	S	Cu	Mn	Zn
		---------- pounds per acre ----------								
Apples	500 bu	30	10	45	8	5	10	0.03	0.03	0.03
Cabbage	20 tons	130	35	130	20	8	44	0.04	0.10	0.08
Peaches	600 bu	35	20	65	4	8	2	--	--	0.01
Potato (sweet)	300 bu	40	18	96	4	4	6	0.02	0.06	0.03
Potato (white)	15 tons	90	48	158	5	7	7	0.06	0.14	0.08
Snap Bean	4 tons	138	33	163	--	17	--	--	--	--
Spinach	5 tons	50	15	30	12	5	4	0.02	0.10	0.10
Tomatoes (fruit)	20 tons	120	40	160	7	11	14	0.07	0.13	0.16

Soil properties that influence nutrient availability

Influence of CEC and base saturation on fertilizer management

A soil's CEC should be considered when determining the appropriate rates and timing of nutrient applications in a fertilizer program. In general, smaller amounts of fertilizer, applied more often, are needed in low CEC soils to prevent leaching losses, while larger amounts may be applied less frequently in high CEC soils. For example, it may not be wise to apply K on very sandy soils with low CEC in the fall to serve the next spring's crops, especially in areas where fall and winter rainfall is high. In comparison, on clayey soils with high CEC, adequate K can be applied in the fall for one or more future crops.

In the past, the concept of base saturation was used to develop fertilizer programs. This school of thought held that certain nutrient ratios, or "balances," are needed for optimum crop nutrition. Most crops grow best at a base saturation of 80% or more; however, research has shown that saturation ranges for specific cations (esp., K, Mg, and Ca) have little or no utility in the majority of agricultural soils. Under field conditions, relative amounts of nutrients can vary widely with no detrimental effects, as long as individual nutrients are present in sufficient levels in the soil to support optimum plant growth.

Ion mobility in soils

Anions (negatively charged ions) usually leach more readily than cations because they are not attracted to the predominantly negative charge of soil colloids. For example, NO_3^- , due to its negative charge and relatively large ionic radius, is not readily retained in the soil and is easily lost from soils by leaching.

An exception to this behavior is phosphorus anions (HPO_4^{2-}, $H_2PO_4^-$). These anionic forms do not easily leach through the soil profile because of their specific complexing reactions with soil components. Surface applications of inorganic and organic sources of P without incorporation will result in the accumulation of P near the soil surface. Estimates of vertical P movement in most agricultural soils are on the order of 0.5 to 1 inch per year with an average rainfall of 36 inches, with greater movement in coarse-textured than fine-textured soils. Since P can accumulate near the soil surface, losses of P from agricultural systems are associated with a combination of residual soil P levels and soil erosion.

Effect of pH on nutrient availability

Many soil elements change form as a result of chemical reactions in the soil. Plants may or may not be able to use elements in some of these forms. Because pH influences the soil concentration and, thus, the availability of plant nutrients, it is responsible for the solubility of many nutrient elements. Figure 4.1 illustrates the relationship between soil pH and the relative plant availability of nutrients.

- **K, Ca, and Mg**: These nutrients are most present in soils with pH levels greater than 6.0. They are generally not as available for plant uptake in acid soils since they may have been partially leached out of the soil profile.

- **P**: Phosphorus solubility and plant availability are controlled by complex soil chemical reactions, which are often pH-dependent. Plant availability of P is generally greatest in the pH range of 5.5 to 6.8. When soil pH falls below 5.8, P reacts with Fe and Al to produce insoluble Fe and Al phosphates that are not readily available for plant uptake. At high pH values, P reacts with Ca to form Ca phosphates that are relatively insoluble and have low availability to plants.

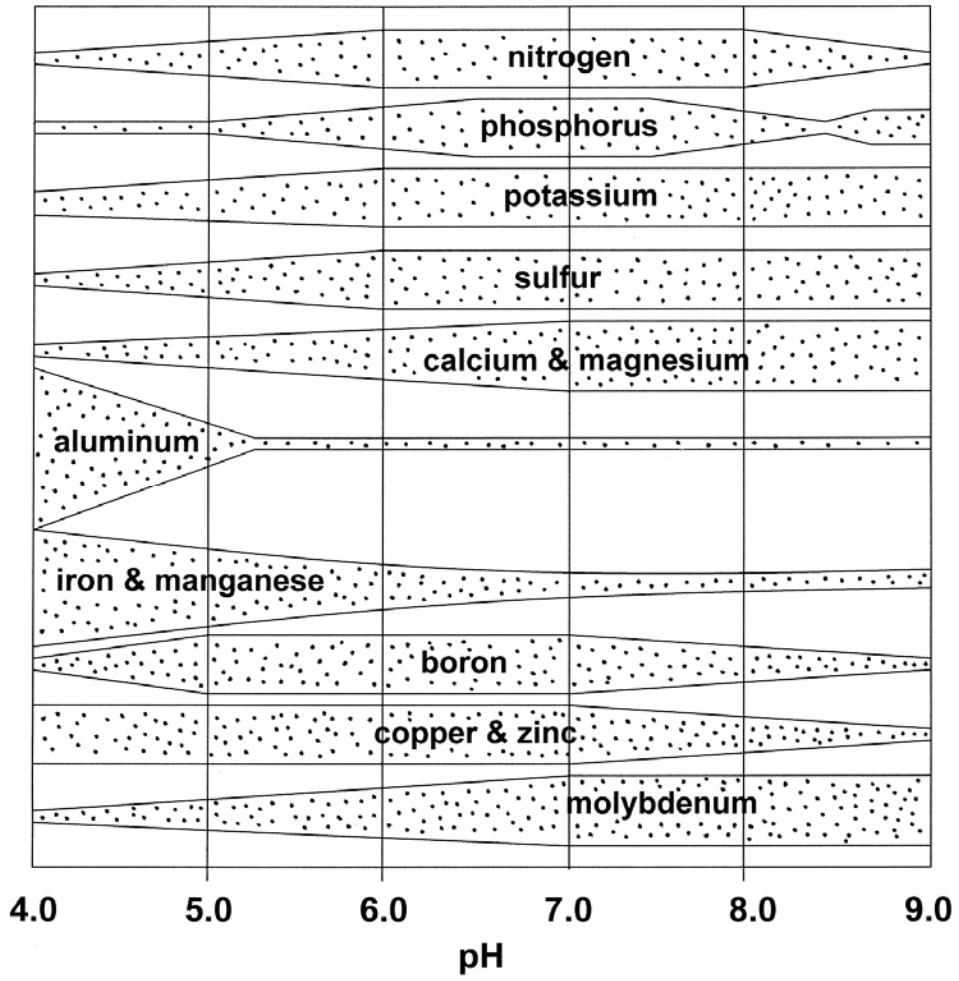
- **Micronutrients**: In general, most micronutrients are more available in acid than alkaline soils. As pH increases, micronutrient availability decreases, and the potential for deficiencies increase. An exception to this trend is Mo, which becomes less available as soil pH decreases. In addition, B becomes less available when the pH is <5.0 and again when the pH exceeds 7.0.

- **Al, Fe, and Mn Toxicity**: At pH values less than 5.0, Al, Fe, and Mn may be soluble in sufficient quantities to be toxic to the growth of some plants. Aluminum toxicity limits plant growth in most strongly acid soils. Aluminum begins to solubilize from silicate clays and aluminum hydroxides below a pH of approximately 5.3, which increases the activity of exchangeable Al^{3+}. High concentrations of exchangeable Al are toxic and detrimental to plant root development.

- **Soil Organisms**: Soil organisms grow best in near-neutral soil. In general,

acid soil inhibits the growth of most organisms, including many bacteria and earthworms. Thus, acid soil slows many important activities carried on by soil microbes, including nitrogen fixation, nitrification, and organic matter decay. *Rhizobia* bacteria, for instance, thrive at near-neutral pH and are sensitive to solubulized Al.

Figure 4.1. Relationship between soil pH and nutrient availability.



Liming

Introduction

Acid soil limits crop yields on many farms in the Mid-Atlantic region. With only a few exceptions, the climate in this region causes non-limed soils to be moderately to strongly acidic. Acidification is a natural process that occurs continuously in soils throughout the Mid-Atlantic region. It is caused by the following factors:

- The **breakdown of organic matter** can cause acidification of the soil as amino acids are converted into acetic acid, hydrogen gas, dinitrogen gas, and carbon dioxide by the reaction:

$$\mathbf{2C_3H_7NO_3 + O_2 \rightarrow 2HC_2H_3O_2 + 3H_2 + N_2 + 2CO_2}$$

- The **movement of acidic water from rainfall** through soils slowly leaches basic essential elements such as Ca, Mg, and K below the plant root zone and increases the concentration of exchangeable soil Al. Soluble Al^{3+} reacts with water to form H^+ ($Al^{3+} + H_2O \leftrightarrow Al(OH)^{2+} + H^+$), which makes the soil acid.

- **Soil erosion** removes exchangeable cations adsorbed to clay particles.

- Hydrogen is released into the soil by plants' root systems as a result of respiration and ion uptake processes during **plant growth**.

