SOIL NUTRIENTS, SOURCES AND UPTAKE

Essential Plant Nutrients

All green plants have the ability to manufacture their own food by using energy derived from the sun to combine chemical elements, taken up in the inorganic ion form, into a multitude of organic compounds.

Seventeen elements are considered essential for plant growth. If any of these 17 elements are lacking, plants cannot complete their vegetative or reproductive cycles. Some of these nutrients combine to form compounds which compose cells and enzymes. Others must be present in order for certain plant chemical processes to occur.

Carbon, hydrogen and oxygen are supplied to the plants through air and water. These three elements comprise about 95% of the total dry matter of most plants. The remaining 5% of the dry matter is made up of 14 essential mineral elements along with many other elements that may be taken up in small amounts by the plants but are not know to perform any essential functions within the plant.

When plant growth is limited because of lack of an essential element it is usually due to a deficiency of one or more of these 14 elements. These elements are primarily taken up by plants from the soil solution.

The 14 mineral nutrients required for plant growth are classified as *primary*, *secondary*, or *micronutrients* according to the quantity required by plants and/or how widespread deficiencies of the nutrients are

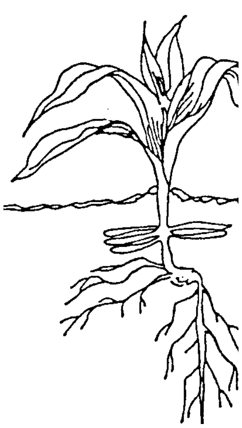
Primary nutrients are used in the largest quantities and are usually the first to become deficient in the soil. Primary nutrients and the secondary nutrients are sometimes known as macro nutrients.

Secondary nutrients are macronutrients but are less frequently deficient in soils.

Micronutrients, also known as trace or minor elements, are required in very small amounts and are less frequently deficient. Even though nutrients are used in different amounts, each of the essential nutrients is equally important for plant growth.

The 17 essential plant nutrients are shown below. The chemical symbols are a shorthand method of identifying elements. The student of soil fertility should become familiar with these symbols

Source of Plant Nutrients



From Air

Carbon (C)
Oxygen (O)

From Water

Hydrogen (H)
Oxygen (O)

Mineral Nutrients From Soil

Primary Nutrients	***Secondary Nutrients***	***Micronutrients***	
Nitrogen (N)	**Calcium (Ca)**	**Boron (B)**	**Manganese (Mn)**
Phosphorous (P)	**Magnesium (Mg)**	**Chlorine (Cl)**	**Molybdenum (Mo)**
Potassium (K)	**Sulfur (S)**	**Copper (Cu)**	**Zinc (Zn)**
		Iron (Fe)	**Nickel (Ni)**

Forms Of Nutrients Used By Crops

All chemical elements, including plant nutrients exist in nature in an electrically charged form called ions. Ions carry either a positive or negative electrical charge. Ions with positive charges are called *cations* while those with negative charges are *anions*.

Plants can only utilize nutrients in an ion form although some nutrients are utilized by plants in more than one ionic form. A partial list of common soil cations and anions is shown below.

Cation: (+)	**A Positively Charged Ion**
Anion: (-)	**A Negatively Charged Ion**

Cations in Soil		**NUTRIENTS**	**Anions in Soil**	
K^+	**Potassium**		**NO_3^-**	**Nitrate**
NH_4^+	**Ammonium**		**SO_4^{-2}**	**Sulfate**
Mg^{+2}	**Magnesium**		**$H_2PO_4^-$**	**Phosphate**
			HPO_4^{-2}	
Ca^{+2}	**Calcium**		**Cl^-**	**Chloride**
Mn^{+2}	**Manganese**		**BO_3^{-2}**	**Borate**
Zn^{+2}	**Zinc**		**MoO_3^{-2}**	**Molybdate**
		NON-NUTRIENTS		
Na^+	**Sodium**		**OH^-**	**Hydroxyl**
H^+	**Hydrogen***		**$H_2CO_3^-$**	**Bicarbonate**
Al^{+3}	**Aluminum**		**CO_3^{-3}**	**Carbonate**

***** Hydrogen as a nutrient is obtained primarily from water. H+ ions in the soil affect soil pH and many chemical and biological processes.

