Plant Mineral Nutrition

Essential Elements

Identification, Macro- / Micronutrients, Yield and Mineral Nutrition

Mineral Deficiencies

Visible Symptoms, Phloem Mobility, Plant Defense

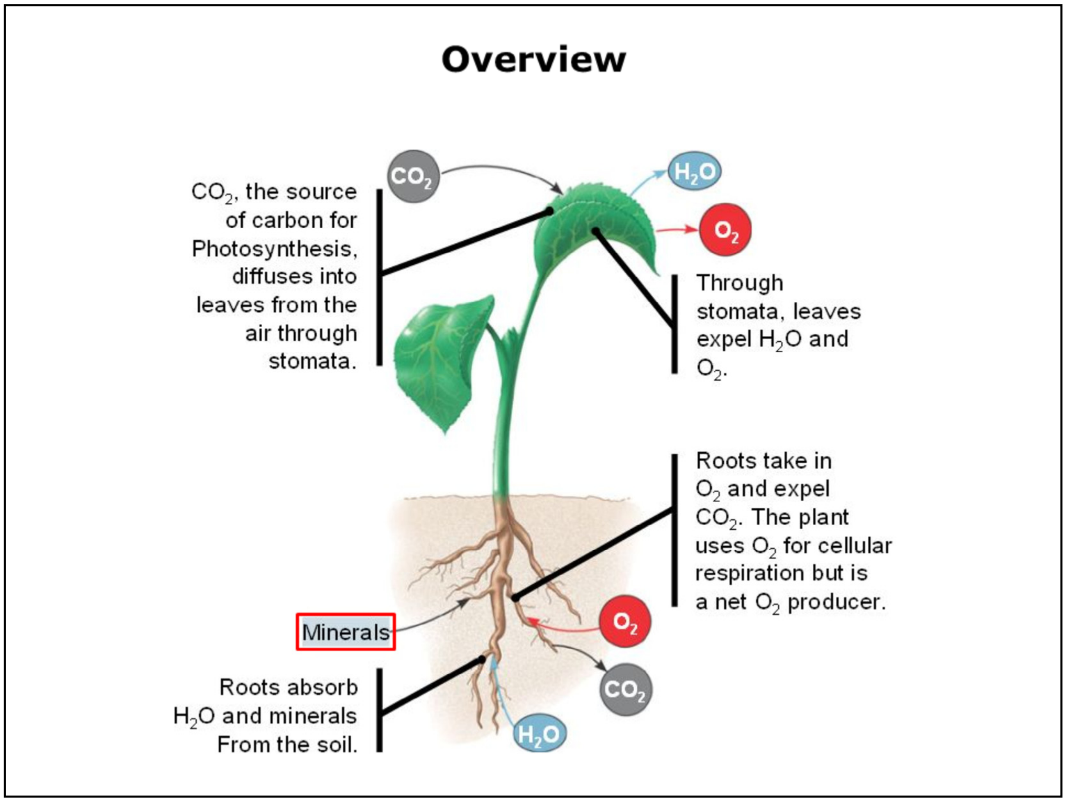
Soil

Soil Types, Cation Exchange, pH Effects, Fertilizer, Salt Stress

Roots and Mycorrhizae

Rhizosphere, Depletion Zone, Ecto- and Endomycorrhiza

Lecture Content

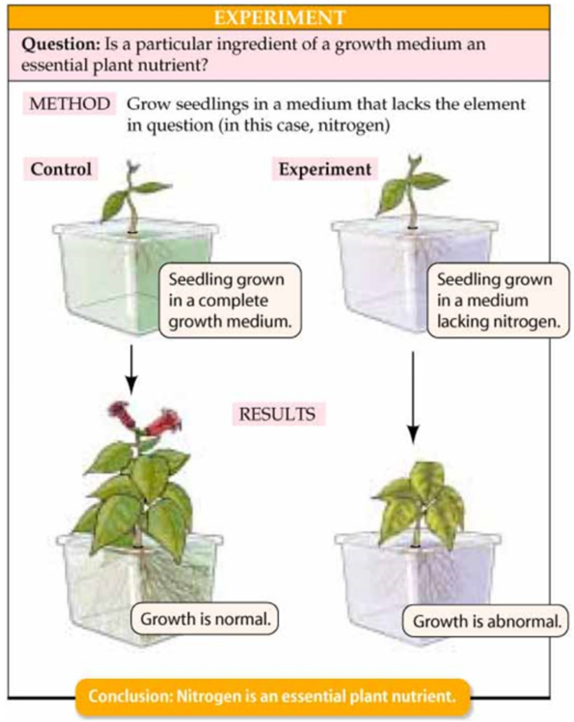


The Uptake of Nutrients by a Plant: an Overview.

Roots absorb water and minerals from the soil, with mycorrhizae and root hairs greatly increasing the surface area for absorption. Carbon dioxide, the source of carbon for photosynthesis, diffuses into leaves from the surrounding air through stomata. (Plants also need O_2 for cellular respiration, although the plant is a net producer of O_2.) From these inorganic nutrients the plant can produce all of its own organic material.

Plants are Autotrophs

Essential Element



How to Identify Essential Elements

Using hydroponic culture to identify essential nutrients: In the technique called hydroponic culture (see below), a researcher bathes the roots of plants in solutions of various minerals dissolved in known concentrations. Aerating the water provides the roots with oxygen for cellular respiration. A particular mineral, such as potassium, can be omitted from the culture medium to test whether it is essential to the plant. If the element deleted from the mineral solution is an essential nutrient, then the incomplete medium will cause plants to become abnormal in appearance compared with controls grown in a complete mineral medium. The most common symptoms of mineral deficiency are stunted growth and discolored leaves. The environment in such experiments must be rigorously controlled because some essential elements are needed in only tiny amounts, and may be present in sufficient quantities as contaminants.

Essential Elements are …

According to Arnon & Stout (1939) for an element to be considered essential three criteria must be met:

1. A given plant must be unable to complete its life cycle in the absence of the mineral element.
2. The function of the element must not be replaceable by another mineral element.
3. The element must be directly involved in plant metabolism – for example as a cofactor of an enzyme.

Essential Element - Definition

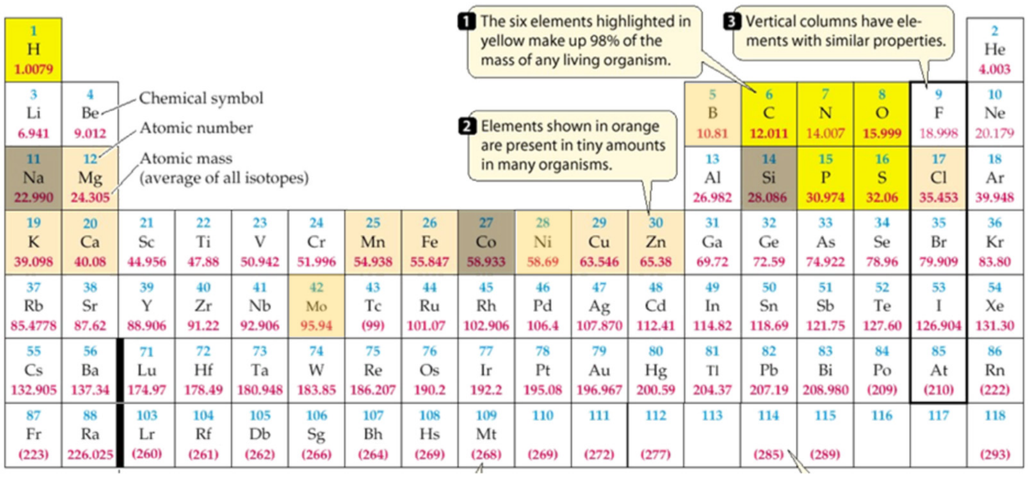
Modified from Marschner (2nd ed.) p. 4

or from Life 6th ed. (Purves et al.).

There are three criteria for calling a mineral nutrient an **essential element**:

- The element must be *necessary* for normal growth and reproduction.
- The element cannot be *replaceable* by another element.
- The requirement must be *direc*t—that is, not the result of an indirect effect, such as the need to relieve toxicity caused by another substance.