- **Nitrogen fertilization** speeds up the rate at which acidity develops, primarily through the acidity generated by nitrification:

$$\mathbf{2NH_4^+ + 4O_2 \rightarrow 2H_2O + 4H^+ + 2NO_3^-}$$

- The **harvesting of crops** removes basic cations.

Effect of pH/liming on crop yields

Liming is a critical management practice for maintaining soil pH at optimal levels for growth of plants. Over-liming can induce micronutrient deficiencies by increasing pH above the optimum range.

Most crops grow well in the pH range 5.8 to 6.5. Legumes generally grow better in soils limed to pH values of 6.2 to 6.8. Plants such as blueberries, mountain laurel, and rhododendron grow best in strongly acid (pH < 5.2) soils. Most crops will grow well on organic soils (>20% organic matter), even if the pH is in the range of 5.0 to 5.5, because much of the acidity such soils is derived from non-toxic organic matter functional groups rather than toxic Al.

Benefits of liming

- Liming reduces the solubility and potential toxicity of Al and Mn.
- Liming supplies the essential elements Ca and/or Mg. Both are generally low in very acid soils.
- Liming increases the availability of several essential nutrients.
- Liming stimulates microbial activity (i.e., nitrification) in the soil.
- Liming improves symbiotic nitrogen fixation by legumes.
- Liming improves the physical conditions of the soil.
- Maintaining a proper soil pH helps to improve the efficiency of some herbicides.

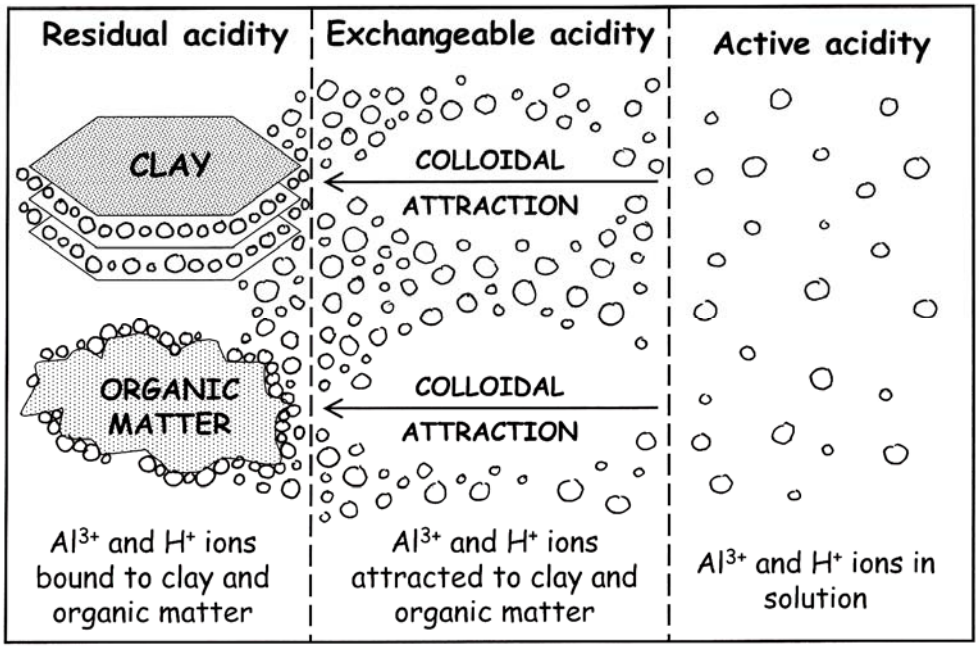
Determining lime requirements

Soil pH is an excellent indicator of soil acidity; however, it does not indicate how much total acidity is present, and it cannot be used to determine a soil's lime requirement when used alone.

The *lime requirement* for a soil is the amount of agricultural limestone needed to achieve a desired pH range for the cropping system used. Soil pH determines only active acidity (the amount of H^+ in the soil solution at that particular time), while the lime requirement determines the amount of exchangeable, or reserve acidity, held by soil clay and organic matter (Figure 4.2).

Most laboratories use soil pH in combination with "buffered" solutions to extract and measure the amount of reserve acidity, or *buffering capacity* (see Chapter 3) in a soil. The measured amount of exchangeable/reserve acidity is then used to determine the proper amount of lime needed to bring about the desired increase in soil pH. **The rate of agricultural limestone applied to any agricultural field should be based on soil test recommendations**.

Figure 4.2. Relationship between residual, exchangeable, and active acidity in soils.



Selecting a liming material

Factors to consider in selecting a liming material include:

- **Calcium carbonate equivalence (CCE)**: CCE is a measure of the liming capability of a material relative to pure calcium carbonate expressed as a percentage. A liming material with a CCE of 50 has 50% of the liming capability of calcium carbonate.

- **Length of time between application of lime and planting of crop**: The choice between a slower acting and a quick-acting liming material is often determined by the time between application of lime and crop planting.

- **Crop value**: The value of the crop, especially those crops that are acid-sensitive or have a critical pH requirement, should be considered in determining what lime source to use. It may be desirable to use pulverized, hydrated ($Ca(OH)_2$), or burned (CaO) lime, which will neutralize soil acidity quickly, when growing an acid-sensitive crop in strongly acid soils. Although the cost per acre will be greater, improved crop performance should result in higher net income. Aglime has its maximum effect in a period of one to three years, while suspension lime, burned lime, and hydrated lime have their maximum effect in three to six months.

- **Need for magnesium**: Calcitic lime should be used in soils with high magnesium levels, while dolomitic limes should be used on soils low in magnesium. Use soil test data to determine which type of lime to use.

Frequency of lime applications

Intensive cropping systems result in more frequent need for liming as Ca and Mg are depleted with crop removal and soil becomes acidified due to higher ammonium-N applications. A soil test every two or three years will reveal whether or not lime is needed. Sandy soils generally require less lime at any one application than silt loam or clay soils to decrease soil acidity by a given amount. Sandy soils, however, usually need to be limed more frequently because their buffering capacity is low.

Applying lime

Lime moves slowly in soil from the point of application, and lime particles dissolve more slowly as acidity is reduced. In conventionally tilled systems, lime should be mixed to tillage depth in order to effectively neutralize soil acidity in the primary root zone. On moderately acid soils (pH 5.2 - 5.7), a single application of lime made either before or after tillage will usually give good results. For strongly acid soils (pH 5.0 and lower) that have very high lime requirements, it may be desirable to apply one-half of the lime before tillage and the remaining half after tillage. For large areas that have high lime requirements (3-4 tons/acre), it may be best to apply half of the required lime in a first year application and the remainder in the second year.

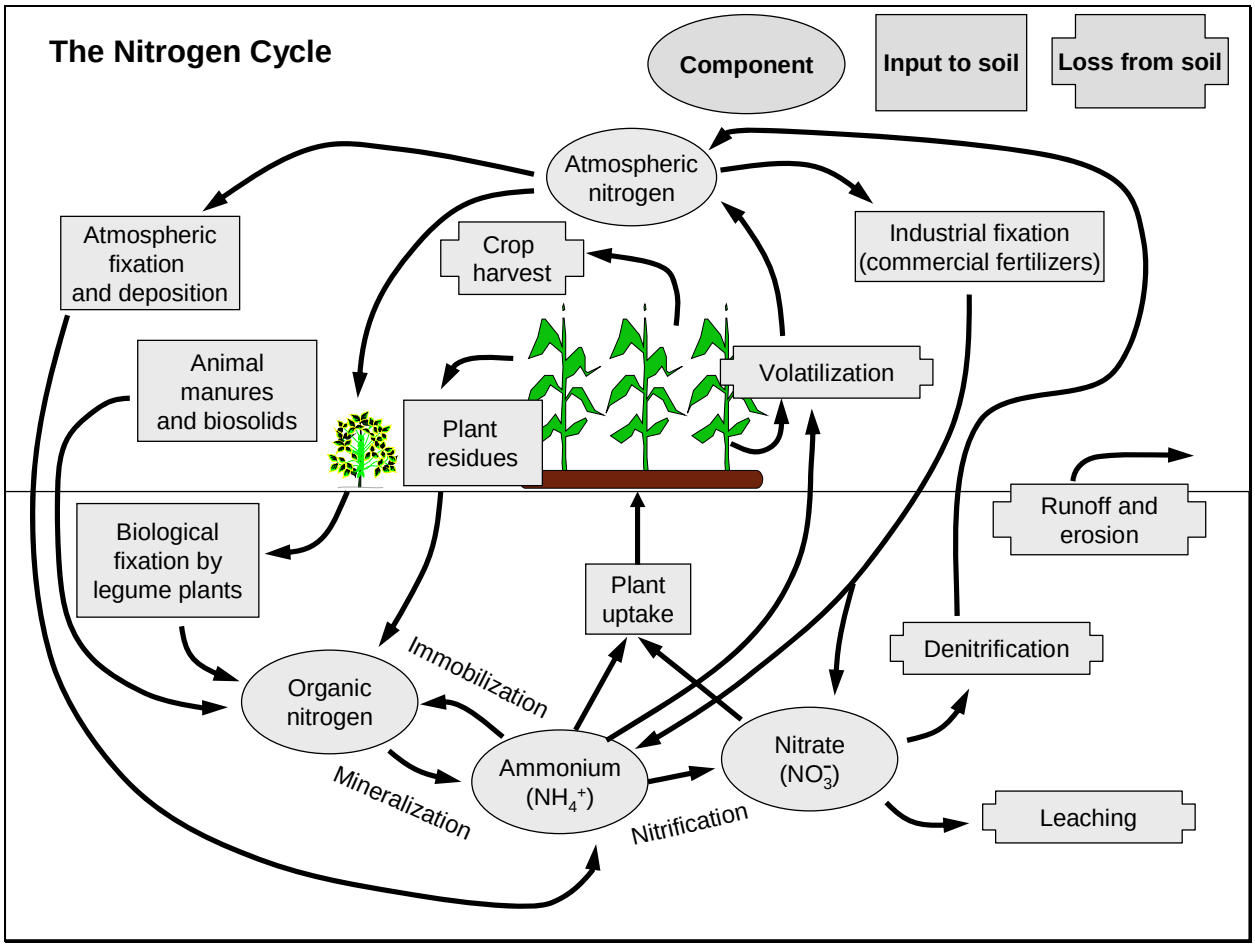
Agricultural limestone can be applied anytime between the harvest of a crop and the planting of the next. Lime is usually broadcast on the soil surface before tillage operations and incorporated into the soil. In conservation tillage systems and on pastures and hay fields, surface applications can be made whenever soil conditions allow spreaders to enter the fields. Research with no-tillage corn and forages has shown that surface applied lime has been effective in reducing soil acidity in the surface two to four inches of soil.