Soil Organic Matter: A Source Of Plant Nutrients

Soil organic matter and humus are terms which refer to the partially decomposed residue of plants, animals, and other organisms. Organic matter refers to all *organic material* including fresh crop residues. *Humus* is the more stable decomposed organic residue. Organic matter has long been recognized as having many beneficial effects on physical and chemical properties of the soil. Some of the more important effects of organic matter are :

- *Improves Soil Structure*. Organic matter acts as a bonding agent which holds soil particles together in aggregates. Without organic matter, aggregates are less stable and are easily broken apart. Good soil structure promotes water movement and root penetration while reducing soil crusting, clod formation, and erosion.
- *Contributes to Cation Exchange Capacity (CEC)* (see next section). Soil organic matter has great ability to attract and hold cations
- *Provides Plant Nutrients*. One of the most important attributes of organic matter is its contribution to soil fertility.
  - o Approximately 90% to 98% of the total N and S and 30% to 50% of the P exist in the soil in organic forms.

- o Soil organic matter is approximately 5% N and 0.5% P or S.
- o Organic matter is also the primary reservoir for available forms of most of the micronutrients.
- o Potassium is an important exception and does not exist in organic forms.

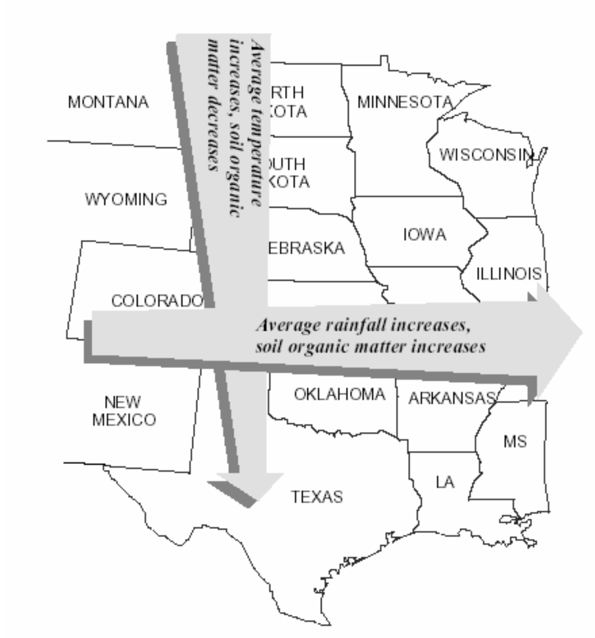
Even though plants are not able to utilize nutrients in organic matter directly, decomposition of humus releases ionic forms of nutrients which are available to plants. It is estimated that in temperate zones of the U.S. about 1% to 3% of the soil organic matter decomposes annually, releasing nutrients in the process. Soil organic matter contains about 5% N, or about 1,000 lb of total N for each 1% soil organic matter. Thus, a soil containing 2.0% organic matter has about 2,000 lb/acre of N. If 2% of this N is released each year, 40 lb of N is available for plants(2,000 x 0.02).

<u>Factors affecting soil organic matter levels.</u> The amount of organic matter in any soil depends on a number of factors. In general, high *temperature* favors a high rate of decomposition or organic residues. As a result, soil organic matter tends to be higher in the northern U.S. than in the southern states.