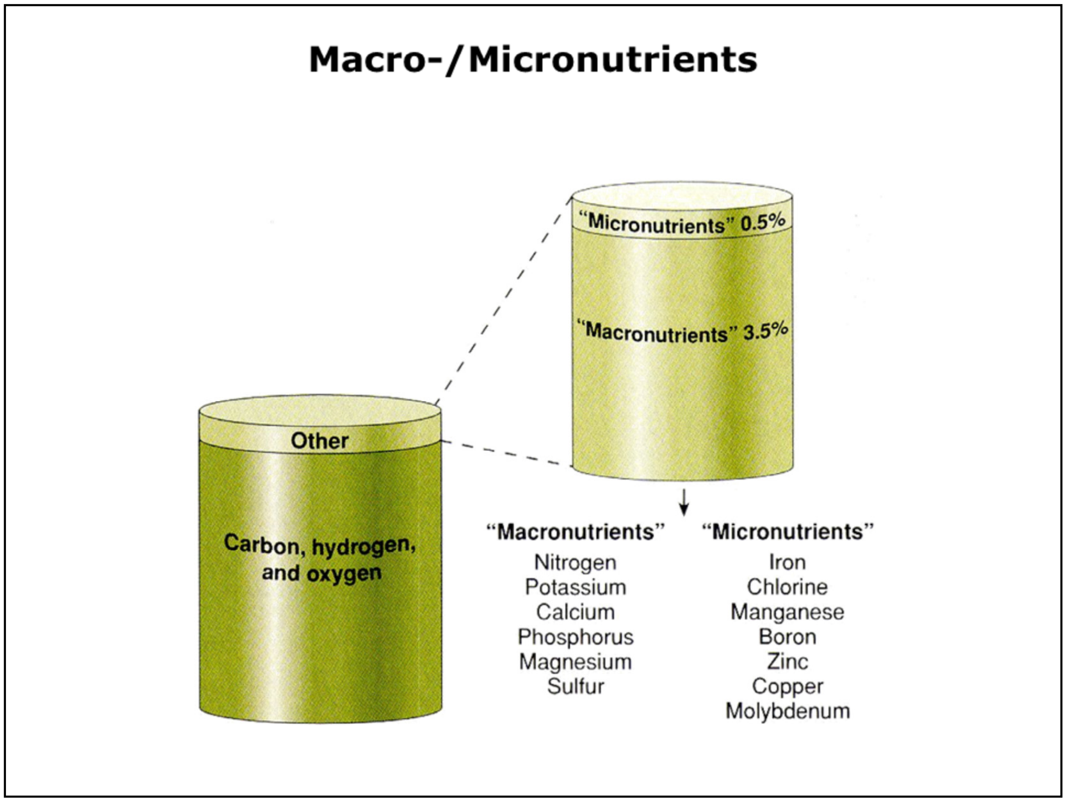
Periodic Table



The Periodic Table

The periodic table groups the elements according to their physical and chemical properties. Here those elements essential for plant and / or animal life are marked.

For plants H, B, C, N, O, Mg, P, S, Cl, K, Ca, Mn, Fe, Ni, Cu, Zn, and Mo are essential elements. Na, Si, and Co are beneficial elements. Beneficial elements are mineral elements which either stimulate growth but are not essential or which are essential only for certain plant species, or under specific conditions.



Macronutrients - Micronutrients

The proportional weights of various elements in plants. Macronutrients and micronutrients together total only 4% of the total dry weight of the plant, but they are essential to the plant's life and growth.

Plant tissues need macronutrients in concentrations of at least 1 gram per kilogram of their dry matter, and they need micronutrients in concentrations of less than 100 milligrams per kilogram of their dry matter.

Tissue Levels I

TABLE 5.1
Tissue levels of essential elements required by most plants (*Part 1*)

Element	Chemical symbol	Concentration in dry matter (% or ppm)[a]	Relative number of atoms with respect to molybdenum
Obtained from water or carbon dioxide			
Hydrogen	H	6	60,000,000
Carbon	C	45	40,000,000
Oxygen	O	45	30,000,000
Obtained from the soil			
Macronutrients			
Nitrogen	N	1.5	1,000,000
Potassium	K	1.0	250,000
Calcium	Ca	0.5	125,000
Magnesium	Mg	0.2	80,000
Phosphorus	P	0.2	60,000
Sulfur	S	0.1	30,000
Silicon	Si	0.1	30,000

Source: Epstein 1972, 1999.

[a]The values for the nonmineral elements (H, C, O) and the macronutrients are percentages. The values for micronutrients are expressed in parts per million.

Tissue Levels of Essential Elements

Tissue Levels II

TABLE 5.1
Tissue levels of essential elements required by most plants (*Part 2*)

Element	Chemical symbol	Concentration in dry matter (% or ppm)[a]	Relative number of atoms with respect to molybdenum
Micronutrients			
Chlorine	Cl	100	3,000
Iron	Fe	100	2,000
Boron	B	20	2,000
Manganese	Mn	50	1,000
Sodium	Na	10	400
Zinc	Zn	20	300
Copper	Cu	6	100
Nickel	Ni	0.1	2
Molybdenum	Mo	0.1	1

Source: Epstein 1972, 1999.

[a]The values for the nonmineral elements (H, C, O) and the macronutrients are percentages. The values for micronutrients are expressed in parts per million.

Tissue Levels of Essential Elements

Biochemical Functions I

TABLE 5.2
Classification of plant mineral nutrients according to biochemical function (*Part 1*)

Mineral nutrient	Functions
Group 1	**Nutrients that are part of carbon compounds**
N	Constituent of amino acids, amides, proteins, nucleic acids, nucleotides, coenzymes, hexosamines, etc.
S	Component of cysteine, cystine, methionine. Constituent of lipoic acid, coenzyme A, thiamine pyrophosphate, glutathione, biotin, 5′-adenylylsulfate, and 3′-phosphoadenosine.
Group 2	**Nutrients that are important in energy storage or structural integrity**
P	Component of sugar phosphates, nucleic acids, nucleotides, coenzymes, phospholipids, phytic acid, etc. Has a key role in reactions that involve ATP.
Si	Deposited as amorphous silica in cell walls. Contributes to cell wall mechanical properties, including rigidity and elasticity.
B	Complexes with mannitol, mannan, polymannuronic acid, and other constituents of cell walls. Involved in cell elongation and nucleic acid metabolism.

Source: After Evans and Sorger 1966 and Mengel and Kirkby 2001.

Biochemical Function of Essential Elements

Biochemical Functions II

TABLE 5.2
Classification of plant mineral nutrients according to biochemical function (*Part 2*)

Mineral nutrient	Functions
Group 3	**Nutrients that remain in ionic form**
K	Required as a cofactor for more than 40 enzymes. Principal cation in establishing cell turgor and maintaining cell electroneutrality.
Ca	Constituent of the middle lamella of cell walls. Required as a cofactor by some enzymes involved in the hydrolysis of ATP and phospholipids. Acts as a second messenger in metabolic regulation.
Mg	Required by many enzymes involved in phosphate transfer. Constituent of the chlorophyll molecule.
Cl	Required for the photosynthetic reactions involved in O_2 evolution.
Mn	Required for activity of some dehydrogenases, decarboxylases, kinases, oxidases, and peroxidases. Involved with other cation-activated enzymes and photosynthetic O_2 evolution.
Na	Involved with the regeneration of phosphoenolpyruvate in C_4 and CAM plants. Substitutes for potassium in some functions.

Source: After Evans and Sorger 1966 and Mengel and Kirkby 2001.

Biochemical Function of Essential Elements

Potassium (K^+) Uptake Drives Plant Growth (MOVIE)

K^+ is the ion with the highest concentration in plant cells (under normal mineral nutrition). K^+ compensates the negative charges of anionic macromolecules and anionic metabolites. It contributes significantly to the solute potential of a plant cell and thus affects water uptake and turgor pressure. The latter is the driving force for plant cell extension. So, K^+ uptake drives plant growth.

Biochemical Functions III

TABLE 5.2
Classification of plant mineral nutrients according to biochemical function (*Part 3*)

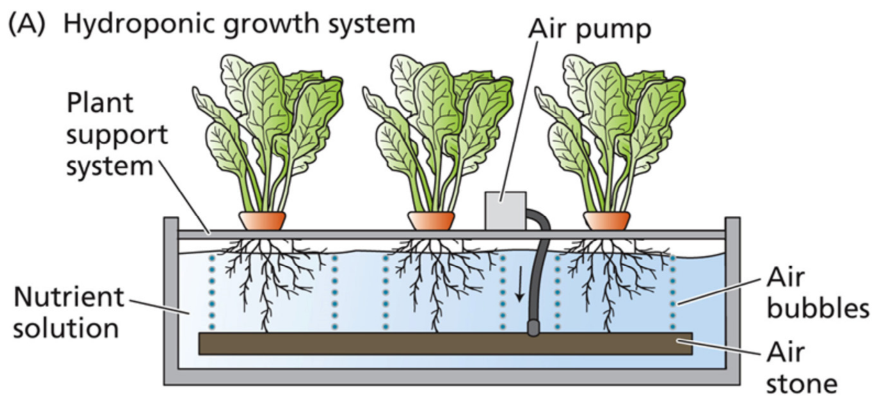
Mineral nutrient	Functions
Group 4	**Nutrients that are involved in redox reactions**
Fe	Constituent of cytochromes and nonheme iron proteins involved in photosynthesis, N_2 fixation, and respiration.
Zn	Constituent of alcohol dehydrogenase, glutamic dehydrogenase, carbonic anhydrase, etc.
Cu	Component of ascorbic acid oxidase, tyrosinase, monoamine oxidase, uricase, cytochrome oxidase, phenolase, laccase, and plastocyanin.
Ni	Constituent of urease. In N_2-fixing bacteria, constituent of hydrogenases.
Mo	Constituent of nitrogenase, nitrate reductase, and xanthine dehydrogenase.