Nitrogen

The nitrogen cycle

Nitrogen is subject to more transformations than any other essential element. These cumulative gains, losses, and changes are collectively termed the *nitrogen cycle* (Figure 4.3). The ultimate source of N is N_2 gas, which comprises approximately 78% of the earth's atmosphere. Inert N_2 gas, however, is unavailable to plants and must be transformed by biological or industrial processes into forms which are plant-available. As a result, modern agriculture is heavily dependent on commercial N fertilizer. Some of the more important components of the N cycle are discussed below.

Figure 4.3. The nitrogen cycle (modified from the Potash & Phosphate Institute web site at www.ppi-ppic.org).



Nitrogen fixation

Nitrogen fixation is the process whereby inert N_2 gas in the atmosphere is transformed into forms that are plant-available, including NH_4^+ or NO_3^-. Fixation can take place by biological or by non-biological processes.

- **Biological N fixation** processes include:
  - **Symbiotic N fixation**: This process is mediated by bacteria with the ability to convert atmospheric N_2 to plant-available N while growing in association with a host plant. Symbiotic *Rhizobium* bacteria fix N_2 in nodules present on the roots of legumes. Through this relationship, the bacteria make N_2 from the atmosphere available to the legume as it is excreted from the nodules into the soil. In the Mid-Atlantic region, the quantity of N fixed by most leguminous crops is probably less than 150 lbs/acre/year.

  - **Non-symbiotic N fixation**: This is a N_2 fixation process that is performed

by free-living bacteria and blue-green algae in the soil. The amount of N_2 fixed by these organisms is much lower than that fixed by symbiotic N_2 fixation.

- **Non-biological N fixation** processes include:
  - **Atmospheric additions**: Small amounts of N in the order of 5-15 lbs/acre/year can be added to the soil in the form of rain or snowfall. This includes N that has been fixed by the electrical discharge of lightning in the atmosphere and industrial pollution.

  - **Synthetic or industrial processes of N fixation**: The industrial fixation of N is the most important source of N as a plant nutrient. The production of N by industrial processes is based on the Haber-Bosch process where hydrogen (H_2) and N_2 gases react to form NH_3:

$$\mathbf{N_2 + 3H_2 \rightarrow 2\ NH_3}$$

    Hydrogen gas for this process is obtained from natural gas and N2 comes directly from the atmosphere. The NH3 produced can be used directly as a fertilizer (anhydrous NH3) or as the raw material for other N fertilizer products, including ammonium phosphates, urea, and ammonium nitrate.

Residual N from legume cover crops

Nitrogen contained in the residues from a previous legume crop is an important source of N and should be considered when developing an N fertilization program. The amounts of residual N left in the soil from previous legume crops are summarized in Table 4.4. Accounting for residual N from legumes can reduce both N fertilizer costs and the risk of NO_3^- losses by leaching.

Table 4.4. Residual nitrogen credits provided by legumes, by Mid-Atlantic state. Sources: Pennsylvania: Pennsylvania Agronomy Guide, 2005-2006, 2005; Maryland: Maryland Nutrient Management Manual, 2005; Delaware: Sims and Gartley, 1996; Virginia/West Virginia: Virginia Division of Conservation and Recreation, 2005.

Legume	Criteria	----------State----------			
		Pennsylvania	Maryland	Delaware	Virginia/ West Virginia
		---------- nitrogen credit, lbs/acre ----------			
Alfalfa	First Year After Legume	---	100-150[‡]	90	---
	> 50% stand	80-120[†]	---	---	90
	25-49% stand	60-80[†]	---	---	70
	< 25% stand	40	---	---	50
Red clover & trefoil	First Year After Legume		40	60	
	> 50% Stand	60-90[†]	---	---	80[††]
	25-49% stand	50-60[†]	---	---	60[††]
	< 25% stand	40	---	---	40[††]
Ladino clover		---	60	---	---
Crimson clover		---	50-100[¶]	---	---
Hairy vetch		---	75-150[¶]	---	50-100[‡‡]
Austrian winter peas		---	75-150[¶]	---	---
Lespedeza		---	20	---	---
Peanuts		---	---	---	45
Soybeans	First Year After Grain	1 lb N/bu soybeans	15-20[§]	0.5 lb/bu soybeans	0.5 lb/bu of soybeans or 20 lbs if yield is unknown

[†] Actual rate depends on soil productivity group.

[‡] Depends on stand; if stand is good (> 4 plants per square foot), credit 150 lbs.; if stand is fair (1.5 to 4 plants per square foot), credit 125 lbs.; if stand is poor (< 1.5 plants per square foot), credit 100 lbs.

[¶] Depends on planting date (and biomass production), kill date and subsequent tillage.

[§] A minimum of 15 lbs. and may be as much as 1 lb per bushel of soybeans, up to a maximum of 40 lbs.

[††] Applies to red clover only.

[‡‡] Depends on stand: if stand is good (80-100%), credit 100 lbs.; if stand is fair (50-79%), credit 75 lbs.; if stand is poor (<50%), credit 50 lbs.

Forms of soil nitrogen

Soil N occurs in both inorganic and organic forms. Most of the total N in surface soils is present as organic N.

- **Inorganic forms of soil N** include:
  – ammonium (NH_4^+)
  – nitrite (NO_2^-)
  – nitrate (NO_3^-)
  – nitrous oxide (N_2O_{gas})
  – nitric oxide (NO_{gas})
  – elemental N ($N_{2\ gas}$)

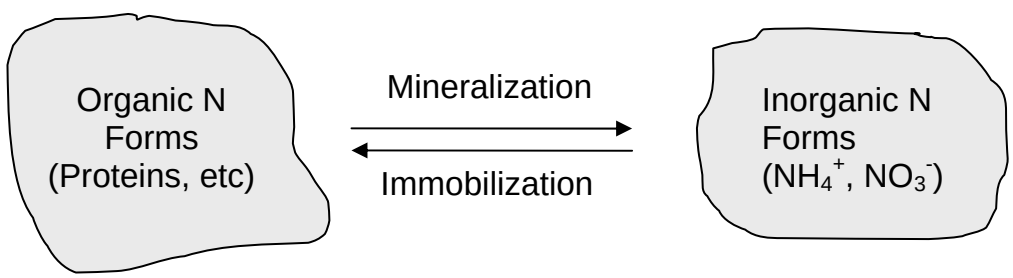
  NH_4^+, NO_2^-, and NO_3^- are the most important plant nutrient forms of N and usually comprise 2 to 5% of total soil N.

- **Organic soil N** occurs in the form of amino acids, amino sugars, and other complex N compounds.

N *mineralization* (Figure 4.4) is the conversion of organic N to NH_4^+. This is an important process in the N cycle since it results in the liberation of plant-available inorganic N forms.

N *immobilization* is the conversion of inorganic plant available N (NH_4^+ or NO_3^-) by soil microorganisms to organic N forms (amino acids and proteins). This conversion is the reverse of mineralization, and these immobilized forms of N are not readily available for plant uptake.