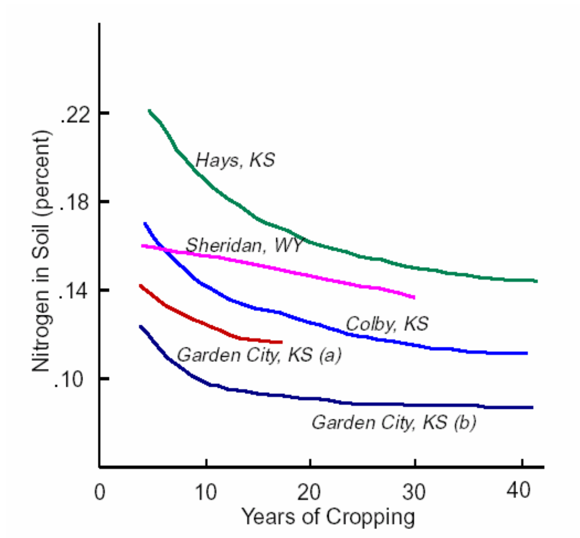
Higher annual *precipitation* tends to favor more plant growth and higher organic matter levels. *Excessive soil moisture* in poorly drained soils reduces oxygen supplies for microbial activity and results in higher levels of organic matter. In some northern states, poorly drained swamp or bog areas have resulted in peat soils that contain over 80% organic matter.

Soil organic matter levels tend to decline as soils are farmed . In many Great Plains soils the present organic matter content is about 50% of the native level present when the land was first plowed. Constant *tillage* of the soil has increased the rate of decomposition of organic matter and increased erosion of topsoil.

Additionally, crop rotations which include a fallow period hasten a decline in soil organic matter content since crop residues are not supplied to



the soil while decomposition of soil organic matter continues. At the present time, it is likely that organic matter levels in more intensive crop production systems have stabilized - or are changing only slowly – if soil erosion has been contained.



No-till or reduced tillage practices can reverse the decline of soil organic matter. In many cases, the organic matter content of the surface 2" or 3" increases significantly over a period of 5 to 10 years of no-till.

The use of fertilizer has a positive effect on the soil organic matter level since properly fertilized crops leave more crop residue

Increasing Soil Organic Matter Levels. It is difficult to increase soil organic matter very quickly. Let us look at what it takes to raise the organic matter percentage of soil. There are approximately 2,000,000 lbs of soil in an acre-furrow slice. To raise the organic matter content of the 6- to 7-inch depth layer 1%, about 20,000 pounds of stable humus must be added. (1% of 2,000,000 lbs.). During decomposition of crop residues, about two-thirds of the carbon is given off as carbon dioxide - leaving only a fraction of added carbon to form stable humus. Thus increasing soil organic matter through additions of organic residues is often very slow. Reducing or eliminating tillage operations, controlling soil erosion and producing high *crop yields* are essential to increase soil organic matter.

While organic matter has many desirable effects on soil and soil productivity, many soils containing relatively low levels of soil organic matter are very productive.

Cation Exchange Capacity

During soil formation, minerals are broken down into microscopic clay particles as described previously. The smallest of these clay particles, along with soil organic matter, are called soil colloids. These colloids possess tremendous surface area and make up the chemically active portion of the soil. Clay colloids are plate-like in structure and are composed of mica-like layers that could be compared to miniature slices of bread or a deck of cards.

Each colloid has a net negative electrical charge that developed during its formation. These charges attract and hold opposite (positive) charges much as unlike poles of a magnet attract each other. Similarly, negatively charged colloids repel negatively charged particles like as poles of a magnet repel.
The attraction of unlike charges also enables negatively charged soil particles to attract and hold cations. Cations are held on the soil colloids (clay and humus) rather tightly yet not permanently in a form that resists removal by leaching. But through an exchange process, these cations may be released into soil solution where they can be absorbed by plant roots. One cation can exchange for another on the surface of the colloids; thus the negative charges on the colloid are called exchange sites. The ability of soils to attract and hold positively charged nutrients is one of the most important soil properties in soil fertility and plant nutrition..