Source: After Evans and Sorger 1966 and Mengel and Kirkby 2001.

Metals as Micronutrients Involved in Redox Reactions

Most of the metal ions taken up by plants are needed as cofactors in enzymes catalyzing redox reactions, such as the proteins involved in photosynthetic or respiratory electron transport.

Hydroponic Farming

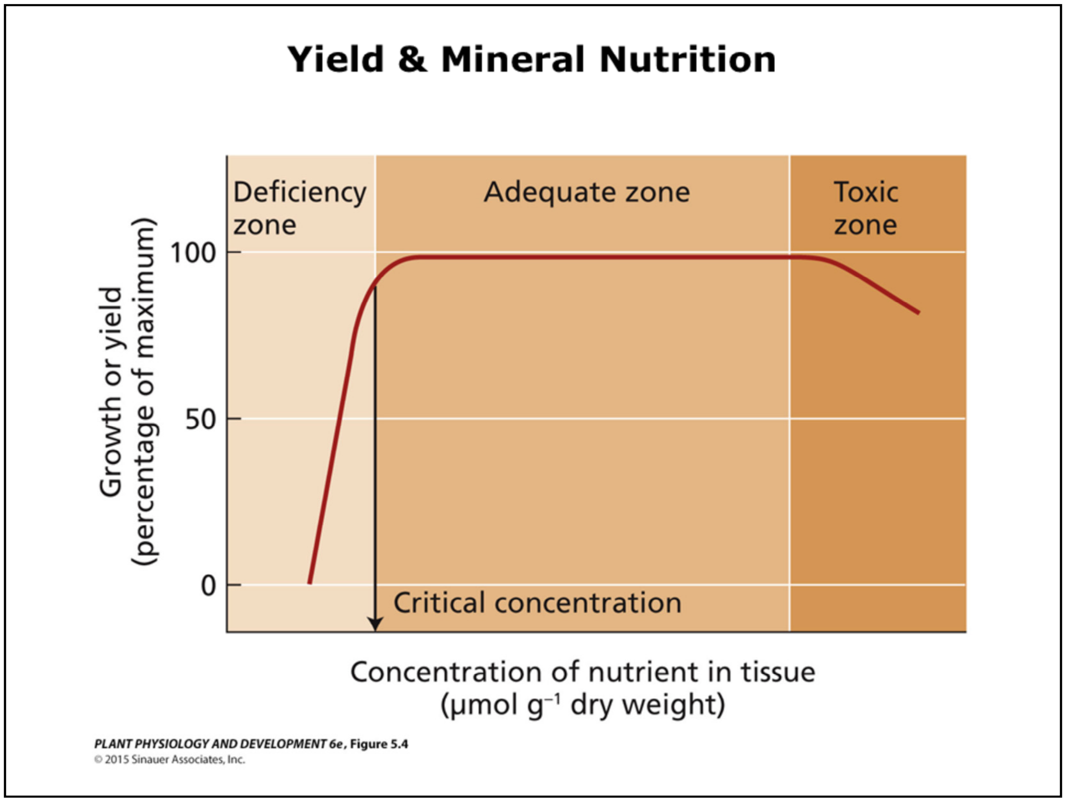


PLANT PHYSIOLOGY AND DEVELOPMENT 6e, Figure 5.2 (Part 1)

Nutrient Solutions Can Sustain Rapid Plant Growth

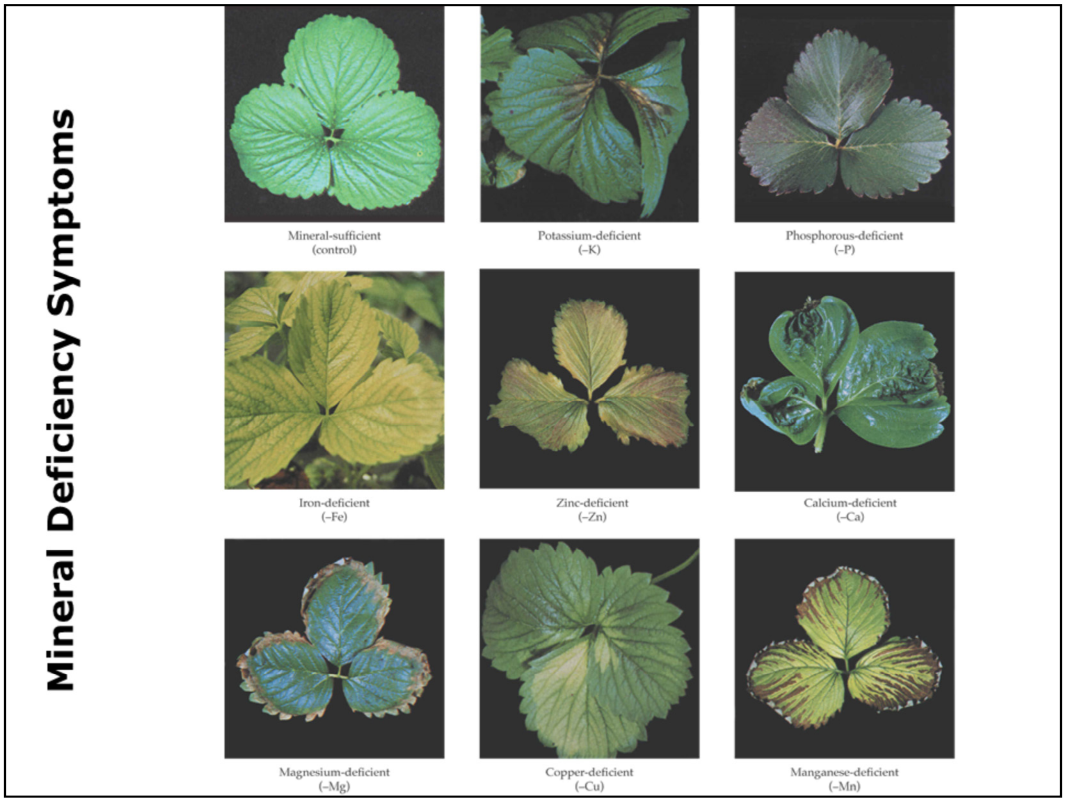
Hydroponic and other systems (see Fig. 5.3 of textbook) for growing plants in nutrient solutions in which composition and pH can be automatically controlled. In a hydroponic system, the roots are immersed in the nutrient solution, and air is bubbled through the solution.

(Compare Table 5.3 of textbook)



Yield as a Function of Nutrient Content

Relationship between yield (or growth) and the nutrient content of the plant tissue. The yield parameter may be expressed in terms of shoot dry weight or height. The deficiency, adequate, and toxic zones are indicated on the graph. To yield data of this type, plants are grown under conditions in which the concentration of one essential nutrient is varied while all others are in adequate supply. The effect of varying the concentration of this nutrient during plant growth is reflected in the growth or yield. The critical concentration for that nutrient is the concentration below which yield or growth is reduced.



Deficiency Symptoms Reveal Inadequate Nutrition

Before a plant that is deficient in an essential element dies, it usually displays characteristic deficiency symptoms. Such symptoms help horticulturists diagnose mineral nutrient deficiencies in plants.

Shown here: **Visible Deficiency Symptoms**

Symptoms observed in leaves of strawberry plants deficient in K, P, Fe, Zn, Ca, Mg, Cu, or Mn. A leaf from a mineral-sufficient control plant is also shown.

Phloem Mobility

Table 3.9
Characteristic Differences in Mobility of Mineral Nutrients in the Phloem

High Mobility	Intermediate Mobility	Low Mobility
Potassium	Iron	Calcium
Magnesium	Zinc	Manganese
Phosphorus	Copper	
Sulfur	Boron	
Nitrogen (amino-N)	Molybdenum	
Chlorine		
(Sodium)		

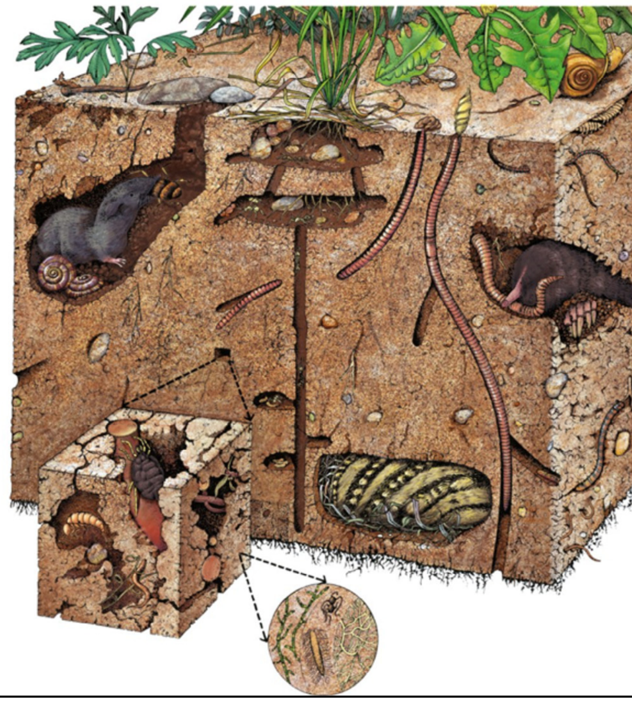
Phloem Mobility

Visible symptoms of mineral deficiencies are closely related to the phloem mobility of the respective mineral element. Symptoms appear preferentially on either older or younger leaves, depending on whether the mineral nutrient in question is readily retranslocated. Phloem mobile elements under mineral deficiency are retranslocated from older to younger leaves giving rise to visible deficiency symptoms in older leaves first. Phloem immobile mineral elements cannot sufficiently be remobilized and visible deficiency symptoms appear first in young growing leaves that have the highest demand in mineral nutrients.