Figure 4.4. Forms of soil nitrogen



Carbon to nitrogen ratios (C:N)

Immobilization and mineralization are ongoing processes in the soil and are generally in balance with one another. This balance can be disrupted by the incorporation of organic residues that have high carbon to nitrogen ratios (C:N). The ratio of %C to %N, or the C:N ratio, defines the relative quantities of these elements in residues and living tissues. Whether N is mineralized or immobilized depends on the C:N ratio of the organic matter being decomposed by soil microorganisms:

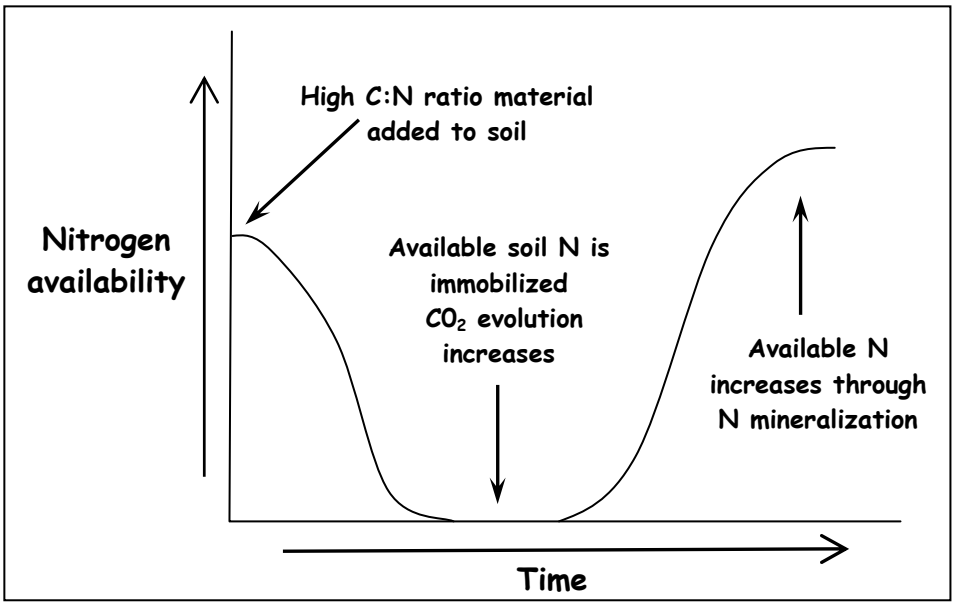
- **Wide C:N ratios of > 30:1**: Immobilization of soil N will be favored. Residues with wide C:N ratios include hay, straw pine needles, cornstalks, dry leaves, and sawdust.

- **C:N ratios of 20:1 to 30:1**: Immobilization and mineralization will be nearly equal.

- **Narrow C:N ratios of < 20:1**: Favor rapid mineralization of N. Residues with narrow C:N ratios include alfalfa, clover, manures, biosolids, and immature grasses.

The decomposition of a crop residue with a high C:N ratio is illustrated in Figure 4.5. Shortly after incorporation, high C:N ratio residues are attacked and used as an energy source by soil microorganisms. As these organisms decompose the material, there is competition for the limited supply of available N since the residue does not provide adequate N to form proteins in the decaying organisms. During this process, available soil N is decreased and the C in the residues is liberated as CO_2 gas. As decomposition proceeds, the residue's C:N ratio narrows and the energy supply is nearly exhausted. At this point, some of the microbial populations will die and the mineralization of N in these decaying organisms will result in the liberation of plant-available N. The timing of this process will depend on such factors as soil temperature, soil moisture, soil chemical properties, fertility status, and the amount of residues added. The process can be accelerated by applying N fertilizer sources at the time of application of the residue.

Figure 4.5. Nitrogen immobilization and mineralization after material with a high C:N ratio is added to soil.



Nitrification

Nitrification is the biological oxidation of ammonium (NH_4^+) to nitrate (NO_3^-) in the soil. Sources of NH_4^+ for this process included both commercial fertilizers and the mineralization of organic residues. Nitrification is a two-step process where NH_4^+ is converted first to NO_2^- and then to NO_3^- by two autotrophic bacteria in the soil (*Nitrosomonas* and *Nitrobacter*). These bacteria get their energy from the oxidation of N and their C from CO_2.

$$2NH_4^+ + 3O_2 \xrightarrow{\text{Nitrosomonas}} 2NO_2^- + 2H_2O + 4H^+$$

$$2NO_2^- + O_2 \xrightarrow{\text{Nitrobacter}} NO_3^-$$

Nitrification is important because:

- Nitrate is readily available for uptake and use by crops and microbes.

- Nitrate is highly mobile and subject to leaching losses. NO_3^- leaching is generally a major N loss mechanism from agricultural fields in humid climates and under irrigation. Potential losses are greater in deep sandy soils as compared to fine textured soils. Nitrogen losses can be minimized through proper N management, including the proper rate and timing of N fertilizer applications.

- Nitrate-nitrogen (NO_3-N) can be lost through denitrification, the process where NO_3^- is reduced to gaseous nitrous oxide (N_2O) or elemental N (N_2) and lost to the atmosphere.

- During nitrification, 2 H^+ ions are produced for every NH_4^+ ion that is oxidized. These H^+ cations will accumulate and significantly reduce soil pH; thus, any ammonium-containing fertilizer will ultimately decrease soil pH due to nitrification. This acidity can be managed through a well-planned liming program.

Note: The proper way to express NO_3^- concentrations is as **NO_3-N** or as elemental **N**. Use the following conversions, which are based on molecular weight:
- To convert NO_3-N to NO_3^-: $NO_3\text{-N} \times 4.4 = NO_3^-$
- To convert NO_3^- to NO_3-N: $NO_3^- \times 0.23 = NO_3\text{-N}$

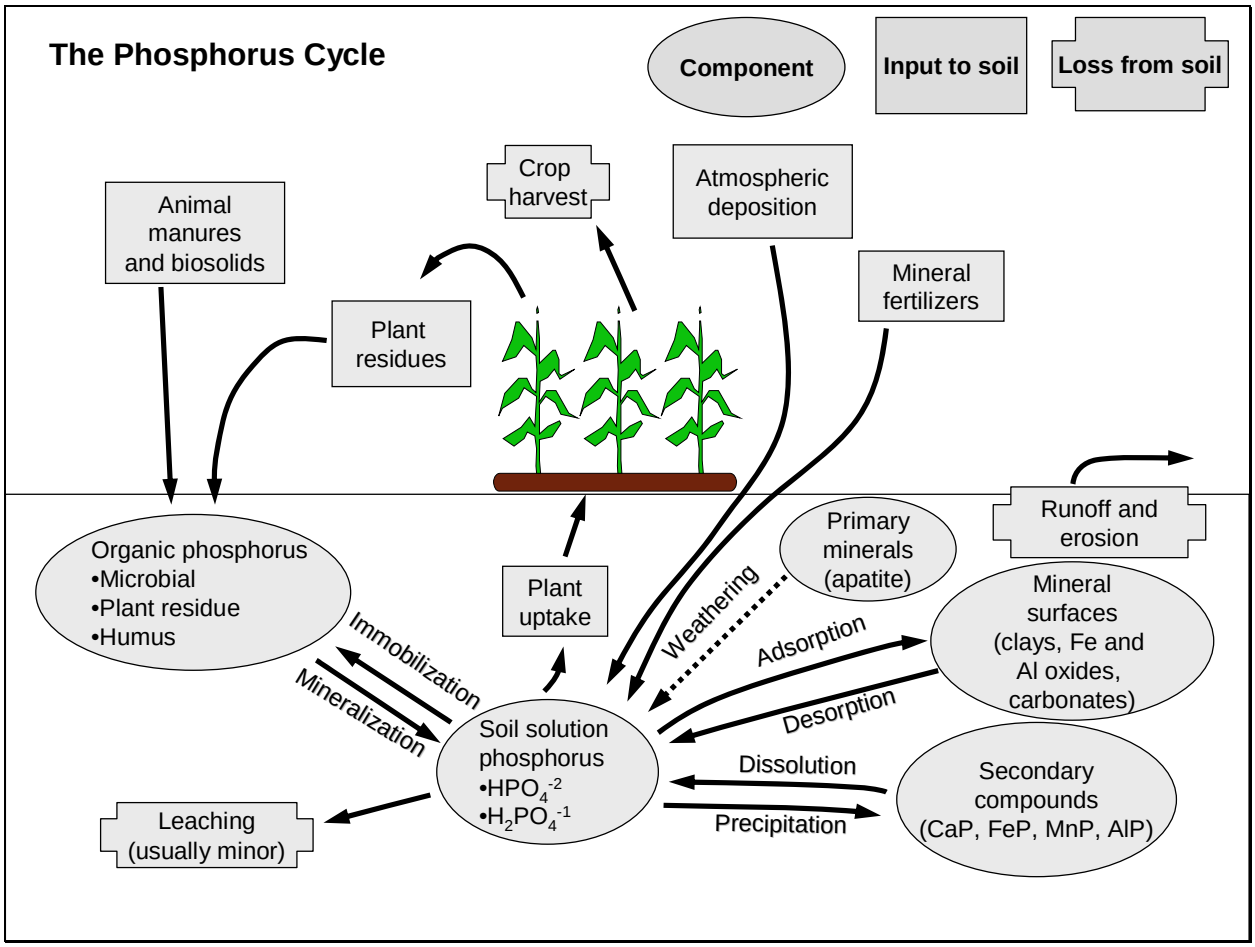
Phosphorus

The phosphorus cycle

Soil phosphorus (P) originates primarily from the weathering of soil minerals such as apatite and from P additions in the form of fertilizers, plant residues, agricultural wastes, or biosolids (Figure 4.6). Orthophosphate ions (HPO_4^{-2} and $H_2PO_4^-$) are produced when apatite breaks down, organic residues are decomposed, or fertilizer P sources dissolve. These forms of P are taken up by plant roots and are present at very low concentrations in the soil solution.

