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J. A. Silva and R. Uchida, eds. College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa, ©2000

Chapter 3

Essential Nutrients for Plant Growth: Nutrient Functions and Deficiency Symptoms

R. Uchida

Plants, like all other living things, need food for their growth and development. Plants require 16 essential elements. Carbon, hydrogen, and oxygen are derived from the atmosphere and soil water. The remaining 13 essential elements (nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, zinc, manganese, copper, boron, molybdenum, and chlorine) are supplied either from soil minerals and soil organic matter or by organic or inorganic fertilizers.

For plants to utilize these nutrients efficiently, light, heat, and water must be adequately supplied. Cultural practices and control of diseases and insects also play important roles in crop production.

Each type of plant is unique and has an optimum nutrient range as well as a minimum requirement level. Below this minimum level, plants start to show nutrient deficiency symptoms. Excessive nutrient uptake can also cause poor growth because of toxicity. Therefore, the proper amount of application and the placement of nutrients is important.

Soil and plant tissue tests have been developed to assess the nutrient content of both the soil and plants. By analyzing this information, plant scientists can determine the nutrient need of a given plant in a given soil. In addition to the levels of plant-available nutrients in soils, the soil pH plays an important role in nutrient availability and elemental toxicity (see p. 46).

This chapter describes the essential nutrients, the chemical forms in which they are available to plants, their function in plants, symptoms of their deficiencies, and recommended nutrient levels in plant tissues of selected crops.

Nitrogen

symbol: N; available to plants as nitrate (NO_3^-), and ammonium (NH_4^+) ions.

Nutrient functions

- N is biologically combined with C, H, O, and S to create amino acids, which are the building blocks of proteins. Amino acids are used in forming protoplasm, the site for cell division and thus for plant growth and development.
- Since all plant enzymes are made of proteins, N is needed for all of the enzymatic reactions in a plant.
- N is a major part of the chlorophyll molecule and is therefore necessary for photosynthesis.
- N is a necessary component of several vitamins.
- N improves the quality and quantity of dry matter in leafy vegetables and protein in grain crops.

Deficiency symptoms (p. 33)

- Stunted growth may occur because of reduction in cell division.
- Pale green to light yellow color (chlorosis) appearing first on older leaves, usually starting at the tips. Depending on the severity of deficiency, the chlorosis could result in the death and/or dropping of the older leaves. This is caused by the translocation of

N from the older to the younger tissues.
- Reduced N lowers the protein content of seeds and vegetative parts. In severe cases, flowering is greatly reduced.
- N deficiency causes early maturity in some crops, which results in a significant reduction in yield and quality.

Phosphorus

symbol: P; available to plants as orthophosphate ions (HPO_4^{2-}, $H_2PO_4^-$).

Nutrient functions

- In photosynthesis and respiration, P plays a major role in energy storage and transfer as ADP and ATP (adenosine di- and triphosphate) and DPN and TPN (di- and triphosphopyridine nucleotide).
- P is part of the RNA and DNA structures, which are the major components of genetic information.
- Seeds have the highest concentration of P in a mature plant, and P is required in large quantities in young cells, such as shoots and root tips, where metabolism is high and cell division is rapid.
- P aids in root development, flower initiation, and seed and fruit development.
- P has been shown to reduce disease incidence in some plants and has been found to improve the quality of certain crops.

Deficiency symptoms (p. 34)

- Because P is needed in large quantities during the early stages of cell division, the initial overall symptom is slow, weak, and stunted growth.
- P is relatively mobile in plants and can be transferred to sites of new growth, causing symptoms of dark to blue-green coloration to appear on older leaves of some plants. Under severe deficiency, purpling of leaves and stems may appear.
- Lack of P can cause delayed maturity and poor seed and fruit development.

Potassium

symbol: K; available to plants as the ion K^+

Nutrient functions

- Unlike N and P, K does not form any vital organic compounds in the plant. However, the presence of K is vital for plant growth because K is known to be an enzyme activator that promotes metabolism.
- K assists in regulating the plant’s use of water by controlling the opening and closing of leaf stomates, where water is released to cool the plant.
- In photosynthesis, K has the role of maintaining the balance of electrical charges at the site of ATP production.
- K promotes the translocation of photosythates (sugars) for plant growth or storage in fruits or roots.
- Through its role assisting ATP production, K is involved in protein synthesis.
- K has been shown to improve disease resistance in plants, improve the size of grains and seeds, and improve the quality of fruits and vegetables.

Deficiency symptoms (p. 35)

- The most common symptom is chlorosis along the edges of leaves (leaf margin scorching). This occurs first in older leaves, because K is very mobile in the plant.
- Because K is needed in photosynthesis and the synthesis of proteins, plants lacking K will have slow and stunted growth.
- In some crops, stems are weak and lodging is common if K is deficient.
- The size of seeds and fruits and the quantity of their production is reduced.

. . . continued on p. 49

—Color Section— Symptoms of plant nutrient deficiencies and toxicities

Photo credits

Abbreviations given for sources of the photographs are as follows:

ASHS: From *Avocado Production in California*, a slide set produced by Eugene Memmler and formerly distributed by the American Society for Horticultural Science.

APS: © The American Phytopathological Society; from *Nutrient Deficiencies and Toxicities in Crop Plants*, W.F. Bennett (editor), 1993; used with permission.

PPI: Potash & Phosphate Institute; used with permission.

USSL: USDA-ARS George E. Brown, Jr. Salinity Laboratory, Riverside, CA; eucalyptus photos courtesy of Catherine M. Grieve.

Nitrogen deficient potato plant (left) is chlorotic; plant at right is normal.

Nitrogen deficient corn; yellowing proceeds down the midrib of older leaves.

Nitrogen deficient soybean; lower leaves turn uniformly pale green, then yellow.

Nitrogen deficient cucumber fruit is misshapen and chlorotic.

Severe nitrogen deficiency in citrus.

Deficiency symptoms

- Stunted growth may occur because of reduction in cell division.
- Pale green to light yellow color (chlorosis) appearing first on older leaves, usually starting at the tips. Depending on the severity of deficiency, the chlorosis could result in the death and/or dropping of the older leaves. This is caused by the translocation of N from the older to the younger tissues.
- Reduced N lowers the protein content of seeds and vegetative parts. In severe cases, flowering is greatly reduced.
- N deficiency causes early maturity in some crops, which results in a significant reduction in yield and quality.

N


PPI

Phosphorus deficient sugarbeet plants are stunted, with dark green leaves.


Y. N. Tamimi

Phosphorus deficient corn; lower leaves become reddish-purple.


PPI

Phosphorus deficient tomato leaves have purple interveinal tissue on their undersides.