Sensitivity to Pathogen Attack

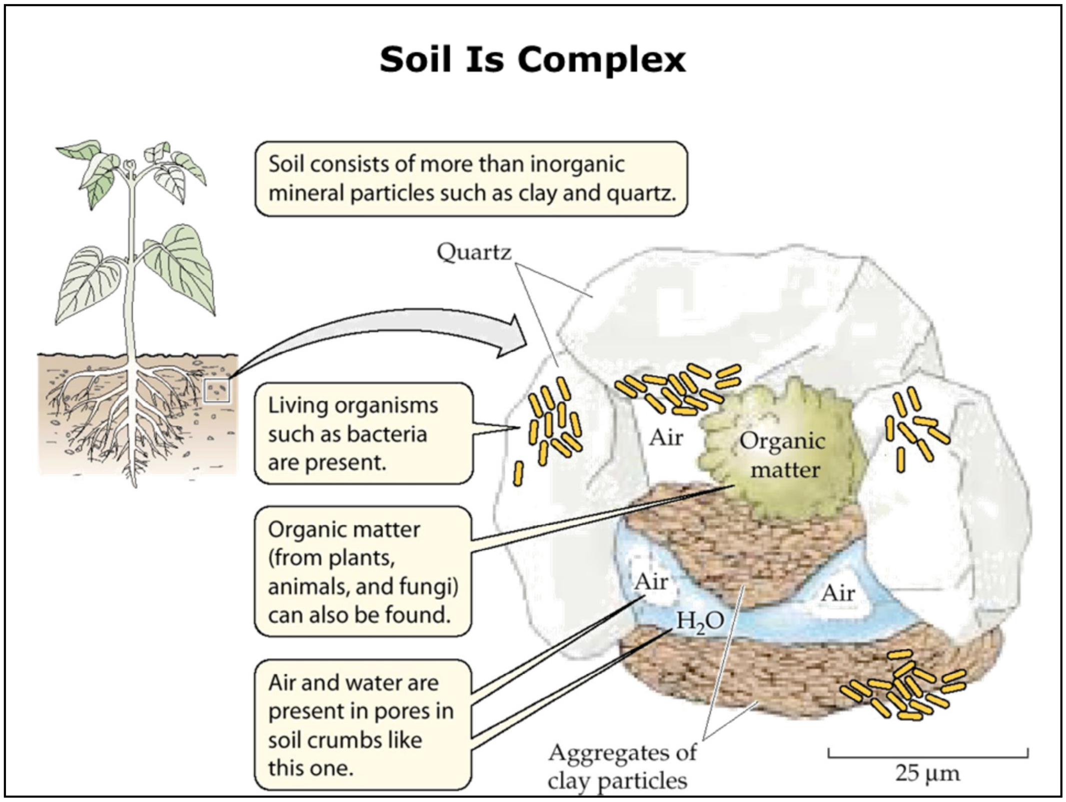
A Pathogen's Prey: These tomato fruits, weakened by a **calcium deficiency** were easy prey for a fungal pathogen.

Soil Is ‘Alive’



Living organisms of the top soil

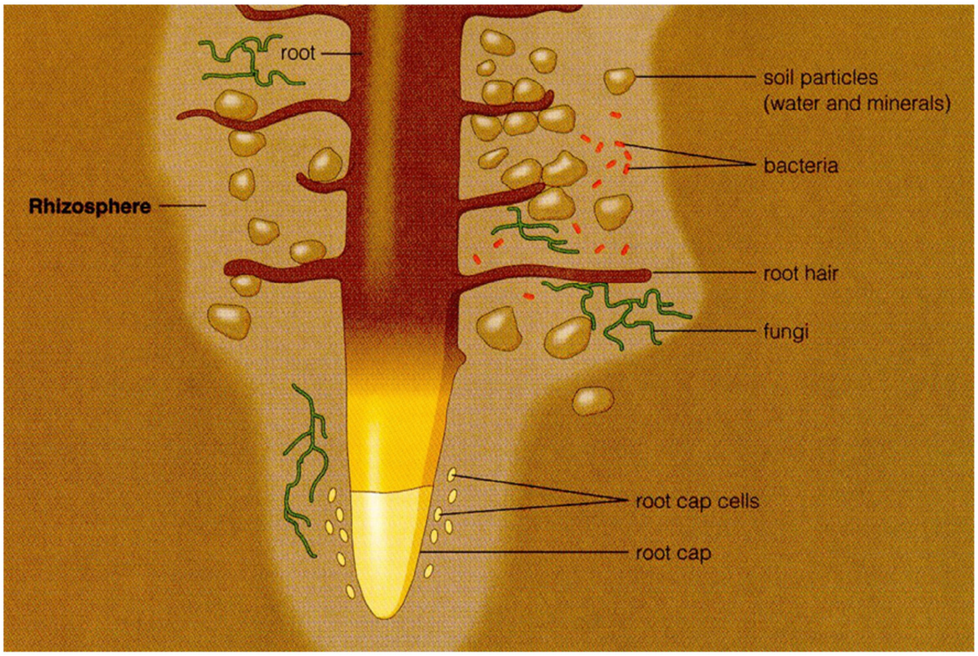
Plants share the soil with a vast number of living organisms, ranging from microbes to small mammals such as moles, shrews, and ground squirrels. Multitudes of burrowing creatures—most notably ants and earthworms—aerate the soil and improve its ability to absorb water. Called by Aristotle “the intestines of the Earth,” earthworms refine the soil by processing it through their gut. The refined soil is then deposited on the soil surface in the form of castings. In a single year, the combined activities of earthworms may produce as much as 500 metric tons of castings per hectare. The castings are very fertile, containing 5 times the nitrogen content of the surrounding soil, 7 times the phosphorus, 11 times the potassium, 3 times the magnesium, and twice the calcium. Bacteria and fungi are the principal decomposers of the organic matter in soil.



The Complexity of Soil

Soil has both organic and inorganic components. The weathering of rocks produces the inorganic nutrients utilized by plants.

Rhizosphere



The **Rhizosphere**, the soil area immediately around a root. This area, shown near the root tip, is rich in soil microorganisms, bacteria and fungi, and in organic compounds from the root body and sloughed-off root cap cells.