Many soils contain large amounts of P (800 to 1600 lbs P/acre), but most of that P is unavailable to plants. The type of P-bearing minerals that form in soil is highly dependent on soil pH. Soluble P, regardless of the source, reacts very strongly with Fe and Al to form insoluble Fe and Al phosphates in acid soils and with Ca to form insoluble Ca phosphates in alkaline soils. Phosphorus in these insoluble forms is not readily available for plant growth and is said to be “fixed.”

Figure 4.6. The phosphorus cycle (modified from the Potash & Phosphate Institute web site at www.ppi-ppic.org).



Phosphorus availability and mobility

Phosphorus is a primary nutrient and plant roots take up P in the forms of HPO_4^{-2} and $H_2PO_4^{-}$. The predominant ionic form of P present in the soil solution is pH-dependent. In soils with pH values greater than 7.2, the HPO_4^{-2} form is predominant, while in soils with a pH between 5.0 and 7.2, the $H_2PO_4^{-}$ form predominates.

P has limited mobility in most soils because P reacts strongly with many elements, compounds, and the surfaces of clay minerals. The release of soil P to plant roots and its potential movement to surface waters is controlled by several chemical and biological processes (Figure 4.6). Phosphorus is released to the soil solution as P-bearing minerals dissolve, as P bound to the surface of soil minerals is uncoupled or *desorbed*, and as soil organic matter decomposes or *mineralizes* (Figure 4.7). Most of the P added as fertilizer and organic sources is rapidly bound by soil minerals in chemical forms that are not subject to rapid release; thus, soil solution P concentrations are typically very low. Soluble P in the soil solution of most agricultural soils ranges from

< 0.01 to 1 ppm; thus, an entire acre-furrow slice of soil generally contains less than 0.4 lb P in solution at any one time. As illustrated (Figure 4.7), supplying adequate P to a plant depends on the soil's ability to replenish the soil solution throughout a growing season.

Phosphorus availability and mobility is influenced by several factors:

- **Effect of soil pH**: In acid soils, P precipitates as relatively insoluble Fe and Al phosphate minerals. In neutral and calcareous soils, P precipitates as relatively insoluble Ca phosphate minerals. As illustrated in Figures 4.1 and 4.8, soil P is most available in the pH range of 5.5 to 6.8, which is where soluble Al and Fe are low.

- **Movement of soil P to plant roots**: Phosphorus moves from soil solids to plant roots through the process of *diffusion*. Diffusion is a slow and short-range process with distances as small as 0.25 inches. This limited movement has important implications since soil P located more than 0.25 inches from a plant root will never reach the root surface. Dry soils reduce the diffusion of P to roots; therefore, plants take up P best in moist soils.

- **Fertilizer P recovery**: A crop uses only 10 to 30% of the P fertilizer applied during the first year following application. The rest goes into reserve and may be used by later crops. Many growers in the Mid-Atlantic have built up large reserves of soil P.

- **Timing and placement of P fertilizer**: Although most agricultural soils are naturally low in available P, many years of intensive P fertilization, the application of organic P sources, or both, has resulted in many soils that now test high in available P. On these soils, broadcast P applications are not very efficient. Low rates of P in starter fertilizers placed with or near the seed are potentially beneficial on high-P soils when the crop is stressed by cold conditions. Newly-planted crops need a highly available P source in order to establish a vigorous root system early in the season, but once the root system begins to explore the entire soil volume, there should be adequate amounts of plant available P to maintain crop growth.

Figure 4.7. Phosphorus content of the soil solution.

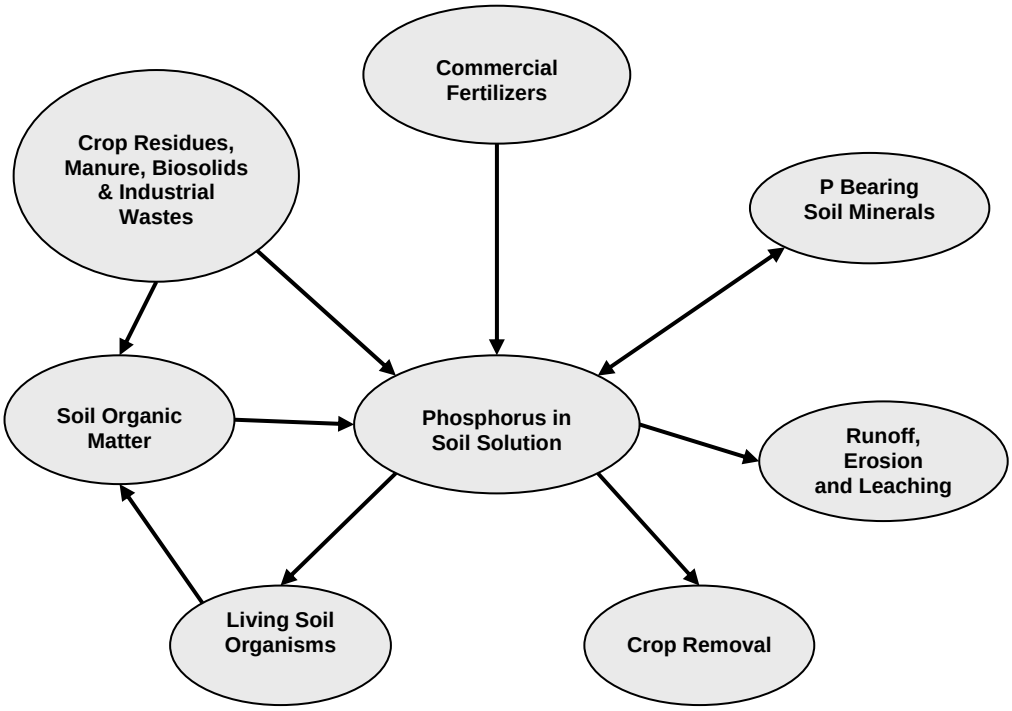
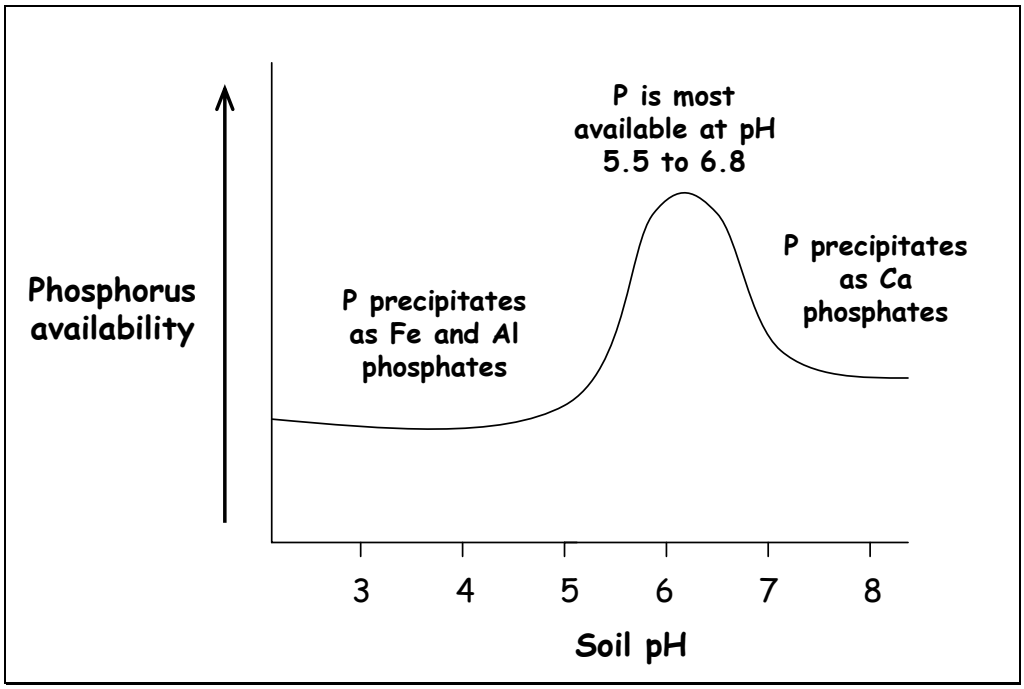


Figure 4.8. Effect of pH on P availability to plants.



Phosphorus transport to surface waters

Transport of soil P occurs primarily via surface flow (runoff and erosion). Although leaching and subsurface lateral flow should also be considered in soils with high degrees of P saturation and artificial drainage systems. Water flowing across the soil surface can dissolve and transport soluble P, or erode and transport particulate P, out of a field. Virtually all soluble P transported by surface runoff is biologically available, but particulate P that enters streams and other surface waters must undergo solubilization before becoming available for aquatic plants. Thus, both soluble and sediment bound P are potential pollutants of surface waters and both can contribute to excessive growth of aquatic organisms, which can have detrimental environmental impacts.