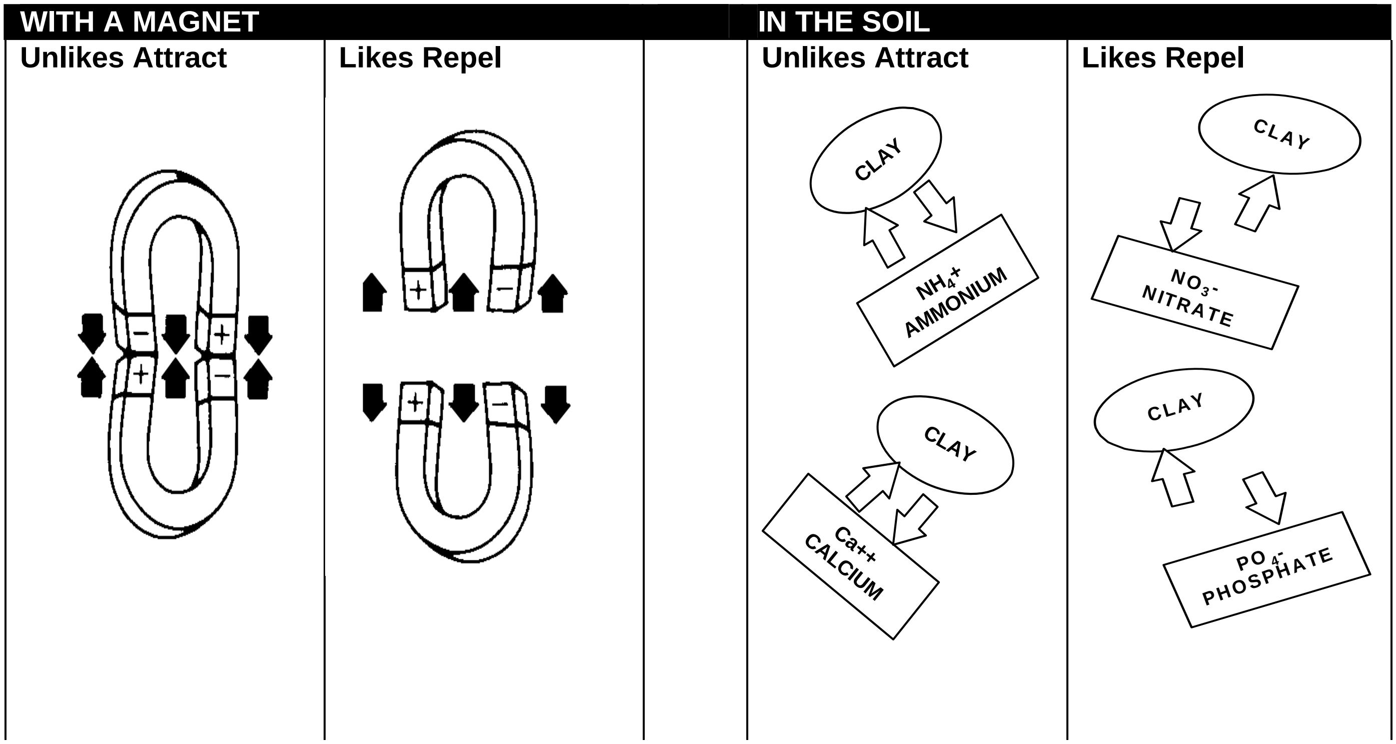
The capacity of a soil to hold exchangeable ions of various nutrients is termed "cation exchange capacity." This capacity may range from 3 to almost 100 milliequivalents (m.e.) per 100 grams of clay. Soils with cation exchange capacity of 10 to 20 m.e./100 gm of soil or higher are good soils as far as plant nutrient relationships are concerned.

Kaolinite has a very low cation exchange capacity (3 to 15 m.e./100 gm). The ability of kaolinite to hold positively charged plant nutrients is very limited. So is its ability to hold certain herbicides and insecticides. Of what practical application is this to us? In the southeast United States where kaolinite clays predominate, farmers have to apply heavy rates of fertilizers because the soil cannot retain nutrients. One ton per acre fertilizer applications for tobacco in North Carolina are a common practice. Because the soil can't hold these nutrients they must be applied as near as possible to the time the crop will use them. Winter applications are not possible unless winter cover crops are grown. Then the nutrients are taken up by the cover crop and later, when it decays, are available for use by the summer crop.

Soils high in kaolinitic clays can't hold much water. Despite the high rainfall in S.E. United States, drought can be severe if rains don't come about every week.