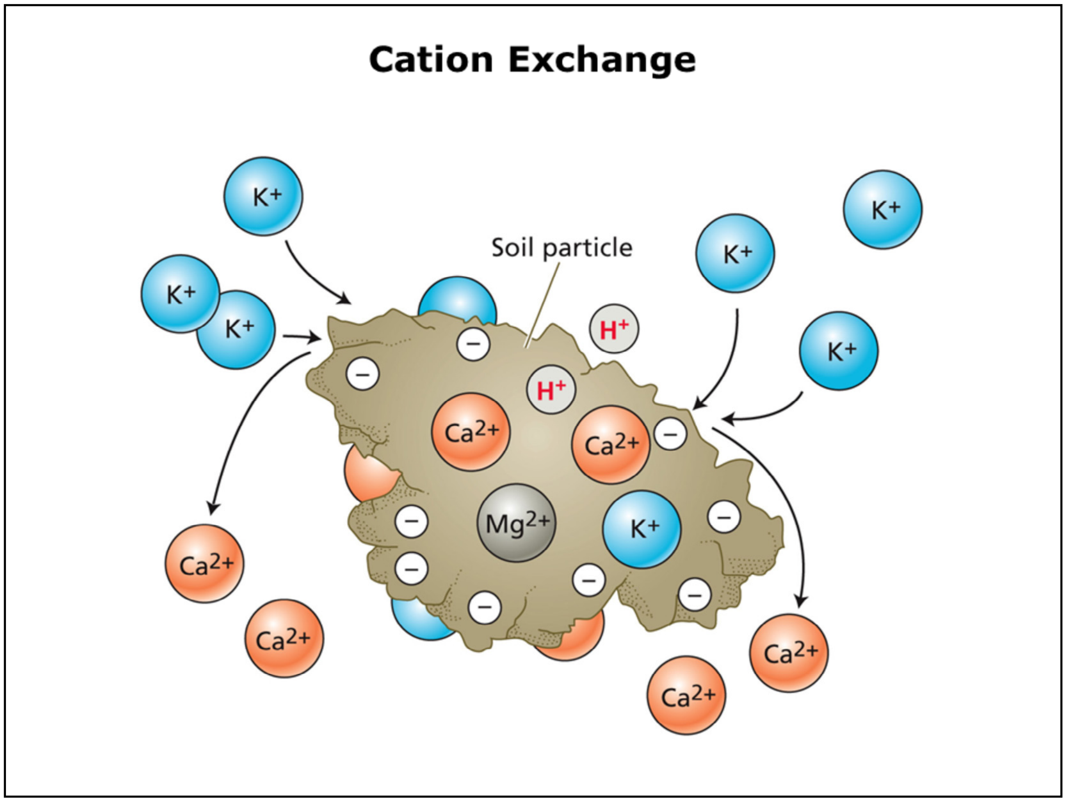
Soil Types

36.3 **Two Systems for Classifying Soil Particles**

UNITED STATES DEPARTMENT OF AGRICULTURE		INTERNATIONAL SOCIETY FOR SOIL SCIENCE	
SOIL TYPE	PARTICLE SIZE (MM)	SOIL TYPE	PARTICLE SIZE (MM)
Sand	0.05–2.0	Coarse sand	0.2–2.0
		Fine sand	0.02–0.2
Silt	0.002–0.05	Silt	0.002–0.02
Clay	<0.002	Clay	<0.002

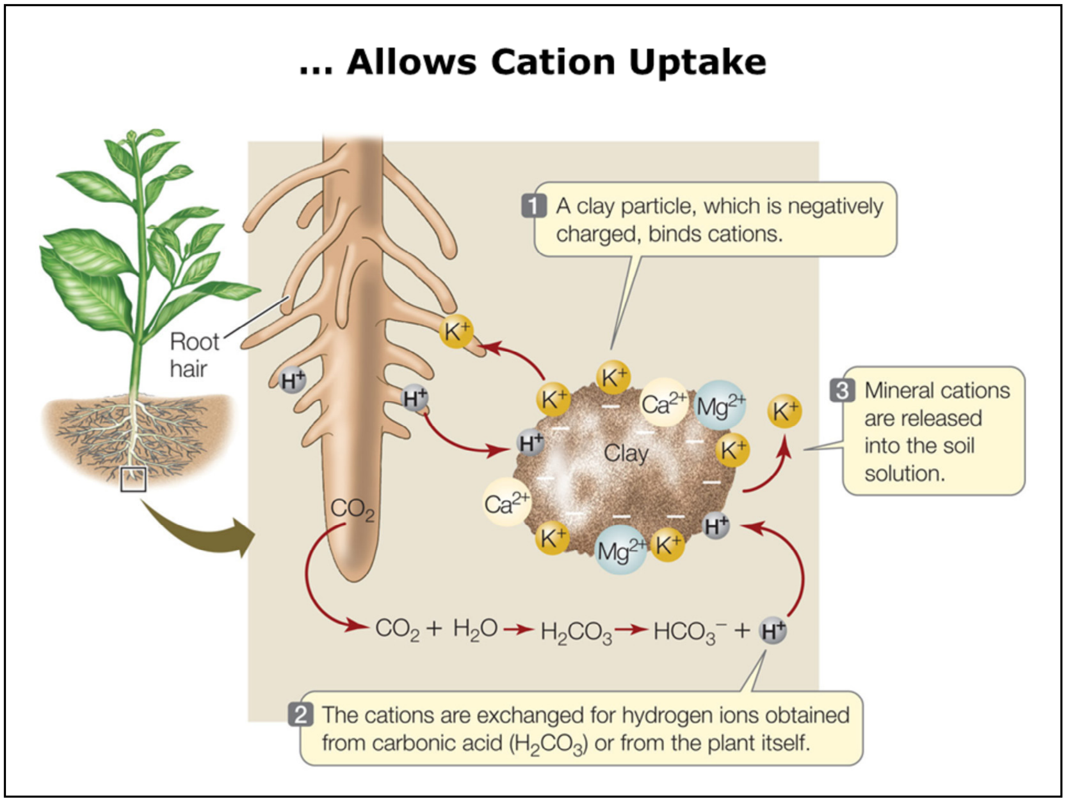
Soil Types

Inorganic soils are categorized by particle size: Gravel consists of particles larger than 2 mm, coarse sand of particles between 0.2 and 2 mm, fine sand of particles between 0.02 and 0.2 mm, silt of particles between 0.002 and 0.02, and clay of particles smaller than 0.002 mm



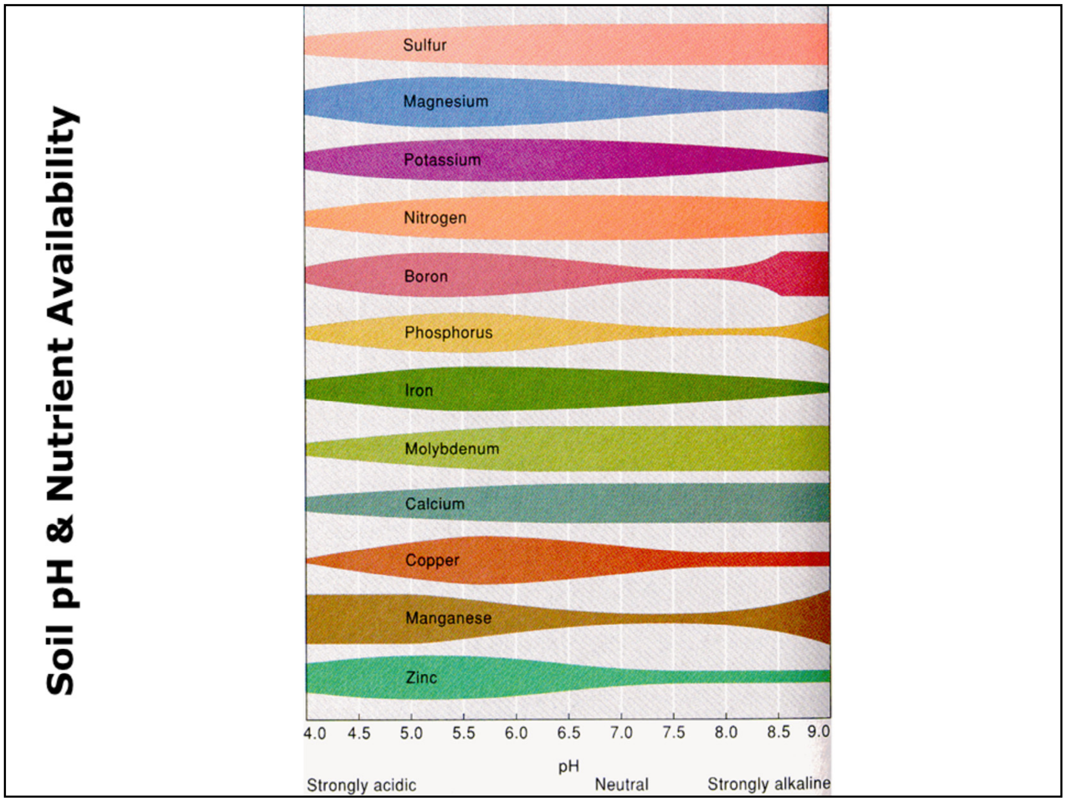
The principle of cation exchange

on the surface of a soil particle. Negatively charged clay micelles bind cations such as K^+ and Ca^{2+}, thereby preventing these cations from being washed from soil by rainfall. Addition of one cation, such as potassium (K^+), to the soil solution can displace other cations, such as calcium (Ca^{2+}), from the surface of the soil particle and make available for uptake by roots.