Soils have a finite capacity to bind P. When a soil becomes saturated with P, desorption of soluble P can be accelerated, with a consequent increase in dissolved inorganic P in runoff. **Thus, if the level of residual soil P is allowed to build up by repeated applications of P in excess of crop needs, a soil can become saturated with P and the potential for soluble P losses in surface runoff will increase significantly.** Recent research conducted in the Mid-Atlantic shows that the potential loss of soluble P will increase with increasing levels of soil test P. Very high levels of soil test P can result from over-application of manure, biosolids, or commercial phosphate fertilizer. Soils with these high soil test P levels will require several years of continuous cropping without P additions to effectively reduce these high P levels.

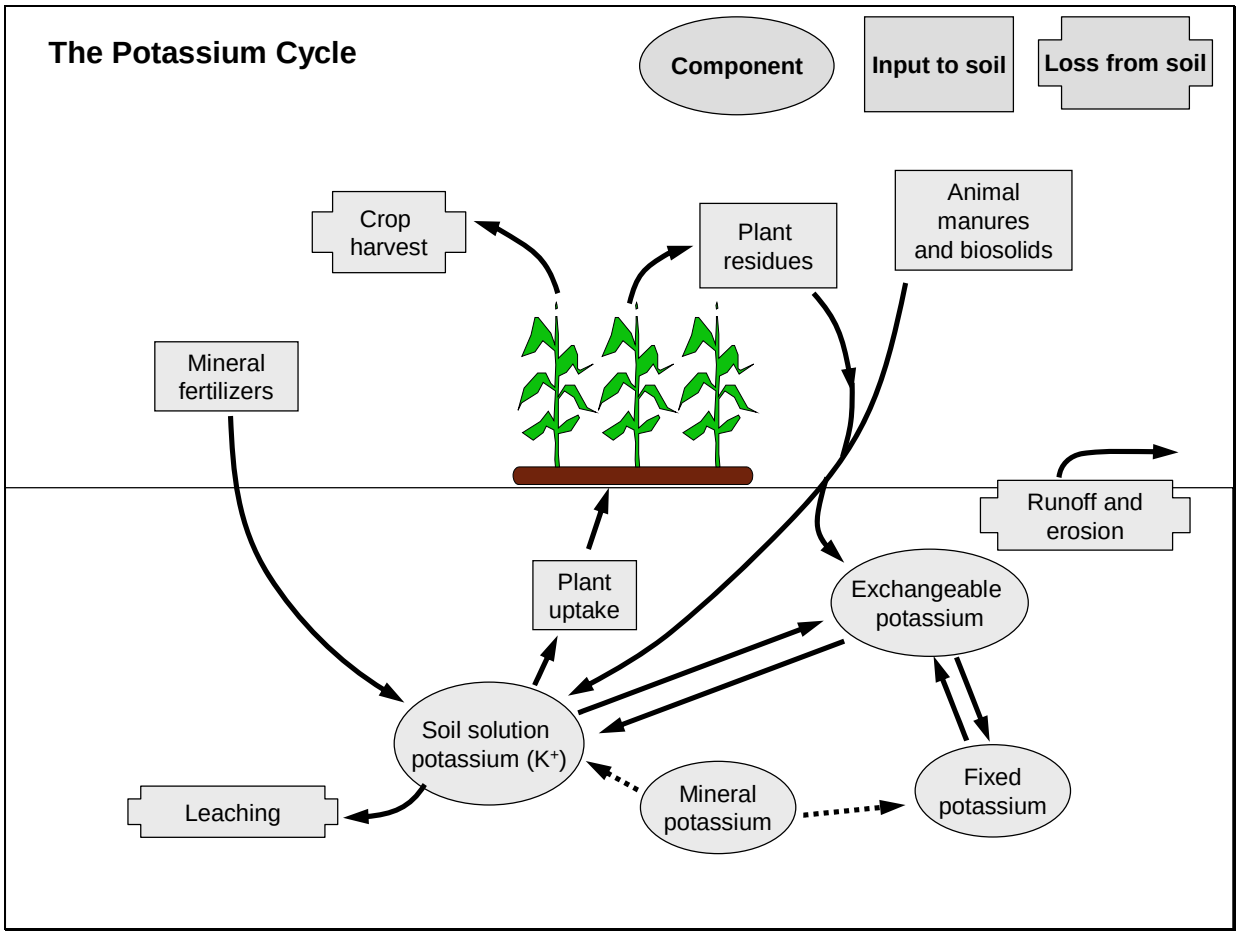
Potassium

The potassium cycle

Potassium is the third primary plant nutrient and is absorbed by plants in larger amounts than any other nutrient except N. Plants take up K as the monovalent cation K^+. Potassium is present in relatively large quantities in most soils, but only a small percentage of the total soil K is readily available for plant uptake.

In the soil, weathering releases K from a number of common minerals including feldspars and micas. The released K^+ can be taken up easily by plant roots, adsorbed by the cation exchange complex of clay and organic matter, or “fixed” in the internal structure of certain 2:1 clay minerals. Potassium that is “fixed” by these clay minerals is very slowly available to the plant. The various forms of K in the soil are illustrated in Figure 4.9.

Figure 4.9. The potassium cycle (modified from the Potash & Phosphate Institute web site at www.ppi-ppic.org).



Potassium availability and mobility

- **Plant-available K**: Although mineral K accounts for 90 to 98% of the total soil K, readily and slowly available K represent only 1 to 10% of the total soil K. Plant available K (K that can be readily absorbed by plant roots) includes the portion of the soil K that is soluble in the soil solution and exchangeable K held on the exchange complex.

- **Exchangeable K** is that portion of soil K which is in equilibrium with K in the soil solution:

  Exchangeable K ↔ Solution K

  K is continuously made available for plant uptake through the cation exchange process. There can be a continuous, but slow, transfer of K from soil minerals to exchangeable and slowly available forms as K is removed from the soil solution by crop uptake and leaching.

- **Effect of K fertilization on soil K forms**: Potassium applied as fertilizer can have various fates in the soil:
  - Potassium cations can be attracted to the cation exchange complex where it is held in an exchangeable form and readily available for plant uptake.
  - Some of the K^+ ions will remain in the soil solution.
  - Exchangeable and soluble K may be absorbed by plants.
  - In some soils, some K may be "fixed" by the clay fraction.
  - Applied K may leach from sandy soils during periods of heavy rainfall.

- **Movement of K in the soil**: Potassium moves more readily in soil than P, but less readily than N. Since K is held by cation exchange, it is less mobile in fine-textured soils and most readily leached from sandy soils. Most plant uptake of soil K occurs by diffusion.

Timing and placement of K fertilizer

Potassium fertilizers are completely water-soluble and have a high salt index; thus, they can decrease seed germination and plant survival when placed too close to seed or transplants. The risk of fertilizer injury is most severe on sandy soils, under dry conditions, and with high rates of fertilization. Placement of the fertilizer in a band approximately three inches to the side and two inches below the seed is an effective method of preventing fertilizer injury. Row placement of K fertilizer is generally more efficient than broadcast applications when the rate of application is low or soil levels of K are low.

A convenient and usually effective method of applying K fertilizers is by broadcasting and mixing with the soil before planting. Fertilizer injury is minimized by this method but, on sandy soils, some K may be lost by leaching.

Split application of K fertilizer on long-season crops such as alfalfa or grass crops that are harvested several times during the growing season is often recommended. *Luxury consumption* is a term used to describe the tendency of plants to take up K far in excess of their needs if sufficiently large quantities of available K are present in the soil. The excess K absorbed does not increase crop yields to any extent. Split application of K can minimize luxury consumption and provide adequate available K during the latter part of the growing season.

Secondary plant nutrients

Introduction

Secondary macronutrients, which include calcium (Ca), magnesium (Mg), and sulfur (S), are required in relatively large amounts for good crop growth. These nutrients are usually applied as soil amendments or applied along with materials which contain primary nutrients. Many crops contain as much or more S and Mg as P, but in some plants Ca requirements are greater than those for P. Secondary nutrients are as important to plant nutrition as major nutrients since deficiencies of secondary nutrients can depress plant growth as much as major plant nutrient deficiencies.

Calcium and magnesium

- **Behavior of Ca and Mg in the soil**: Calcium and Mg have similar chemical properties and thus behave very similarly in the soil. Both of these elements are cations (Ca^{2+}, Mg^{2+}), and both cations have the same amount of positive charge and a similar ionic radius. The mobility of both Ca and Mg is relatively low, especially compared to anions or to other cations such as Na and K; thus, losses of these cations via leaching are relatively low.

- **Soil Ca**: Total Ca content of soils can range from 0.1% in highly weathered tropical soils to 30% in calcareous soils. Calcium is part of the structure of several minerals and most soil Ca comes from the weathering of common minerals, which include dolomite, calcite, apatite, and Ca-feldspars. Calcium is present in the soil solution and since it is a divalent cation, its behavior is governed by cation exchange as are the other cations. Exchangeable Ca is held on the negatively charged surfaces of clay and organic matter. Calcium is the dominant cation on the cation exchange complex in soils with moderate pH levels. Normally, it occupies 70-90% of cation exchange sites above pH 6.0.