Soils with kaolinitic clay do have some advantages. They do not get sticky when wet; they can be tilled soon after heavy rains just like sandy soils in Kansas. They do not swell on wetting or shrink on drying. Thus they make good building sites. They won't puddle or form clay pans.

Illite and montmorillonite type of clays have much greater exchange capacities than kaolinite, as shown below. Organic matter also has a very high exchange capacity, therefore being valuable as a storehouse for nutrients as well as improving soil structure and moisture holding capacities of a soil.

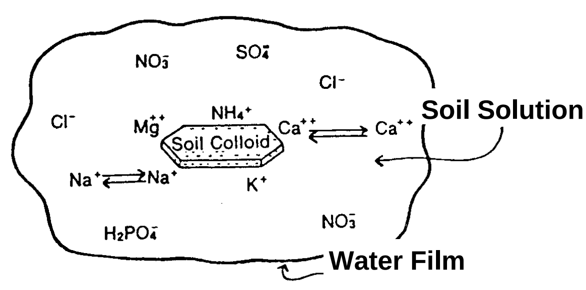


Hydrogen (H^+), ammonium (NH_4^+), sodium (Na^+), potassium (K^+), calcium (Ca^{++}), magnesium (Mg^{++}), zinc (Zn^{++}), and other cations react with the soil clays and are held loosely enough for plant roots to recover them. Anions, the nutrients with negative charges, including nitrates (NO_3^-), sulfates (SO_4^+), hydroxyl (OH^-) etc. are repelled by the soil clays. Clays cannot hold anions. Soluble anions move up and down in the soil as water moves. Thus, they can be lost by leaching.

Soil Colloid	Exchange Capacity (meq/100 grams soil)
Kaolinite	3 -15
Illite	20 – 40
Montmorillonite	20 – 100
Organic Matter	100 - 300

A practical recommendation taking advantage of this principle comes in the winter application of anhydrous ammonia. As long as soil temperature is below 50° F, the ammonium (NH4+) will be very slowly transformed to nitrates (NO3-) by soil microorganisms. Thus the ammonium will be held by the soil clay. We can apply anhydrous ammonia in the winter with little danger of losses. Nitrates will not be held by the clay and can be lost by leaching, especially from sandy soils.

Questions may be raised regarding the relationship of clays to our ability to get effective responses from applications of very low rates of such micro nutrients as zinc. Soil clays hold these cations just like they hold calcium, potassium, and ammonium. The reason for the effectiveness of the light applications lies mainly in the very low plant requirement. It is possible to broadcast a low rate of zinc (5 to 10 lbs/A) and have adequate zinc available to every plant.



A schematic view of cation exchange.

Some cations are held more tightly than others on exchange sites and are released into the soil water solution less easily than are others. Some common cations are listed below in order of the strength of bonding to the exchange sites:

Cation	Bonding Strength
1. Hydrogen	Strongest
2. Aluminum	↑
3. Calcium	
4. Magnesium	
5. Potassium	
6. Ammonium	↓
7. Sodium	Weakest

It is easier for a tightly held cation to replace a less tightly held cation on an exchange site than vice versa. But even Na^+ can replace H^+. Relative concentrations of one nutrient to another also affect exchange. For example, the application of potassium fertilizer increases the concentration of K^+ ions and consequently increases the chance of replacing a more tightly bonded cation at an exchange site.

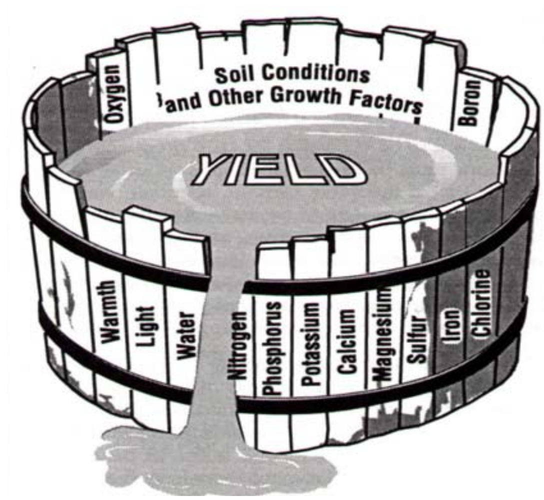
There is an equilibrium balance between cations on the exchange complex and cations moving freely in the water solution. Though the concentration of cations in solution is very small at any one time, most cations are absorbed by plant roots from the solution phase. As nutrients are removed from solution by plant roots, the balance is upset and other cations come off the exchange sites into solution to maintain the correct balance.