APS

Phosphorus deficient potato plants are stunted, with dark green leaves.

Deficiency symptoms

- Because P is needed in large quantities during the early stages of cell division, the initial overall symptom is slow, weak, and stunted growth.
- P is relatively mobile in plants and can be transferred to sites of new growth, causing symptoms of dark to blue-green coloration to appear on older leaves of some plants. Under severe deficiency, purpling of leaves and stems may appear.
- Lack of P can cause delayed maturity and poor seed and fruit development.

P

Potassium deficient banana; older leaves become chlorotic, then necrotic, and the tip of the midrib bends downward.

Potassium deficient tomato leaves have chlorotic and necrotic spotting.

Potassium deficient corn; margins of older leaves become chlorotic and necrotic.

Potassium deficient squash leaf edges become chlorotic and necrotic.

Deficiency symptoms

- The most common symptom is chlorosis along the edges of leaves (leaf margin scorching). This occurs first in older leaves, because K is very mobile in the plant.
- Because K is needed in photosynthesis and the synthesis of proteins, plants lacking K will have slow and stunted growth.
- In some crops, stems are weak and lodging is common if K is deficient.
- The size of seeds and fruits and the quantity of their production is reduced.

K

PPI

Calcium deficient celery; young leaves are necrotic and the growing point dies.

PPI

Calcium deficient tomato; young leaves become twisted and cupped.

Y. N. Tamimi

Calcium deficient corn leaves fail to unfold.

PPI

Calcium deficient bean leaves have chlorotic and necrotic spots.

Deficiency symptoms

- Ca is not mobile and is not translocated in the plant, so symptoms first appear on the younger leaves and leaf tips. The growing tips of roots and leaves turn brown and die.
- Ca deficiency is not often observed in plants because secondary effects of high acidity resulting from soil calcium deficiency usually limit growth, precluding expressions of Ca deficiency symptoms.
- Without adequate Ca, which in the form of calcium pectate is needed to form rigid cell walls, newly emerging leaves may stick together at the margins, which causes tearing as the leaves expand and unfurl. This may also cause the stem structure to be weakened.
- In some crops, younger leaves may be cupped and crinkled, with the terminal bud deteriorating.
- Buds and blossoms fall prematurely in some crops.

Ca

Magnesium deficient soybean; interveinal chlorosis of older leaves.

Magnesium deficient sweetpotato leaves become reddish-purple.

Magnesium deficient corn; interveinal chlorosis of older leaves.

Magnesium deficient tomato; interveinal chlorosis of older leaves.

Deficiency symptoms

- Because Mg is a mobile element and part of the chlorophyll molecule, the deficiency symptom of interveinal chlorosis first appears in older leaves. Leaf tissue between the veins may be yellowish, bronze, or reddish, while the leaf veins remain green. Corn leaves appear yellow-striped with green veins, while crops such as potatoes, tomatoes, soybeans, and cabbage show orange-yellow color with green veins.
- In severe cases, symptoms may appear on younger leaves and cause premature leaf drop.
- Symptoms occur most frequently in acid soils and soils receiving high amounts of K fertilizer or Ca.

Mg

R. L. Fox

Sulfur deficient banana; young leaves are uniformly chlorotic.

R. L. Fox

Sulfur deficient macadamia; young leaves are chlorotic.

PPI

Sulfur deficient tomato; young leaves are uniformly chlorotic.

APS

Sulfur deficient sorghum; young leaves are uniformly chlorotic.

Deficiency symptoms

- Younger leaves are chlorotic with evenly, lightly colored veins. In some plants (e.g., citrus) the older leaves may show symptoms first. However, deficiency is not commonly found in most plants.
- Growth rate is retarded and maturity is delayed.
- Plant stems are stiff, thin, and woody.
- Symptoms may be similar to N deficiency and are most often found in sandy soils that are low in organic matter and receive moderate to heavy rainfall.

S


PPI

Boron deficient radish plants are stunted, with distorted leaves.


APS

Boron deficient potato leaves have light brown edges; crinkling around the center of the leaf blade causes an upward-cupped shape; the plant's growing point dies.


M. Nishina

Boron deficient papaya fruits develop bumps.


PPI

Boron deficient tomato leaves are chlorotic, with some curling.

Deficiency symptoms

- Generally, B deficiency causes stunted growth, first showing symptoms on the growing point and younger leaves. The leaves tend to be thickened and may curl and become brittle.
- In many crops, the symptoms are well defined and crop-specific, such as:
  - peanuts: hollow hearts
  - celery: crooked and cracked stem
  - beets: black hearts
  - papaya: distorted and lumpy fruit
  - carnation: splitting of calyx
  - Chinese cabbage: midribs crack, turn brown
  - cabbage, broccoli, and cauliflower: pith in hollow stem

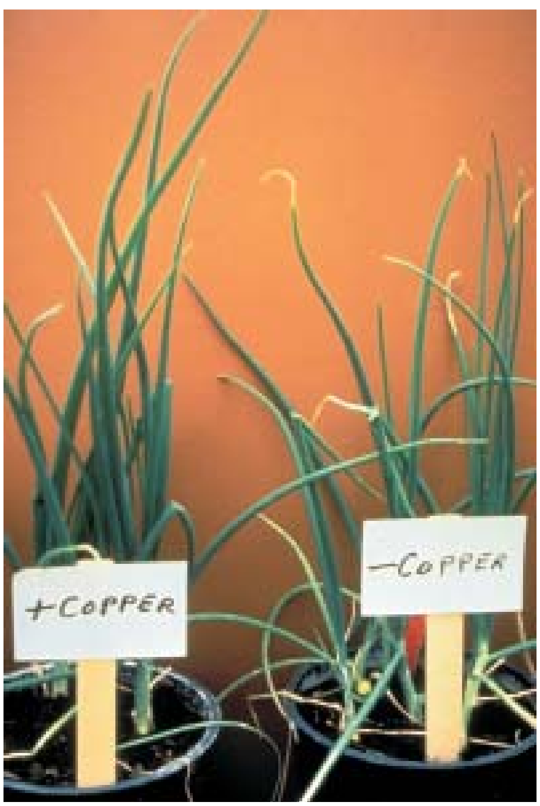
B

PPI

Copper deficient corn leaf tips bend and droop.

PPI

Copper deficient lettuce leaves are stunted and cupped, with darker tissue near the petiole.



APS

Copper deficient onion leaves have white tips and twist in spirals or right angles.

PPI

Copper deficient tomato leaves are stunted and deformed.