- **Soil Mg**: Total soil Mg content can range from 0.1% in coarse, humid-region soils to 4% in soils formed from high-Mg minerals. Magnesium occurs naturally in soils from the weathering of rocks with Mg-containing minerals such as biotite, hornblende, dolomite, and chlorite. Magnesium is found in the soil solution and, since it is a divalent cation (Mg^{2+}), its behavior is governed by cation exchange. Magnesium is held less tightly than Ca by cation exchange sites, so it is more easily leached; thus, soils usually contain less Mg than Ca. In the Mid-Atlantic region, Mg deficiencies occur most often on acid and coarse-textured soils.

Sulfur

- **Forms of sulfur and the sulfur cycle**: Most crops need less sulfur (S) relative to the other macronutrients. The S cycle for the soil-plant-atmosphere system is very similar to N and is illustrated in Figure 4.10. Soil

S is present in both inorganic and organic forms. Most of the sulfur in soils comes from the weathering of sulfate minerals such as gypsum; however, approximately 90% of the total sulfur in the surface layers of non-calcareous soils is immobilized in organic matter. Inorganic S is generally present in the sulfate (SO_4^{2-}) form, which is the form of sulfur absorbed by plant roots. Both soluble SO_4^{2-} in the soil solution and adsorbed SO_4^{2-} represent readily plant available S. Elemental S is a good source of sulfur, but it must first undergo biological oxidation to SO_4^{2-}, driven by *Thiobacillus thiooxidans* bacteria, before it can be assimilated by plants. This oxidation can contribute to soil acidity by producing sulfuric acid through the reaction:

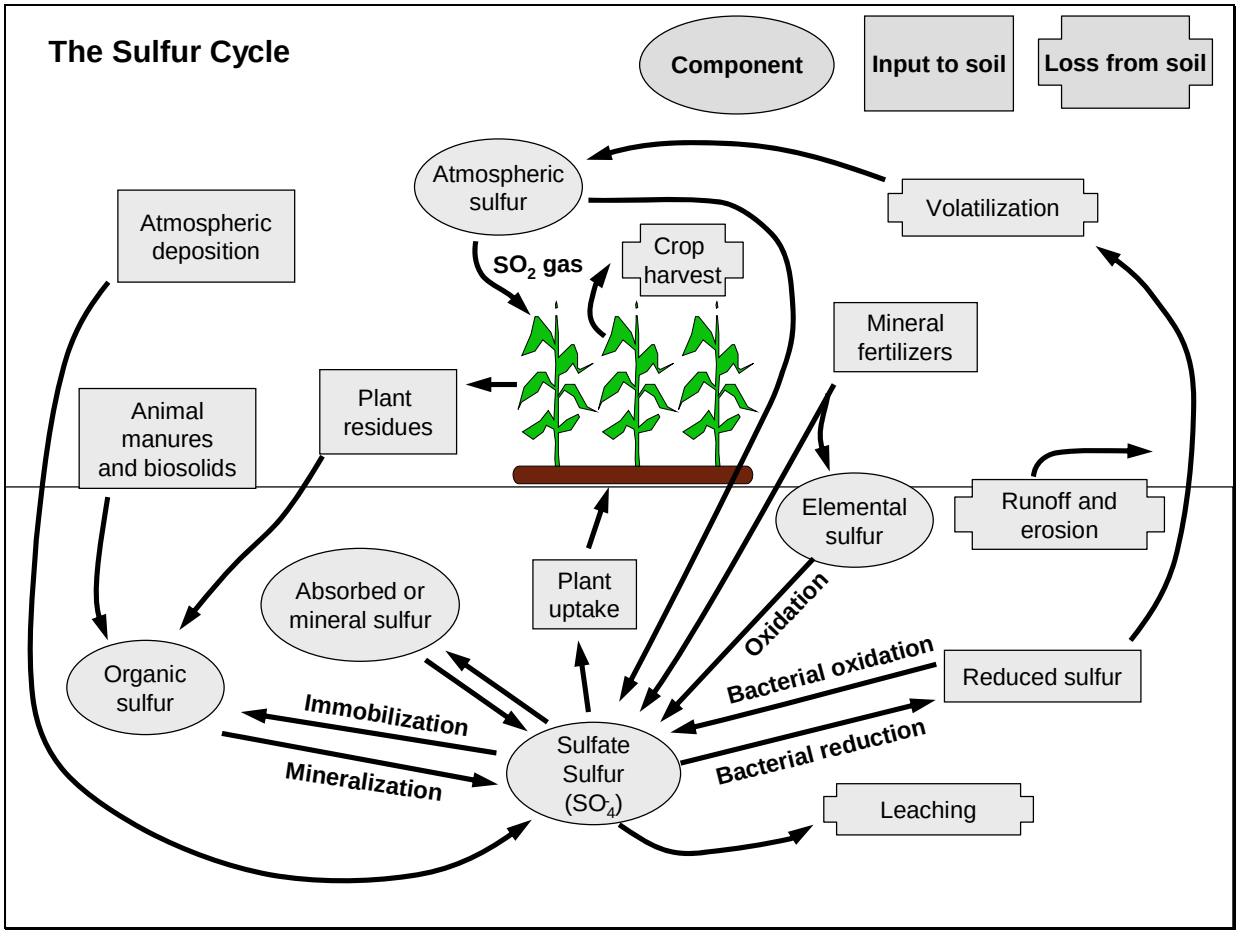
$$\mathbf{2S + 3O_2 + 2\ H_2O \text{ ------> } 2H_2SO_4}$$

- **Sulfur-containing fertilizers and soil acidity**: Several fertilizer materials contain the SO_4^{2-} form of S including gypsum ($CaSO_4$), potassium sulfate (K_2SO_4), magnesium sulfate ($MgSO_4$), and potassium magnesium sulfate (K-Mag, or Sul-Po-Mag). These fertilizer sources are neutral salts and will have little or no effect on soil pH. In contrast, there are other SO_4^{2-} containing compounds including ammonium sulfate ($(NH_4)_2SO_4$), aluminum sulfate ($(Al_2SO_4)_3$) and iron sulfate ($FeSO_4$) that contribute greatly to soil acidity. The SO_4^{2-} in these materials is not the source of acidity. Ammonium sulfate has a strong acidic reaction primarily because of the nitrification of NH_4^+, and Al and Fe sulfates are very acidic due to the hydrolysis of Al^{3+} and Fe^{3+}.

- **Movement of sulfur**: Sulfate, a divalent anion (SO_4^{2-}) is not strongly adsorbed and can be readily leached from most soils. In highly-weathered, naturally acidic soils, SO_4^{2-} often accumulates in subsurface soil horizons, where positively charged colloids attract the negatively charged SO_4^{2-} ion. Residual soil SO_4^{2-} resulting from long term applications of S containing fertilizers can meet the S requirements of crops for years after applications have ceased.

- **Crop responses to sulfur**: Sulfur deficiencies are becoming more common in some areas since both S supplied by pollution and fertilizer-derived S have been reduced in recent years. Acid rain supplies some sulfur due to the emission of SO_2 during the burning of fossil fuels but lowered emissions have reduced the amount of S supplied to soil in rainfall. Commercial fertilizers previously contained significant amounts of S (i.e. normal superphosphate). With the adoption of high analysis fertilizers such as urea, triple superphosphate, and ammonium phosphates, which contain little or no S, application of this important plant nutrient has been reduced.

Figure 4.10. The sulfur cycle (modified from the Potash & Phosphate Institute web site at www.ppi-ppic.org).



Micronutrients

Introduction

Eight of the essential elements for plant growth are called micronutrients or trace elements: B, Cl, Cu, Fe, Mn, Mo, Ni, and Zn. Cobalt (Co) has not been proven to be essential for higher plant growth, but nodulating bacteria need Co for fixing atmospheric N in legumes.

Micronutrients are not needed in large quantities, but they are as important to plant nutrition and development as the primary and secondary nutrients. A deficiency of any one of the micronutrients in the soil can limit plant growth, even when all other essential nutrients are present in adequate amounts.

Determining micronutrient needs

The need for micronutrients has been known for many years, but their wide use in fertilizers has not always been a common practice. Increased emphasis on micronutrient fertility has resulted from a number of factors, including:

- **Crop yields**: Increasing per-acre crop yields remove increasing amounts of micronutrients. As greater quantities of micronutrients are removed from the soil, some soils cannot release adequate amounts of micronutrients to meet today's high-yield crop demands.

- **Fertilizer technology**: Today's production processes for high-analysis fertilizers remove impurities much better than older manufacturing processes so micronutrients are not commonly provided as incidental ingredients in fertilizers.

Micronutrient fertilization should be treated as any other production input. A micronutrient deficiency, if suspected, can be identified through soil tests, plant analysis, or local field demonstrations. One should develop the habit of closely observing the growing crop for potential problem areas. Field diagnosis is one of the most effective tools available in production management.