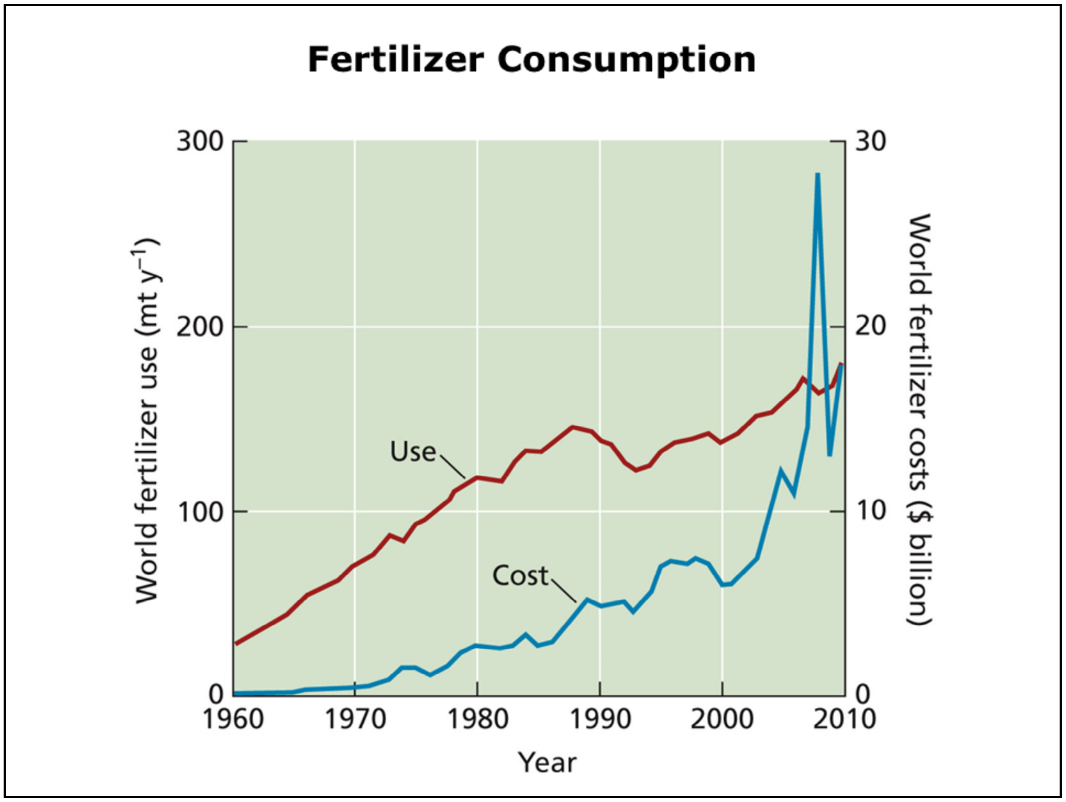
Cation Exchange by Soil Acidification

Hydrogen ions in the soil solution help make certain nutrients available to plants by displacing positively charged minerals (cations) that were bound tightly to the surface of fine soil particles. In addition to secreting H^+ by plasma membrane H^+-ATPases, plants contribute to the pool of H^+ in the soil in the following way: Cellular respiration in roots releases CO_2 to the soil solution, where the CO_2 reacts with water to form carbonic acid (H_2CO_3). Dissociation of this acid adds hydrogen ions to the soil.



Nutrient Availability as a Function of pH

How the pH of soil affects the availability of nutrients. The width of the shaded areas corresponds to the availability of the nutrient to roots. (Compare Fig. 5.5 textbook)



Worldwide fertilizer consumption and costs

over the past five decade

Fertilizer

Industrial Production of Fertilizers

Intensive agriculture relies on the industrial production of nitrogen fertilizer, using a technique that was first engineered in the second half of the 20^{th} century. That same process is now implemented at scores of ammonia factories situated throughout the world. (from Enid News May 15 2013 "Koch Nitrogen has announced a $1 billion plan to increase fertilizer production in Enid “)

Potassium and phosphorous fertilizers are mined.

Crop yields can be improved by addition of fertilizers

Some mineral nutrients can be absorbed by leaves

Saline Soils

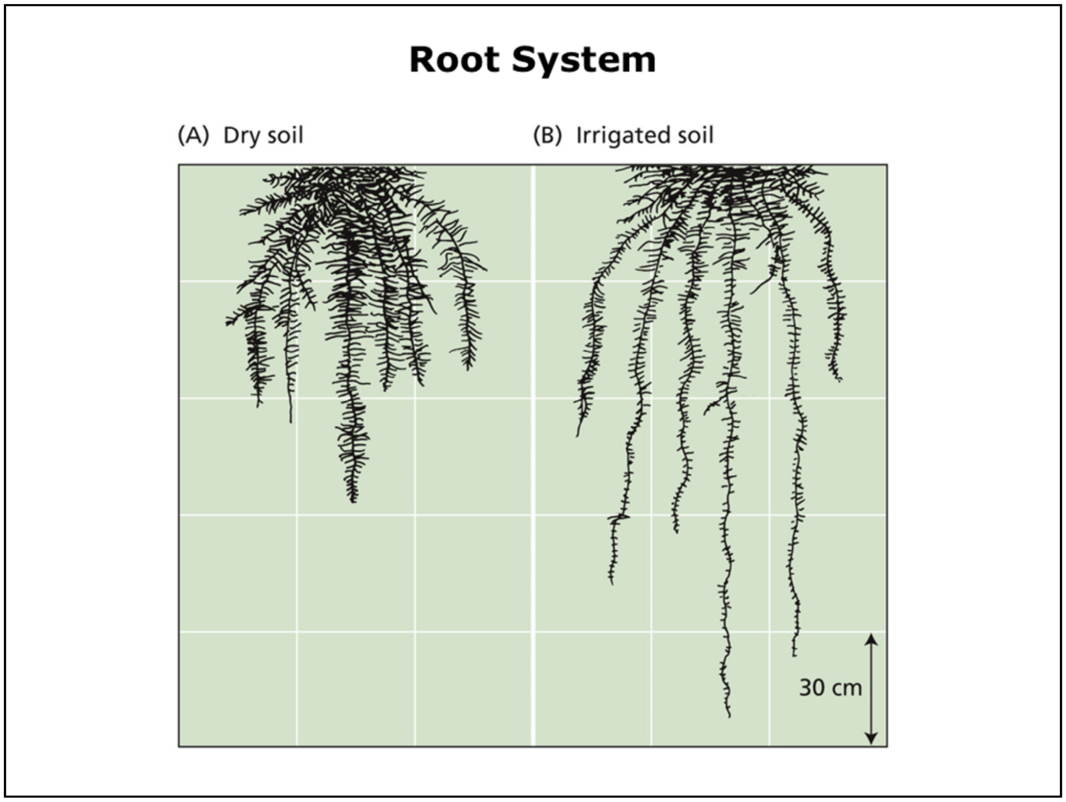
Samuel Zoca, December 08, 2013

Excessive Minerals in the Soil Limit Plant Growth

Especially under furrow irrigation large amount of minerals may accumulate in the soil causing 'salt stress' for the plants.

The picture shows a saline-sodic soil seep where corn cannot grow. The crop is doing well around it, but not where the soil is saline-sodic. The picture was taken (by a former student of mine) on a farm in Marshall, OK, 45 minutes from Stillwater.

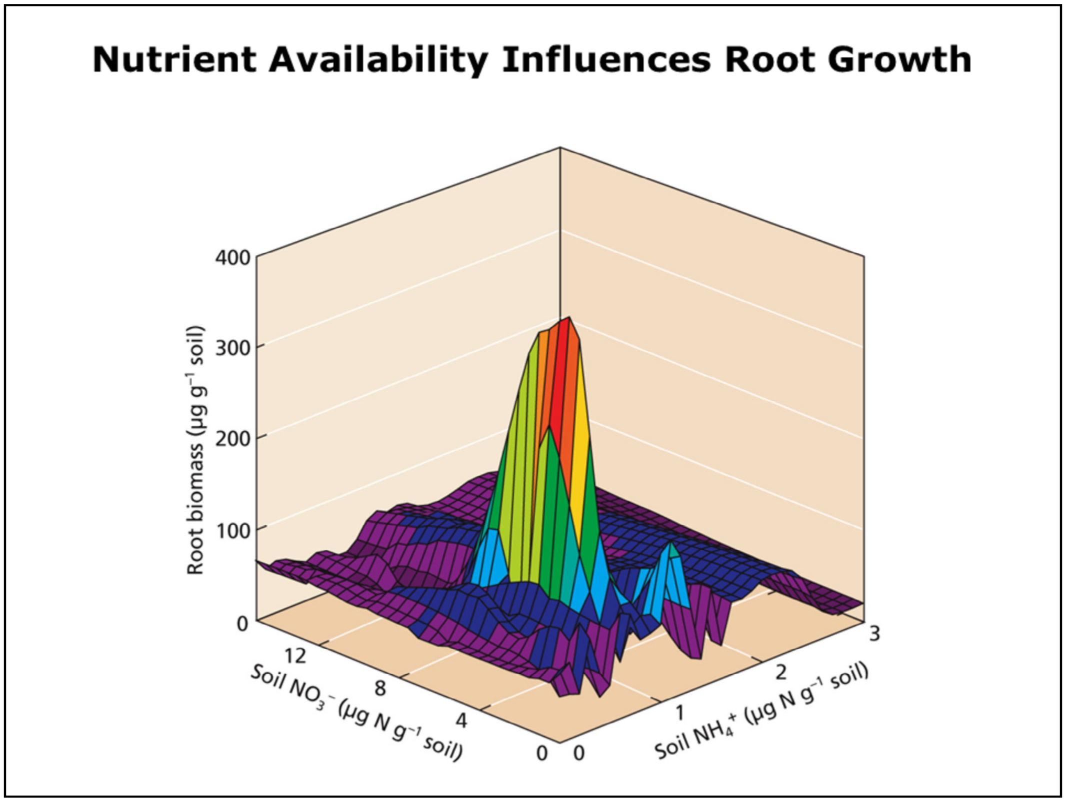
Marshal site	Depth (inches)	ph	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)
Outside Seep	0-3	5.647	78	13	25	8
Outside Seep	3-6	6.428	123	5	17	5
Outside Seep	6-12	7.482	211	4	16	4
Seep	0-3	5.446	4650	91	1879	569
Seep	3-6	5.719	4642	80	1485	440
Seep	6-12	6.876	4915	61	1320	368