Deficiency symptoms
- Reduced growth, distortion of the younger leaves, and possible necrosis of the apical meristem.
- In trees, multiple sprouts occur at growing points, resulting in a bushy appearance. Young leaves becomes bleached, and eventually there is defoliation and dieback of twigs.
- In forage grasses, young leaf tips and growing points are affected first. The plant is stunted and chlorotic.

Cu


PPI

Chlorine deficient tomato; leaf edges roll upward.


APS

Chlorine deficient sugarbeet; young leaves are chlorotic.

Deficiency symptoms
- Chlorosis of younger leaves and wilting of the plant.
- Deficiency seldom occurs because Cl is found in the atmosphere and rainwater.

Cl


R. L. Fox

Iron deficient macademia; young leaves have interveinal chlorosis.


PPI

Iron deficient soybean; young leaves have interveinal chlorosis.


PPI

Iron deficient gardenia; young leaves have interveinal chlorosis.


APS

Iron deficient corn; young leaves have interveinal chlorosis.

Deficiency symptoms

- Interveinal chlorosis in younger leaves. The youngest leaves maybe white, because Fe, like Mg, is involved in chlorophyll production.
- Usually observed in alkaline or over-limed soils.

Fe


APS

Manganese deficient tomato; expanded young leaves have green veins with interveinal chlorosis.


APS

Manganese deficient soybean; young leaves have interveinal chlorosis.


APS

Manganese deficient corn; young leaves are olive-green and slightly streaked.


PPI

Manganese deficient orange; leaves develop a mottled pattern of light and dark green.

Deficiency symptoms

- Symptoms first appear as chlorosis in young tissues. Unlike Fe chlorosis symptoms, in dicots Mn chlorosis shows up as tiny yellow spots.
- In monocots, greenish-grey specks appear at the lower base of younger leaves. The specks may eventually become yellowish to yellow-orange.
- In legumes, necrotic areas develop on the cotyledons, a symptom known as marsh spots.

Mn


PPI

Molybdenum deficient onion leaves show wilting and dieback.


PPI

Molybdenum deficient grapefruit leaves have interveinal chlorosis.


PPI

Molybdenum deficient tomato leaves have interveinal chlorosis.


APS

Molybdenum deficient sugarbeet leaf has slight veining and pronounced necrotic spotting.

Deficiency symptoms

- Deficiency symptoms resemble those of N because the function of Mo is to assimilate N in the plant. Older and middle leaves become chlorotic, and the leaf margins roll inwards.
- In contrast to N deficiency, necrotic spots appear at the leaf margins because of nitrate accumulation.
- Deficient plants are stunted, and flower formation may be restricted.
- Mo deficiency can be common in nitrogen-fixing legumes.

Mo


PPI

Zinc deficient mango shoots have shortened internodes, resulting in leaf rosetting.


ASHS

Zinc deficient avocado; young leaves have interveinal chlorosis.


APS

Zinc deficient onion leaves are twisted (right); plants at left are normal.

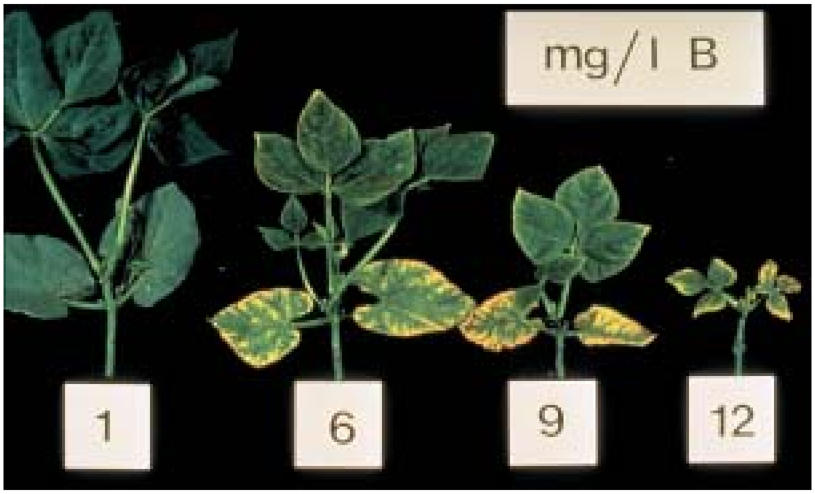

PPI

Zinc deficient corn. Young leaves have interveinal, chlorotic stripes on both sides of the midrib.

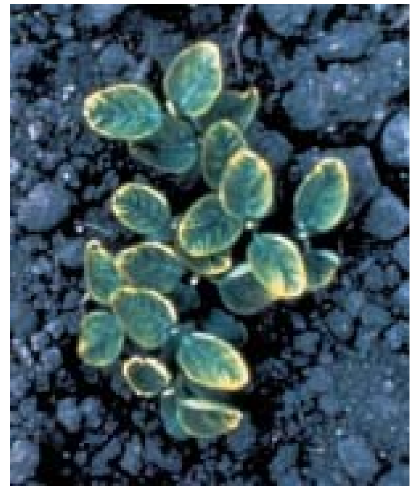
Deficiency symptoms

- Interveinal chlorosis occurs on younger leaves, similar to Fe deficiency. However, Zn deficiency is more defined, appearing as banding at the basal part of the leaf, whereas Fe deficiency results in interveinal chlorosis along the entire length of the leaf.
- In vegetable crops, color change appears in the younger leaves first. The new leaves are usually abnormally small, mottled, and chlorotic.
- In citrus, irregular interveinal chlorosis occurs with small, pointed, mottled leaves. Fruit formation is significantly reduced.
- In legumes, stunted growth with interveinal chlorosis appears on the older, lower leaves. Dead tissue drops out of the chlorotic spots.

Zn



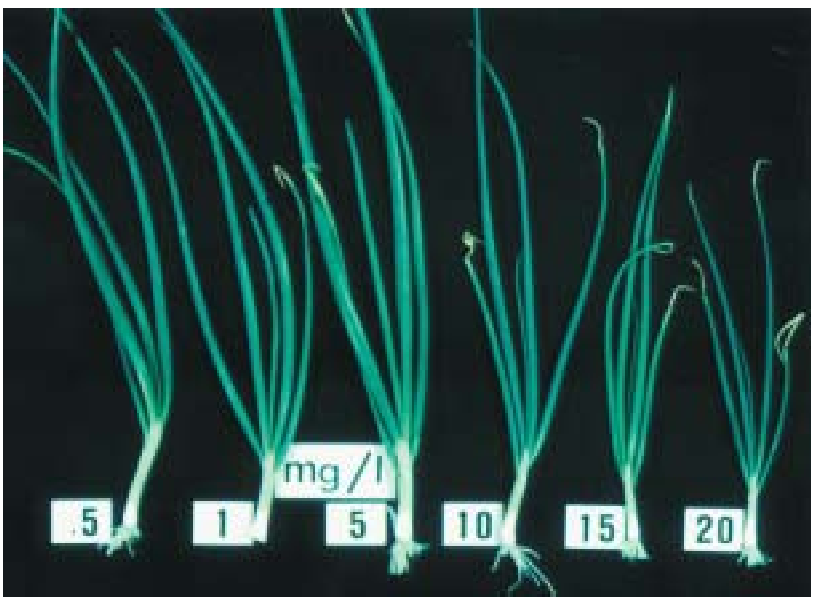
Boron toxicity in bean.
Plants are stunted and become yellow and necrotic.