Anion Retention in Soils Soil colloids have only minimal positive electrical charges. Since anions carry negative electrical charges, they are not retained by soil colloids. Anions such as nitrate, sulfate, and chloride are very soluble and move with water. Sulfate can be loosely held by positive charges that develop on organic matter under low pH conditions.

Phosphate is an anion that does not move freely in soils largely because it forms relatively insoluble compounds with iron and aluminum in acid soils and calcium in high-pH soils.

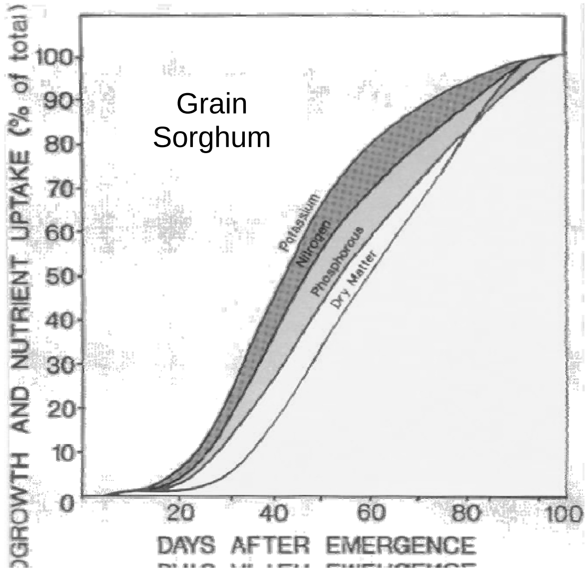
Nutrient Uptake By Plants

One of the most important principles of plant nutrition is the "law of limiting factors." This law states that yield or plant growth is limited by the factor, which is in shortest supply. This concept is illustrated below. The water level in the barrel is limited by the lowest stave. Yield is similarly limited by the nutrient or other growth factor, such as water, which is most limiting.



This law applies not only to nutrients and other growth factors, but to management variables as well. Applying high rates of fertilizers to crops is of no value unless the proper varieties, plant populations and weeds, insects and disease control are used.

Nutrient uptake precedes dry matter accumulation because nutrients are required for plant growth and hence dry matter accumulation. The pattern of growth (dry weight) and nutrient accumulation with growth of sorghum plants points out that the nutrient uptake curves are above the dry matter curve for most of the growth period. For example, the half-bloom stage occurs at 60 days after the emergence and about one-half of the total plant weight has been produced; however, nearly 60 percent of



the phosphorus, 70 percent of the nitrogen and 80 percent of the potassium the plant will utilize already have been taken up. Those percentages emphasize how important proper fertility is at early growth stages in the nutrition of the sorghum plant.

Root development of crops: Crops obtain nutrients and water from the soil through their roots. Roots of plants normally continue to grow as long as soil conditions such as moisture, air, nutrients, temperature, soluble salts and tilth are favorable. If unfavorable conditions exist, root growth will be limited. The most common inhibitors of root growth are dry soil, lack of soil air because of excess water and poor drainage, and soil compaction.