Plants Develop Extensive Root Systems

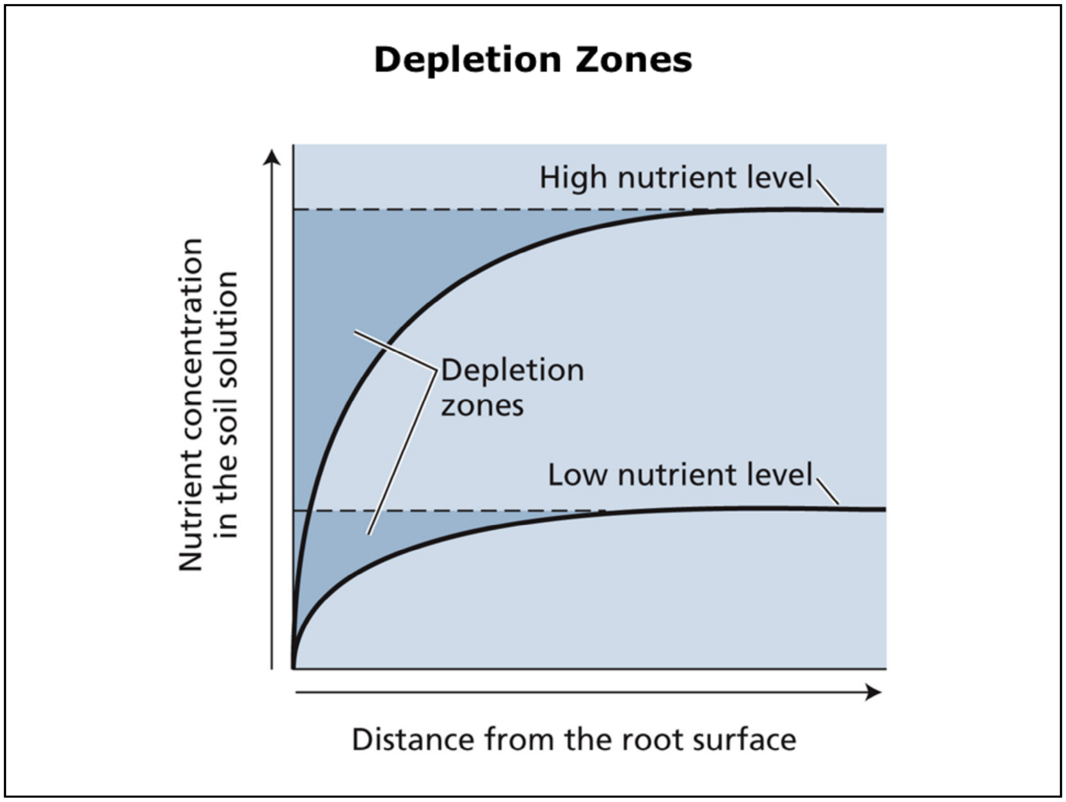
Fibrous root systems of wheat (monocot). (A) The root system of a mature (3-month-old) wheat plant growing in dry soil. (B) The root system of a wheat plant growing in irrigated soil. In the fibrous root system, the primary root axes are no longer distinguishable. It is also apparent that the morphology of the root system is affected by the amount of water present in the soil.

In the late 1930s, H. J. Dittmer examined the root system of a single winter rye plant after 16 weeks of growth and estimated that the plant had 13 x 10^6 primary and lateral root axes, extending more than 500 km in length and providing 200 m^2 of surface area (Dittmer 1937). This plant also had more than 10^{10} root hairs, providing another 300 m^2 of surface area. In the desert, the roots of mesquite (genus *Prosopis*) may extend down more than 50 m to reach groundwater.



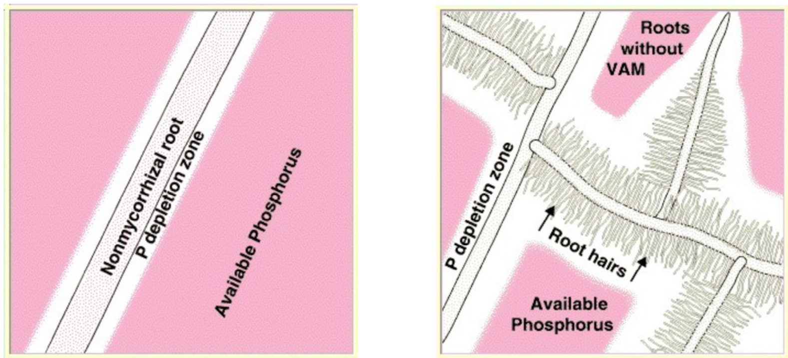
Root biomass as a function of extractable soil NH_4^+ and NO_3^-

The root biomass is shown (µg root dry weight per g soil) plotted against extractable soil NH_4^+ and NO_3^- (µg extractable N per g soil) for tomato growing in an irrigated field that had been fallow the previous 2 years. The colors emphasize the differences among biomasses, ranging from low (purple) to high (red).



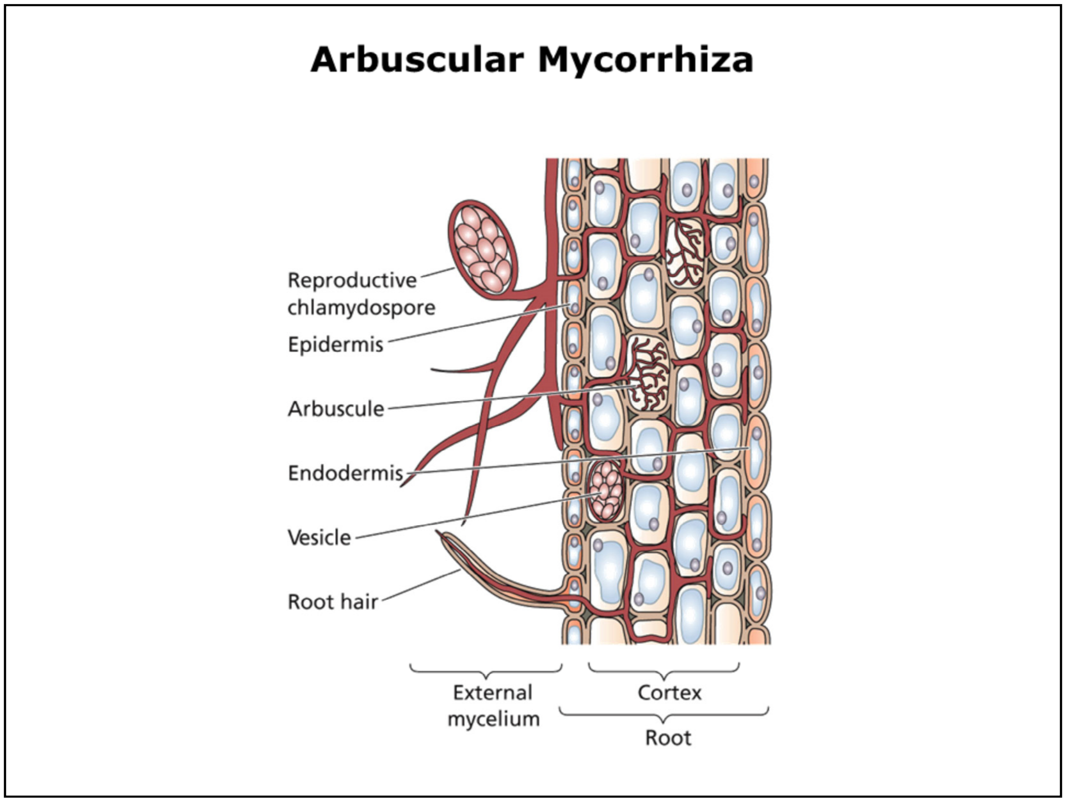
Formation of a **Nutrient Depletion Zone** in the region of the soil adjacent to the plant root. A nutrient depletion zone forms when the rate of nutrient uptake by the cells of the root exceeds the rate of replacement of the nutrient by diffusion in the soil solution. This depletion causes a localized decrease in the nutrient concentration in the area adjacent to the root surface.

Increase in Absorptive Area



Increase in root hair density and length helps to increase the absorptive area of roots and reduce the length of the diffusive pathway for P to reach the root surface.

These diagrams have been simplified to assume that phosphorus is uniformly distributed in the soil and is equally available to roots. They show the extreme situations of a plant with very fine roots and long hairs (such as many grasses) and a plant with thick roots and no root hairs. There are also many plants with intermediate root systems.