Boron toxicity in soybean affecting newly opened leaves.

Elemental toxicity

B



Boron toxicity in green onion.

Boron toxicity in salt-stressed eucalyptus (*Eucalyptus camaldulensis*). Reddish areas close to margins are early symptoms; necrotic leaf tips and margins are later symptoms of boron damage.

Aluminum toxicity in tomato.
Plants are stunted; developing leaves become white.

Al

Manganese toxicity in soybean.
Growth is stunted; leaves have necrotic spots and curl upward.

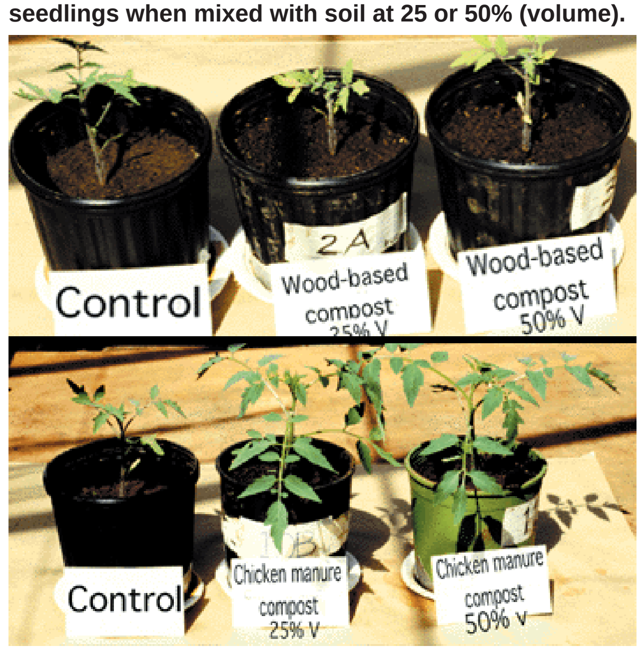
Mn

Elemental toxicity

Color photographs for Chapter 15, Organic Soil Amendments for Sustainable Agriculture

Figure 15-1. Corn field with nitrogen deficiency.

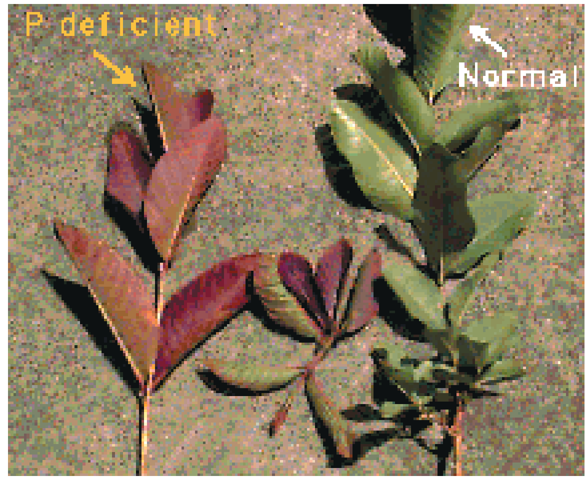
Figure 15-2. Effects of different composts on tomato seedlings when mixed with soil at 25 or 50% (volume).



Color photographs for Chapter 15 (continued)

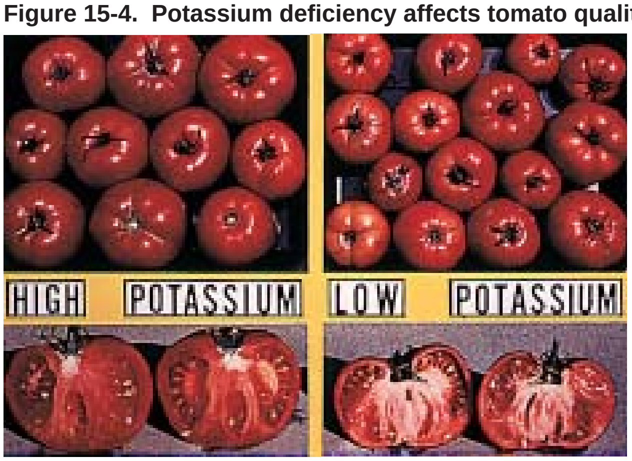
Figure 15-3. Phosphorus deficiency symptoms in corn and guava.

R.L. Fox

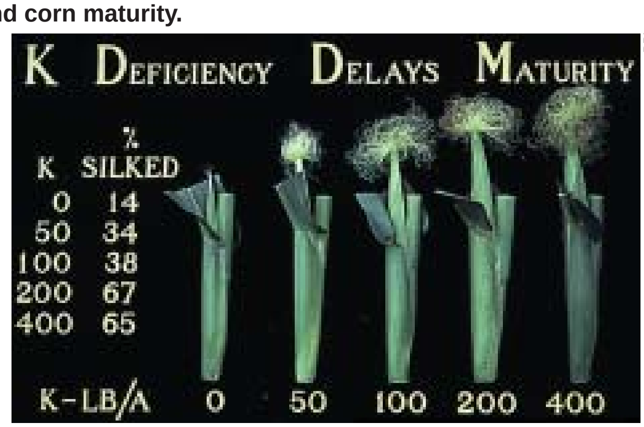


N.V. Hue

Figure 15-4. Potassium deficiency affects tomato quality and corn maturity.

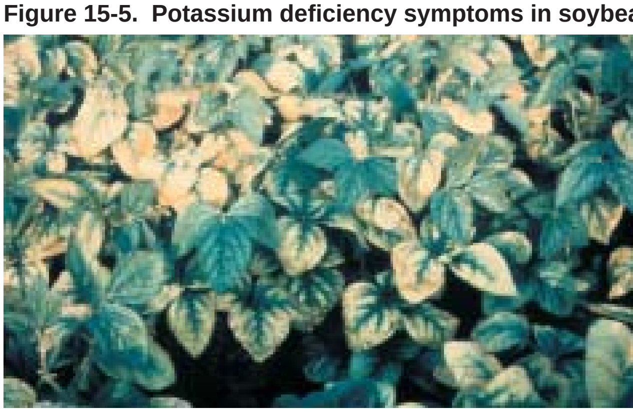


PPI



PPI

Figure 15-5. Potassium deficiency symptoms in soybean and alfalfa.