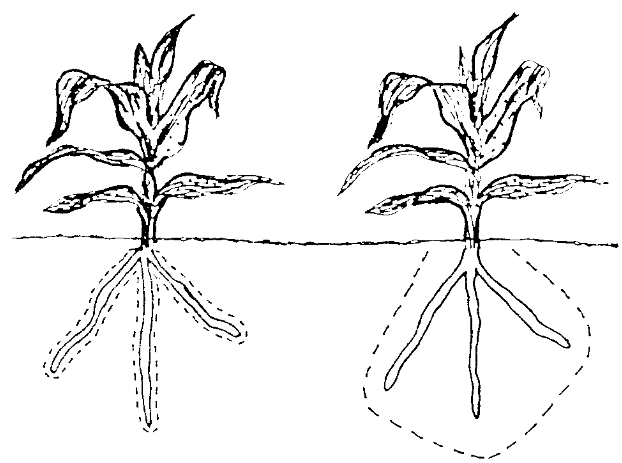
Roots will not grow in dry soil. If there is a layer of dry soil between moist topsoil and deeper moist subsoil, the root system of annual crops will expand only in the moist area above the dry soil. The deep, "carryover" moisture will not be used. Perennials, with root systems already established in the deep, moist subsoil will be able to use this moisture.

Plant roots absorb nutrients in their ionic form. The best placement of fertilizer, the movement of nutrients to the root, and the factors affecting root uptake depend on the mobility of these ions and the rooting characteristics of the crop.
Plant roots absorb nutrients from the water film around soil colloids. Immobile nutrients which are relatively insoluble or are held tightly by the soil exchange complex will not move very far through the water to the root. Phosphate, for example, will move only a fraction of an inch. For immobile nutrients, such as P and K, fertilizer must be placed in the root zone where roots are growing.

Immobile nutrients move to the root surface mainly through a process called *diffusion*. Diffusion is the movement of ions from a zone of high concentration to zones of lower concentration. As plant roots absorb nutrients from soil water, ions diffuse toward the roots as a result of the lower ionic concentration near the root. Diffusion operates only across very short distances.

Mobile nutrients move to the root surface largely with the flow of water into the plant and is termed *mass-flow*. As plants extract water, water moves toward the root and carries mobile nutrients with it. Mass flow allows plants to absorb mobile nutrients that are not initially close to the roots.

Another factor affecting nutrient uptake by plants is *root interception*, or growing of roots into unexplored soil zones.



Zone of plant uptake of Immobile nutrients (PO_4,K,Ca,Mg,Zn, Fe)	Zone of plant uptake of Mobile nutrients (NO_3,SO_4,Cl, BO_3)

Nutrient mobility effect on root uptake zones

Plant roots compete very little with each other for immobile nutrients since each root hair has an absorption zone of a fraction of an inch. In contrast, some nutrients are very soluble and are not held tightly by the soil. These mobile nutrients will move with water, creating a larger root-absorption zone for these nutrients. When fertilizer products of mobile nutrients such as nitrate-nitrogen or sulfate-sulfur are applied to the soil surface, water can transport them down into the root zone. Mobile nutrients can be surface applied, topdressed or applied in irrigation water. Immobile nutrients are generally more available to plants if incorporated into the soil or banded near the plant.

Root competition for mobile nutrients is much greater than for immobile nutrients because of the extent of the root-absorption zones.

Crop Rooting Patterns Rooting patterns of different crop species also affect nutrient uptake, fertilizer placement, and soil sampling techniques. Deep rooted crops can forage effectively in the subsoil for water and mobile nutrients such as nitrate and sulfate. As a result, soil samples taken just from the plow layer may not be sufficient for accurate soil tests of these nutrients.

Some plants forage near the soil surface more effectively than others. Perennial crops, such as alfalfa and pasture grasses, have many fibrous roots near the soil surface during much of the growing season. As a result, topdressing these crops with immobile nutrients such as P and K is relatively effective.

Tillage method can affect distribution of plant roots. No-till systems that leave crop residues on the soil surface encourage more roots near the soil surface. Crop residues keep the surface soil cooler and to reduce the rate of drying.

Use of fertilizer generally increases the root growth of plants. Nitrogen has been shown to double total root weight and increase rooting depth. Fertilizer will increase the ability of crops to forage for water and nutrients. It has been estimated that the total root length in one acre of corn may approach 46,000 miles.

Under limited soil moisture conditions, proper use of fertilizer can be expected to increase crop yield produced per inch of water available.