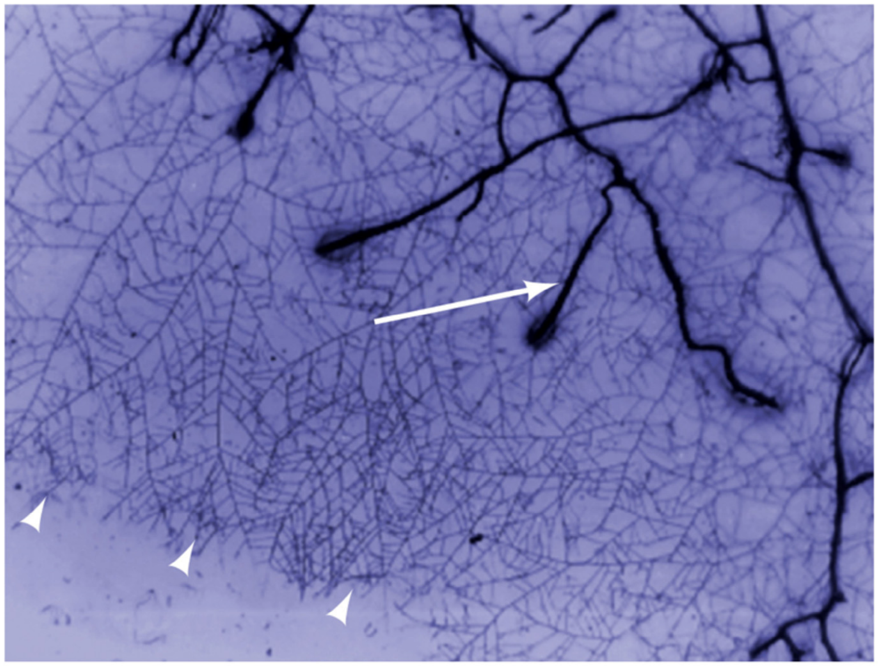


Vesicular-Arbuscular Mycorrhiza (Endomycorrhiza)

The association of vesicular-arbuscular mycorrhizal fungi with a section of a plant root. The external mycelium can bear reproductive chlamydospores and extend out from the root into the surrounding soil. The fungal hyphae grow into the intercellular wall spaces of the cortex and penetrate individual cortical cells. As they extend into the cell, they do not break the plasma membrane or the tonoplast of the host cell. Instead, the hypha is surrounded by these membranes as it occupies intracellular space. In this process, the fungal hyphae may form ovoid structures known as vesicles or branched structures known as arbuscules. The arbuscules participate in nutrient ion exchange between the host plant and the fungus. Arbuscules develop and proliferate following the penetration of the hyphae into the cortical cells of the root. In later stages, the arbuscules separate from the hyphae and degenerate.

(Compare Fig. 5.13 of textbook)

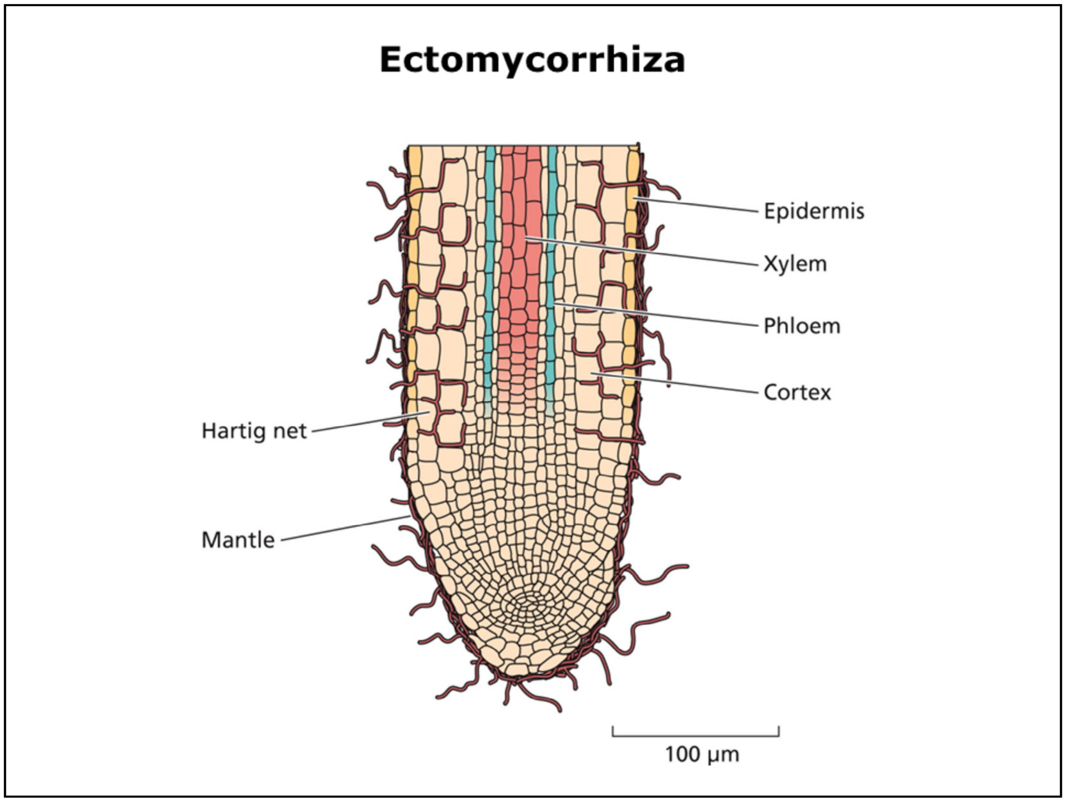
Arbuscular Mycorrhiza



Vesicular-Arbuscular Mycorrhiza (Endomycorrhiza)

Micrograph of the thicker plant roots (cherry plum, *Prunus cerasifera*) and the thin and further extending mycelium of the mycorrhizal symbiont (*Glomus mosseae*).

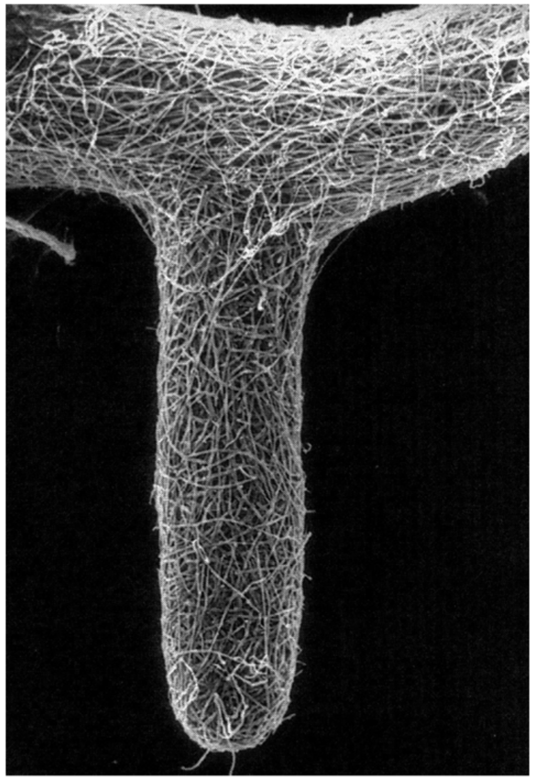
Mycorrhizal Fungi Facilitate Nutrient Uptake by Roots!



Ectomycorrhiza

A tree root infected with ectotrophic mycorrhizal fungi. In the infected root, the fungal hyphae surround the root to produce a dense fungal sheath and penetrate the intercellular spaces of the cortex to form the Hartig net. The total mass of fungal hyphae may be comparable to the root mass itself.

Ectomycorrhiza



Ectomycorrhizae mantle

Hyphae of the fungus *Pisolithus tinctorius* cover this eucalyptus root, forming a mycorrhiza.

Where are Mycorrhizal Plants found?

Vesicular Arbuscular Mycorrhizal (VAM) Plants

- Plants with VAM are common in most habitats.
- It is easier to say where they are not found.

Ectomycorrhizal (ECM) Plants

- Trees with ECM are dominant in coniferous forests, especially in cold boreal or alpine regions.
- ECM trees and shrubs are common in many broad-leaved forests in temperate or Mediterranean regions.
- ECM trees also occur in some tropical or subtropical savanna or rain forests habitats.

Nonmycorrhizal (NM) Plants

- NM plants are most common in disturbed habitats, or sites with extreme environmental or soil conditions.

Occurrence of Mycorrhizal Plants

Mycorrhizae and Plant Growth

Trees with ectotrophic mycorrhizal fungi are dominant in coniferous forests, especially in cold boreal or alpine regions.

What you should have learned today

What is an essential element, how were they discovered and why is it important to know them?

What is the function of different essential elements?

How is yield related to mineral nutrient availability?

How does phloem mobility affect visible mineral deficiency symptoms?

The different types and composition of soils?

How do plants take up cations by a cation exchange mechanism?

About the importance of a proper amount of mineral nutrients in the soil.

Why and how does nutrient availability affect root growth?

Which types of mycorrhiza exist?

How does mycorrhiza improve plant mineral nutrition?

Lecture Summary