PPI

PPI

Calcium

symbol: Ca; available to plants as the ion Ca^{2+}

Nutrient functions

- Ca has a major role in the formation of the cell wall membrane and its plasticity, affecting normal cell division by maintaining cell integrity and membrane permeability.
- Ca is an activator of several enzyme systems in protein synthesis and carbohydrate transfer.
- Ca combines with anions including organic acids, sulfates, and phosphates. It acts as a detoxifying agent by neutralizing organic acids in plants.
- Ca is essential for seed production in peanuts.
- Ca indirectly assists in improving crop yields by reducing soil acidity when soils are limed.

Deficiency symptoms (p. 36)

- Ca is not mobile and is not translocated in the plant, so symptoms first appear on the younger leaves and leaf tips. The growing tips of roots and leaves turn brown and die.
- Ca deficiency is not often observed in plants because secondary effects of high acidity resulting from soil calcium deficiency usually limit growth, precluding expressions of Ca deficiency symptoms.
- Without adequate Ca, which in the form of calcium pectate is needed to form rigid cell walls, newly emerging leaves may stick together at the margins, which causes tearing as the leaves expand and unfurl. This may also cause the stem structure to be weakened.
- In some crops, younger leaves may be cupped and crinkled, with the terminal bud deteriorating.
- Buds and blossoms fall prematurely in some crops.

Magnesium

symbol: Mg; available to plants as the ion Mg^{2+}

Nutrient functions

- The predominant role of Mg is as a major constituent of the chlorophyll molecule, and it is therefore actively involved in photosynthesis.
- Mg is a co-factor in several enzymatic reactions that activate the phosphorylation processes.
- Mg is required to stabilize ribosome particles and also helps stabilize the structure of nucleic acids.
- Mg assists the movement of sugars within a plant.

Deficiency symptoms (p. 37)

- Because Mg is a mobile element and part of the chlorophyll molecule, the deficiency symptom of interveinal chlorosis first appears in older leaves. Leaf tissue between the veins may be yellowish, bronze, or reddish, while the leaf veins remain green. Corn leaves appear yellow-striped with green veins, while crops such as potatoes, tomatoes, soybeans, and cabbage show orange-yellow color with green veins.
- In severe cases, symptoms may appear on younger leaves and cause premature leaf drop.
- Symptoms occur most frequently in acid soils and soils receiving high amounts of K fertilizer or Ca.

Sulfur

symbol: S; available to plants as the sulfate ion, SO_4^{2-}

Nutrient functions

- S is essential in forming plant proteins because it is a constituent of certain amino acids.
- It is actively involved in metabolism of the B vitamins biotin and thiamine and co-enzyme A.
- S aids in seed production, chlorophyll formation, nodule formation in legumes, and stabilizing protein structure.

Deficiency symptoms (p. 38)

- Younger leaves are chlorotic with evenly, lightly colored veins. In some plants (e.g., citrus) the older leaves may show symptoms first. However, deficiency is not commonly found in most plants.
- Growth rate is retarded and maturity is delayed.
- Plant stems are stiff, thin, and woody.
- Symptoms may be similar to N deficiency and are most often found in sandy soils that are low in organic matter and receive moderate to heavy rainfall.

Boron

Symbol: B. Available to plants as borate, H_3BO_3

Nutrient functions

- B is necessary in the synthesis of one of the bases for RNA formation and in cellular activities.
- B has been shown to promote root growth.
- B is essential for pollen germination and growth of the pollen tube.
- B has been associated with lignin synthesis, activities of certain enzymes, seed and cell wall formation, and sugar transport.

Deficiency symptoms (p. 39)

- Generally, B deficiency causes stunted growth, first

showing symptoms on the growing point and younger leaves. The leaves tend to be thickened and may curl and become brittle.
- In many crops, the symptoms are well defined and crop-specific, such as:
  - peanuts: hollow hearts
  - celery: crooked and cracked stem
  - beets: black hearts
  - papaya: distorted and lumpy fruit
  - carnation: splitting of calyx
  - Chinese cabbage: midribs crack, turn brown
  - cabbage, broccoli, and cauliflower: pith in hollow stem

Copper

symbol: Cu; available to plants as the ion Cu^{++}

Nutrient functions
- Cu is essential in several plant enzyme systems involved in photosynthesis.
- Cu is part of the chloroplast protein plastocyanin, which forms part of the electron transport chain.
- Cu may have a role in the synthesis and/or stability of chlorophyll and other plant pigments.

Deficiency symptoms (p. 40)
- Reduced growth, distortion of the younger leaves, and possible necrosis of the apical meristem.
- In trees, multiple sprouts occur at growing points, resulting in a bushy appearance. Young leaves become bleached, and eventually there is defoliation and dieback of twigs.
- In forage grasses, young leaf tips and growing points are affected first. The plant is stunted and chlorotic.

Chlorine

symbol: Cl; available to plants as the chloride ion, Cl^-

Nutrient functions
- Cl is essential in photosynthesis, where it is involved in the evolution of oxygen.
- Cl increases cell osmotic pressure and the water content of plant tissues.
- Cl is found in many bacteria and fungi.
- Cl reduces the severity of certain fungal diseases, e.g., take-all disease of wheat.

Deficiency symptoms (p. 41)
- Chlorosis of younger leaves and wilting of the plant.
- Deficiency seldom occurs because Cl is found in the atmosphere and rainwater.

Iron

symbol: Fe; available to plants as Fe^{2+}, Fe^{3+}

Nutrient functions
- Fe is essential in the heme enzyme system in plant metabolism (photosynthesis and respiration). The enzymes involved include catalase, peroxidase, cytochrome oxidase, and other cytochromes.
- Fe is part of protein ferredoxin and is required in nitrate and sulfate reductions.
- Fe is essential in the synthesis and maintenance of chlorophyll in plants.
- Fe has been strongly associated with protein metabolism.

Deficiency symptoms (p. 42)
- Interveinal chlorosis in younger leaves. The youngest leaves maybe white, because Fe, like Mg, is involved in chlorophyll production.
- Usually observed in alkaline or over-limed soils.

Manganese

symbol: Mn; available to plants as Mn^{2+}, Mn^{3+}

Nutrient functions
- Mn primarily functions as part of the plant enzyme system, activating several metabolic functions. It is a constituent of pyruvate carboxylase.
- Mn is involved in the oxidation-reduction process in photosynthesis.
- Mn is necessary in Photosystem II, where it participates in photolysis.
- Mn activates indole acetic acid oxidase, which then oxidizes indole acetic acid in plants.