Forms in the soil

Micronutrients can exist in several different forms in soil:

- within structures of primary and secondary minerals
- adsorbed to mineral and organic matter surfaces
- incorporated in organic matter and microorganisms
- in the soil solution

Many micronutrients combine with organic molecules in the soil to form complex molecules called chelates. A chelate is a metal atom surrounded by a large organic molecule.

Micronutrient soil-plant relationships

Plant roots absorb soluble forms of micronutrients from the soil solution. Soils vary in micronutrient content, and they usually contain lower amounts of micronutrients than primary and secondary nutrients. Total soil content of a micronutrient does not indicate the amount available for plant growth during a single growing season although it does indicate relative abundance and potential supplying power. Amounts of selected micronutrients taken up by selected crops are given in Tables 4.3a, b, and c. Availability decreases as pH increases for all micronutrients except Mo and Cl. Figure 4.1 shows the relationship between soil pH and availability for each micronutrient. Specific soil-plant relationships for B, Cu, Fe, Mn, Mo, Zn, and Cl are discussed in the next sections.

Boron

- **Soil boron:** Boron exists in minerals, adsorbed on the surfaces of clay and oxides, combined in soil organic matter, and in the soil solution. Organic matter is the most important potentially plant-available soil source of B.

- **Factors affecting plant-available B:**
  - **Soil moisture and weather**: Boron deficiency is often associated with dry or cold weather, which slows organic matter decomposition. Symptoms may disappear as soon as the surface soil receives rainfall or soil temperatures increase and root growth continues, but yield potential is often reduced.
  - **Soil pH**: Plant availability of B is maximum between pH 5.0 and 7.0. Boron availability decreases with increasing soil pH; thus, B uptake is reduced at high pH.
  - **Soil texture**: Coarse-textured (sandy) soils, which are composed largely of quartz, are typically low in minerals that contain B. Plants growing on such soils commonly show B deficiencies. Boron is mobile in the soil and is subject to leaching. Leaching is of greater concern on sandy soils and in areas of high rainfall.

- **Crop needs and potential toxicity**: Crops vary widely in their need for and tolerance to B; however, B should be applied judiciously because the difference between deficient and toxic amounts is narrower than for any other essential nutrient. This is especially important in a rotation involving crops with different sensitivities to B.

- **Rates of boron fertilization**: Recommended rates of B fertilization depend on such factors as soil test levels, plant tissue concentrations, plant species, cultural practices (including crop rotation), weather conditions, soil organic matter, and the method of application. Depending on the crop and method of application, recommended rates of application generally range from 0.5 to 3 lbs/acre.

Copper

- **Soil copper**: In mineral soils, Cu concentrations in the soil solution are controlled primarily by soil pH and the amount of Cu adsorbed on clay and soil organic matter. A majority of the soluble Cu^{2+} in surface soils is complexed with organic matter, and Cu is more strongly bound to soil organic matter than any of the other micronutrients.

- **Copper deficiencies**: Organic soils are most likely to be deficient in Cu. Such soils usually contain plenty of Cu but hold it so tightly that only small amounts are available to the crop. Sandy soils with low organic matter content may also become deficient in Cu because of leaching losses. Heavy, clay-type soils are least likely to be Cu deficient. The concentrations of Fe, Mn, and Al in soil affect the availability of Cu for plant growth, regardless of soil type.

- **Copper toxicity**: Like most other micronutrients, large quantities of Cu can be toxic to plants. Excessive amounts of Cu depress Fe activity and may cause Fe deficiency symptoms to appear in plants. Such toxicities are not common.

Iron

- **Soil iron**: Iron is the fourth most abundant element, with total Fe ranging from 0.7 to 55%. Solubility of Fe is very low and is highly pH-dependent. Iron solubility decreases with increasing soil pH. Iron can react with organic compounds to form chelates or Fe-organic complexes.

- **Iron deficiencies**: Iron deficiency may be caused by an imbalance with other metals such as Mo, Cu, or Mn. Other factors that may trigger Fe deficiency include:
  – Excessive P in the soil.
  – A combination of high pH, high lime, wet, cold soils, and high bicarbonate levels.
  – Plant genetic differences. Plant species can differ significantly in their ability to take up Fe. Fe-efficient varieties should be selected where Fe deficiencies are likely to occur. Roots of Fe-efficient plants can improve Fe availability and uptake by secretion of H, organic acids and organic chelating compounds.
  – Low soil organic matter levels.

  Reducing soil pH in a narrow band in the root zone can correct Fe deficiencies. Several S products will lower soil pH and convert insoluble soil Fe to a form the plant can use.

Manganese

- **Soil manganese**: Availability of Mn to plants is determined by the equilibrium among solution, exchangeable, organic and mineral forms of soil Mn. Chemical reactions affecting Mn solubility include oxidation-reduction and complexation with soil organic matter. Redox or oxidation-reduction reactions depend on soil moisture, aeration and microbial activity.

- **Manganese deficiencies**: Manganese solubility decreases with increasing soil pH:
  – Manganese deficiencies occur most often on high organic matter soils and on those soils with neutral-to-alkaline pH that are naturally low in Mn.
  – Manganese deficiencies may result from an antagonism with other nutrients such as Ca, Mg and Fe.
  – Soil moisture also affects Mn availability. Excess moisture in organic soils favors Mn availability because reducing conditions convert Mn^{4+} to Mn^{2+}, which is plant available.
  – Manganese deficiency is often observed on sandy Coastal Plain soils

under dry conditions that have previously been wet.
– Several plant species have shown differences in sensitivity to Mn deficiencies.

Molybdenum

- **Soil molybdenum**: Molybdenum is found in soil minerals, as exchangeable Mo on the surfaces of Fe/Al oxides, and bound soil organic matter. Adsorbed and soluble Mo is an anion (MoO_4^-).

- **Molybdenum deficiencies**: Molybdenum becomes more available as soil pH increases (Figure 4.1).
  – Deficiencies are more likely to occur on acid soils. Since Mo becomes more available with increasing pH, liming will correct a deficiency if the soil contains enough of the nutrient.
  – Sandy soils are deficient more often than finer-textured soils.
  – Soils high in Fe/Al oxides tend to be low in available Mo because Mo is strongly adsorbed to the surfaces of Fe/Al oxides.
  – Heavy P applications increase Mo uptake by plants, while heavy S applications decrease Mo uptake.
  – Crops vary in their sensitivity to low Mo and Mo-efficient/Mo-inefficient varieties have been identified for some plants species.

Zinc

- **Soil zinc**: The various forms of soil Zn include soil minerals, organic matter, adsorbed Zn on the surfaces of organic matter and clay, and dissolved Zn in the soil solution. Zinc release from soil minerals during weathering can be adsorbed onto the CEC, incorporated into soil organic matter, or react with organic compounds to form soluble complexes. Organically complexed, or chelated, Zn is important for the movement of Zn to plant roots. Soils can contain from a few to several hundred pounds of Zn per acre. Fine-textured soils usually contain more Zn than sandy soils.

- **Factors affecting plant-available Zn**: The total Zn content of a soil does not indicate how much Zn is available. The following factors determine its availability:
  – Zinc becomes less available as soil pH increases. Coarse-textured soils limed above pH 6.0 are particularly prone to develop Zn deficiency. Soluble Zn concentrations in the soil can decrease three-fold for every pH unit increase between 5.0 and 7.0.
  – Zinc deficiency may occur in some plant species on soils with very high P availability and marginal Zn concentrations due to Zn-P antagonisms. Soil pH further complicates Zn-P interactions.
  – Zinc forms stable complexes with soil organic matter. A significant portion of soil Zn may be fixed in the organic fraction of high organic matter soils. It may also be temporarily immobilized in the bodies of soil microorganisms, especially when animal manures are added to the soil.

– At the opposite extreme, much of a mineral soil's available Zn is associated with organic matter. Low organic matter levels in mineral soils are frequently indicative of low Zn availability.
– Zinc deficiencies tend to occur early in the growing season when soils are cold and wet due to slow root growth. Plants sometimes appear to outgrow this deficiency, but yield potential may have already been reduced.
– Zinc availability is affected by the presence of certain soil fungi, called mycorrhizae, which form symbiotic relationships with plant roots. Removal of surface soil in land leveling may remove the beneficial fungi and limit plants' ability to absorb Zn.
– Susceptibility to Zn deficiency is both species and variety dependent. For example, corn, beans, and fruit trees have a high sensitivity to Zn deficiency.

Chlorine

- **Soil chlorine**: In soils, chlorine is found in the form of chloride (Cl^-), a soluble anion which is contained in negligible amounts in the mineral, adsorbed and organic soil fractions. Chloride has a high mobility in soils, which enables it to undergo extensive leaching when rainfall or irrigation exceeds evapotranspiration.

- **Chloride fertilization**: About 60 lbs/acre of Cl^- per surface 2 feet of soil seems to be adequate for top yields of small grains. This amount can be provided by fertilizer or the soil. The most practical source is potassium chloride (KCl), or muriate of potash, which contains about 47% Cl. Preplant, at seeding, and topdressed applications have all been effective. Higher rates should be applied preplant or by topdressing. Since Cl^- is highly mobile in the soil, it should be managed accordingly.

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