Deficiency symptoms (p. 43)
- Symptoms first appear as chlorosis in young tissues. Unlike Fe chlorosis symptoms, in dicots Mn chlorosis shows up as tiny yellow spots.
- In monocots, greenish-grey specks appear at the lower base of younger leaves. The specks may eventually become yellowish to yellow-orange.
- In legumes, necrotic areas develop on the cotyledons, a symptom known as marsh spots.

Molybdenum

symbol: Mo; available to plants as molybdate, MoO_4

Nutrient functions
- Mo is a necessary component of two major enzymes in plants, nitrate reductase and nitrogenase, which

are required for normal assimilation of N.
- Mo is required by some soil microorganisms for nitrogen fixation in soils.

Deficiency symptoms (p. 44)
- Deficiency symptoms resemble those of N because the function of Mo is to assimilate N in the plant. Older and middle leaves become chlorotic, and the leaf margins roll inwards.
- In contrast to N deficiency, necrotic spots appear at the leaf margins because of nitrate accumulation.
- Deficient plants are stunted, and flower formation may be restricted.
- Mo deficiency can be common in nitrogen-fixing legumes.

Zinc
symbol: Zn; available to plants as Zn^{++}

Nutrient functions
- Zn is required in the synthesis of tryptophan, which in turn is necessary for the formation of indole acetic acid in plants.
- Zn is an essential component of several metallo-enzymes in plants (variety dehydorgenases) and therefore is necessary for several different function in plant metabolism.
- The enzyme carbonic anhydrase is specifically activated by Zn.
- Zn has a role in RNA and protein synthesis.

Deficiency symptoms (p. 45)
- Interveinal chlorosis occurs on younger leaves, similar to Fe deficiency. However, Zn deficiency is more defined, appearing as banding at the basal part of the leaf, whereas Fe deficiency results in interveinal chlorosis along the entire length of the leaf.
- In vegetable crops, color change appears in the younger leaves first. The new leaves are usually abnormally small, mottled, and chlorotic.
- In citrus, irregular interveinal chlorosis occurs with small, pointed, mottled leaves. Fruit formation is significantly reduced.
- In legumes, stunted growth with interveinal chlorosis appears on the older, lower leaves. Dead tissue drops out of the chlorotic spots.

The nitrogen cycle

N inputs

Atmospheric nitrogen is converted to forms available to plants through natural atmospheric activity, industrial processes, and biological fixation.

Atmospheric nitrogen (N_2) is a gas at normal atmospheric temperatures and is not directly available to higher plants. Before plants can use N, it must be converted to nitrate (NO_3^-) or ammonia (NH_4^+). Some N is converted to usable forms when lightning's energy breaks the strong bond of the N_2 gas molocule. The resulting oxide forms of N can acquire hydrogen from atmospheric moisture and be precipitated as NH_4^+ in rainfall.

N_2 can also be converted industrially. The gas molocule is destabilized by putting air under great heat and pressure and injecting a hydrogen source (usually natural gas, or methane) to form ammonium (NH_3), which is the building-block of the various inorganic N fertilizers. Because the process uses so much energy—usually fossil-fuel based—inorganic N fertilizers are relatively expensive.

N_2 can be converted by rhizobia bacteria that live in symbiosis with legumes. The rhizobia use enzymatic processes to break the N_2 bond. In addition to rhizobia, there are other microorganisms that can convert N_2 to NO_3^-, either in symbiosis (e.g., *Frankia*, *Anabaena*) or in free-living forms (e.g., *Azotobacter*, various actinomycetes).

Organic nitrogen compounds are converted to plant-available forms when sources such as animal manures and plant residues are naturally degraded in the soil in a process known as mineralization. First, proteins are transformed by microorganisms to their constituent amines and amino acids by *aminization*:

$$\text{Protein} + H_2O = R\text{-}NH_2 + CO_2 + \text{energy}$$

Then the amines and amino acids are *ammonified* by other organisms:

$$R\text{-}NH_2 + H_2O = NH_3 + R\text{-}OH + \text{energy}$$
$$NH_3 + H_2O = NH_4^+ + OH^-$$

Still other soil microorganisms oxidize ammonium (NH_4^+) to nitrate (NO_3^-) in a two-step process called *nitrification*. NH_4^+ is converted to nitrite (NO_2^-) by *Nitrosomonas* bacteria:

$$2HN_4^+ + 3O_2 = 2NO_2^- + 2H_2O + 4H^+$$

Then nitrite is converted to nitrate by *Nitrobacter* bacteria:

$$2NO_2^- + O_2 = 2\ NO_3^-$$

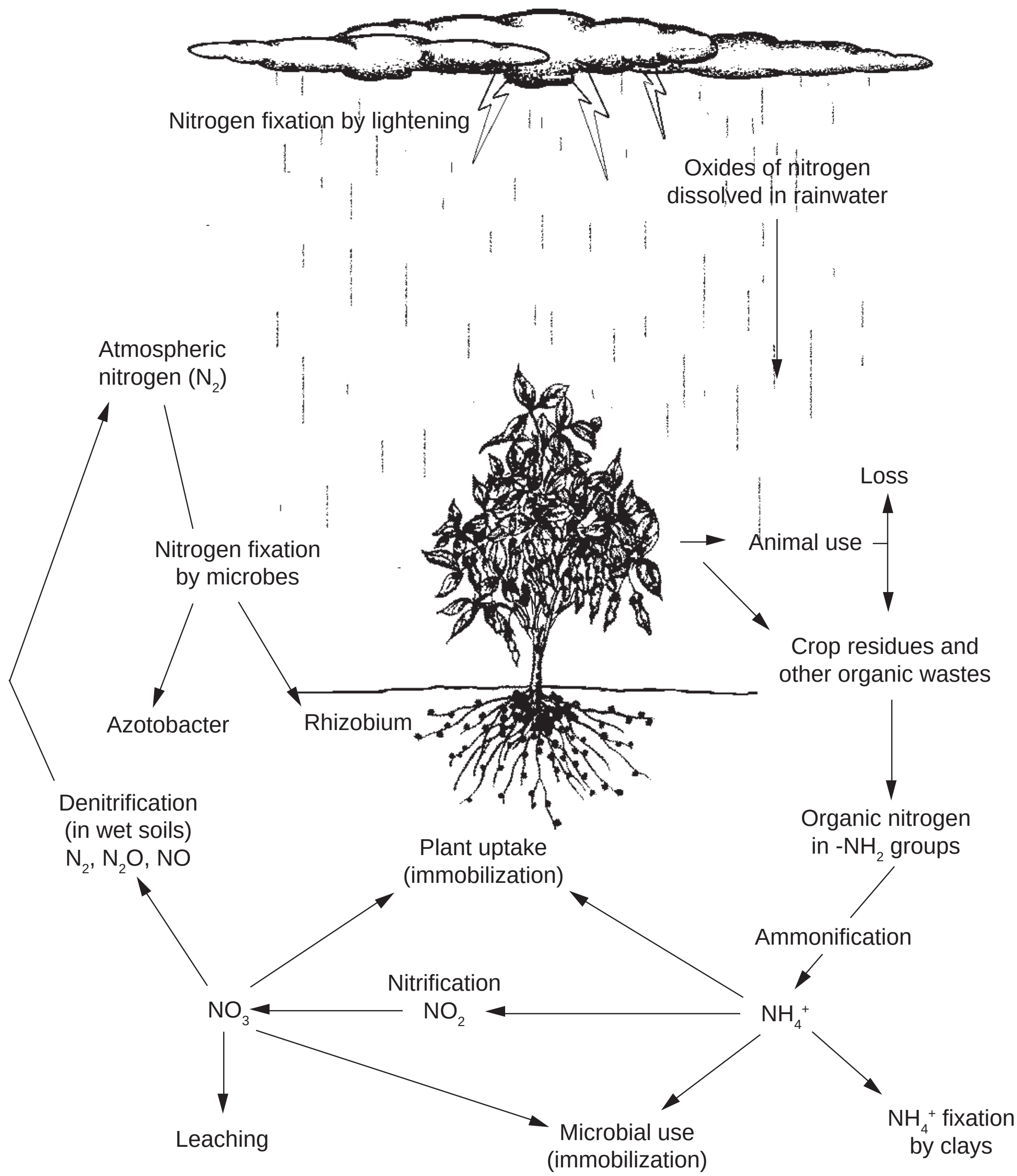
Nitrogen is applied as fertilizer in organic forms as animal manures, composts, and green manure crops. Inorganic N fertilizers are available in liquid, granular, and slow-release formulations. Ammonium-N fertilizers delay leaching because NH_4^+ is held on the soil exchange complex. When NH_4^+ is converted to NO_3^-, N is more subject to leaching loss. Urea fertilizer leaches readily until it is converted in the soil to NH_4^+ by the naturally occuring enzyme urease, usually within a few days of application.

N losses

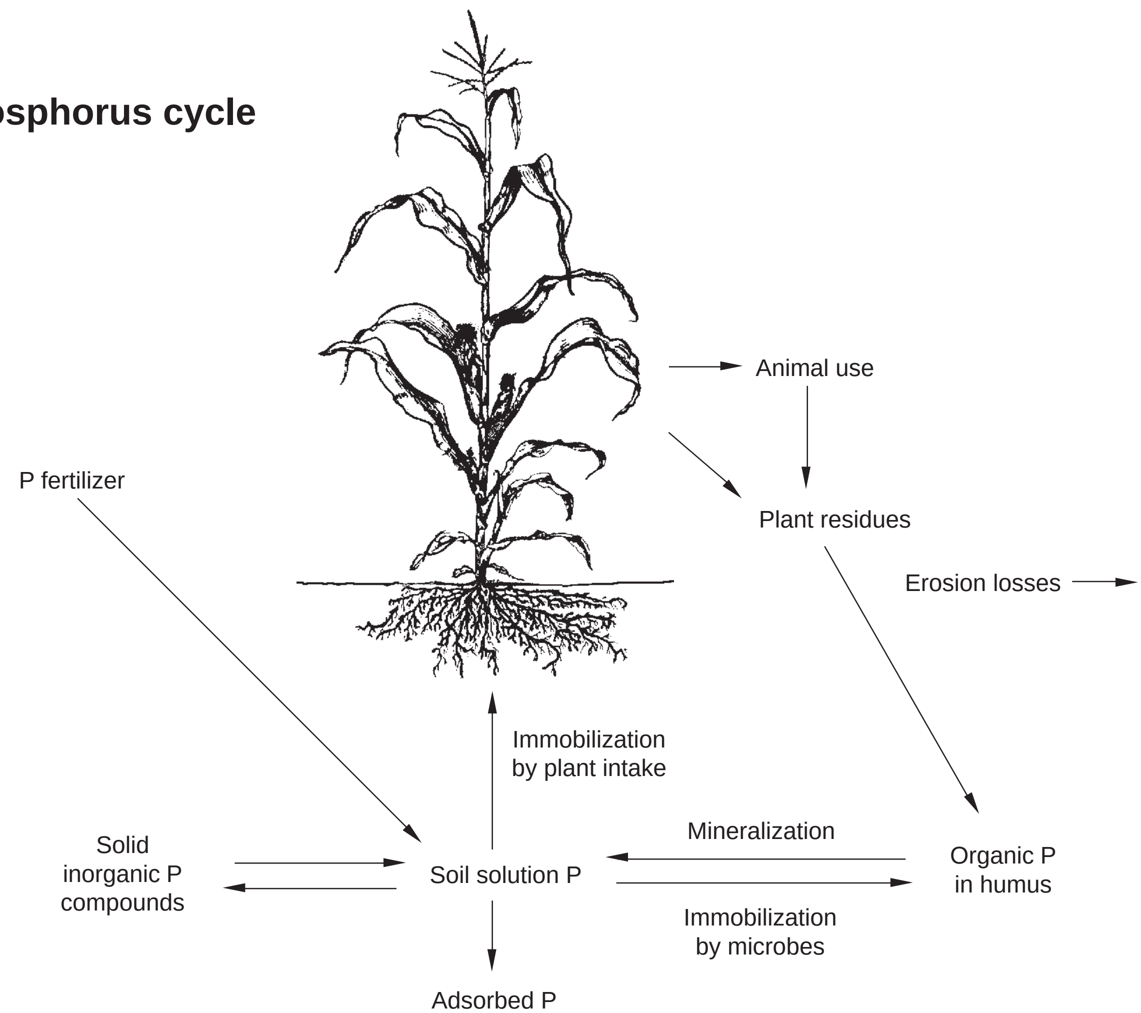
Nitrogen is removed when crops are harvested, and it is also lost by leaching of nitrate ions during periods of heavy rain or over-irrigation. Most soils have only small amounts of positive electrical charge on their exchange complex with which to hold the negatively charged nitrate ion. If NO_3^- is not taken up by plants, it can be leached below the root zone and into groundwaters. Careful planning of irrigations and the amount and timing of N fertilizer applications is necessary to avoid groundwater contamination. Monitoring the crop water balance can help to conserve irrigation water and fertilizer and protect the environment.

Nitrogen can be lost to the atmosphere by volatilization. Under alkaline soil conditions, ammonia can escape from the soil surface. Under anaerobic conditions, denitrification occurs when soil bacteria reduce NO_3^- to N_2 gas and nitrous oxide gas (N_2O), which escape to the atmosphere.

The nitrogen cycle



The phosphorus cycle



The phosphorus cycle

P inputs

Plants absorb P from the soil solution as phosphate in the form $H_2PO_4^-$ at soil pH below 7.2 and HPO_4^{2-} at pH above 7.2. Phosphate dissolved in the soil water exists in an equilibrium between P in solution, labile P, and nonlabile P :

$$\text{Soil solution P} \longleftrightarrow \text{Labile P} \longleftrightarrow \text{Nonlabile P}$$

Labile P is plant-available P that is adsorbed loosely by the soil but can be desorbed into solution. Nonlabile P has formed stable and relatively insoluble compounds with the soil, and it is not available to plants.

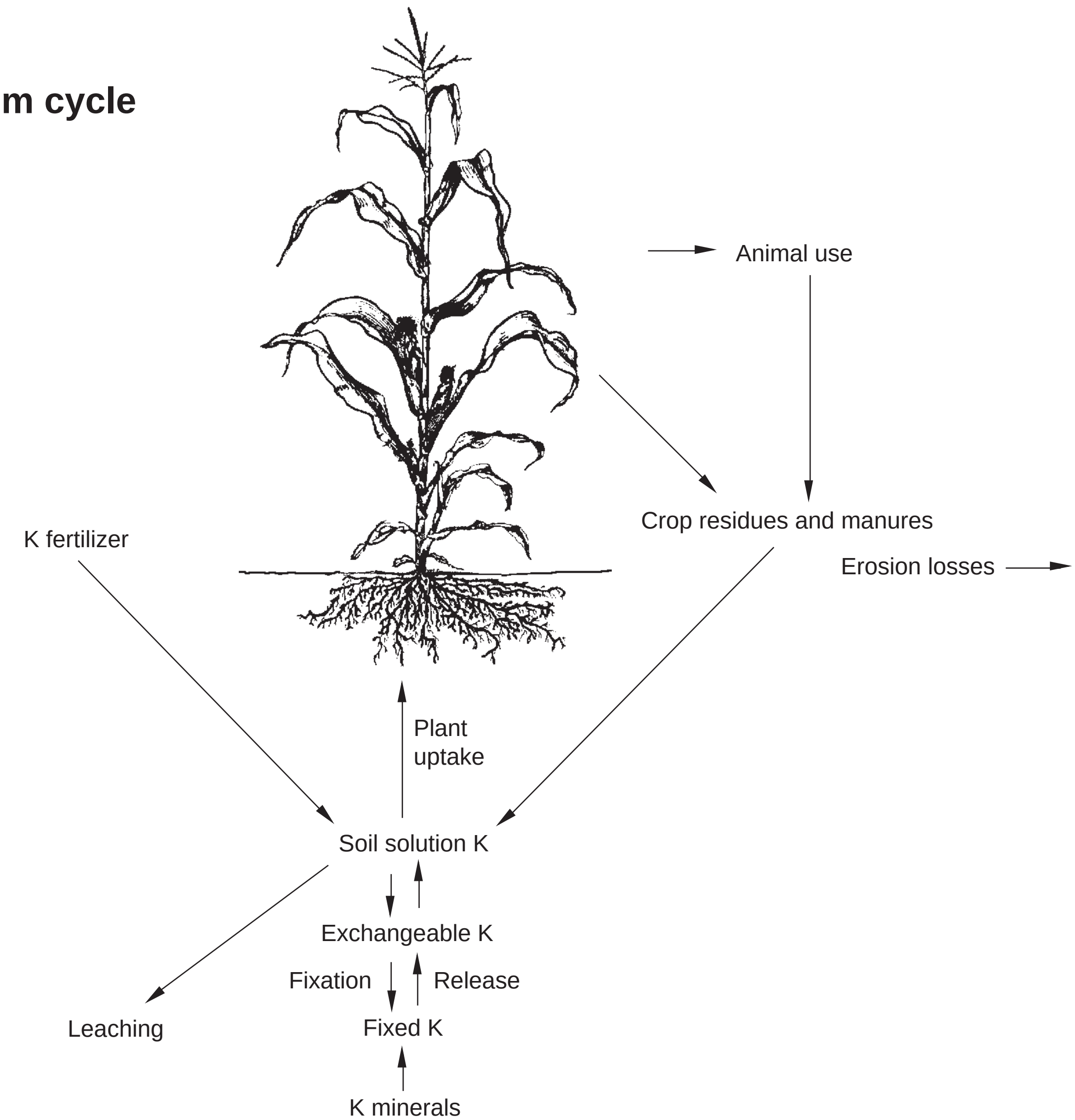
Decomposition of soil minerals through weathering releases P into the soil solution, but the process is gradual. In acid soils, iron and aluminum phosphates are found, while in neutral, calcareous soils, octacalcium phosphate and apatite are found.

Mineralization by microorganisms of P associated with organic matter is important in maintaining levels of P in the soil solution.

P losses

Phosphorus is removed in harvested crop materials, but in lesser amounts than nitrogen or potassium. Soil erosion can be a major source of P loss, because P is held tightly by soils. If soil erosion in not controlled, phosphate pollution of the environment can result. Phosphate can be strongly “fixed” (adsorbed) by soils. Under acidic soil conditions, P combines with iron and aluminum. Under neutral or alkaline soil conditions, P combines with calcium.

The potassium cycle



The potassium cycle

K inputs

Potassium is released into the soil solution from clay minerals. The quantities and rates of release depend on the soil mineralogy, rainfall, and temperature, and can also be influenced by crop management. Most soils in Hawaii have only small quantities of potassium-bearing clay minerals, due to intense weathering.

Inorganic fertilizer K is sold in various formulations including liquid, granular, and slow-release. Relatively small amounts of K become available from decomposition of manures and crop residues. Certain well waters used for irrigation in Hawaii have relatively high amounts of K.

K losses

Since plants take up large amounts of K, its removal in harvested crops can be significant. Leaching of K can occur, particularly in coarse-textured soils, if fertilizers and irrigation water are applied carelessly. K losses with eroded soil are not usually serious and can be minimized with good soil management practices.

Under conditions where K has been severly depleted from the soil minerals, K fixation can occur. K can be fixed in the structural lattices of 2:1 clay minerals, such as illite and vermiculite. Fixed K is not readily available to plants, but may be gradually released for plant uptake.