TECHNICAL NOTES

U.S. DEPARTMENT OF AGRICULTURE Portland, Oregon SOIL CONSERVATION SERVICE

AGRONOMY TECHNICAL NOTE NO. 54 November 1985

SOIL FERTILITY

Attached is a paper prepared by Hugh Gardner, Extension Soils Specialist, of Oregon State University. We believe this **SOILS FERTILITY** paper is a good review of soil fertility and can be used as a handy, quick reference.

SOIL FERTILITY

Prepared by
Hugh Gardner
Extension Soils Specialist
Oregon State University

SOIL FERTILITY DEFINED

The term soil fertility refers to the inherent capacity of a soil to supply nutrients to plants in adequate amounts and in suitable proportions. Because a soil is fertile does not necessarily mean that it will produce high-yielding crops. Other factors such as temperature or poor soil structure might result in limited yields. Good soil fertility is but one of the components essential to high productivity.

ESSENTIAL NUTRIENT ELEMENTS

MAJOR Used in Relatively Large Amounts		MICRO Used in Relatively Small Amounts
Mostly from Air and Water	From Soil Solids	From Soil Solids
Carbon (C) Hydrogen (H) Oxygen (O)	Nitrogen (N) Phosphorus (P) Potassium (K) Calcium (Ca) Magnesium (Mg) Zinc (Zn)	Iron (Fe) Manganese (Mn) Boron (B) Molybdenum (Mo) Copper (Cu) Chlorine (Cl)

All of these nutrients are essential to the growth of plants, and plants will not grow satisfactorily in the absence of any one of them.

SOURCES OF NUTRIENT ELEMENTS

Nutrients are obtained from the weathering or decomposition of rocks and minerals and organic matter in the soil or earth's crust. They are also present in varying amounts in the atmosphere and water and are sometimes provided in the form of fertilizers.

The Earth's Crust Contains Nutrients

Most of the nutrient elements occur naturally in the surface of the earth. The following table indicates the average amounts of some of the nutrient elements in the earth's crust. In specific locations, these amounts might be higher or lower. An acre-foot of soil weighs about 4

million pounds. One percent of an element in an acre-foot of soil, therefore, would be equal to 40,000 pounds.

Percent of Some of the Nutrient Elements in the Earth's Crust		
Iron 5.1	Calcium 3.6	Magnesium 2.1
Potassium 2.6	Phosphorus 0.12	Manganese 0.09
	Sulfur 0.06	

Organic Materials Provide Nutrients

Organic materials in the soil are an important source of some of the nutrient elements. These organic materials consist of the dead remains of plants and animals. They contain nutrient elements which are released as these organic materials decompose. Their rate of decomposition, and therefore rate of nutrient element release, depends upon microbial activity in the soil. Microbial activity is related to other factors such as temperature, moisture, and nutrients. Organic material in the soil is an important source of such elements as nitrogen, phosphorus, sulfur, and several of the micronutrient elements.

Nutrients from the Atmosphere

The atmosphere is also a source of certain nutrient elements. In some localities, appreciable amounts of sulfur, for instance, are removed from the atmosphere by rain and deposited on the soil.

Irrigation Water can Supply Nutrients

Water frequently contains significant amounts of some of the nutrient elements. Irrigation water sometimes is a significant source of certain plant nutrients.

Microbes are Important Providers

Certain microbes play an important role in the supplying of nutrients to plants. One group of microbes known as rhizobia converts atmospheric nitrogen, which is not available to plants, to forms of nitrogen, which are available. These microbes live in nodules found on the roots of legumes. Other microbes convert sulfur into available forms, and microbes are also responsible for the decomposition of organic matter and the subsequent release of nutrients from organic forms.

FORM OF NUTRIENT ELEMENTS

Readily Available	Slowly Available
Soil Solution Exchangeable Some Chemical Compounds	Rocks and Minerals Organic Matter "Fixed " Nutrients Some Chemical Compounds

Nutrient Equilibrium in Soils

The various forms of nutrient elements in soils are in equilibrium with one another. As rocks and minerals or organic matter weather or decompose, nutrient elements are released into the soil solution or are adsorbed as exchangeable nutrients onto the surfaces of clay particles or small organic particles which are known as humus. As plant roots remove nutrient elements from the soil solution, more nutrient elements are transferred to the soil solution from exchangeable or slowly available forms. Plant roots readily remove nutrients from soil solution and exchangeable nutrients are replaced from the exchangeable form into the soil solution. Some chemical compounds found in soils have a comparatively high solubility and therefore release nutrients readily into the soil solution.

"Fixation" of Nutrients

Sometimes nutrient elements become "fixed" by certain components in the soil. Potassium can become trapped between adjacent plate-like layers of clay particles. Potassium which is trapped in this way is not readily available to plants. Certain chemical compounds which are formed in the soil have a low solubility. When phosphorus fertilizer is added to the soil, the phosphorus frequently combines with iron, aluminum, or calcium to form compounds which, under certain soil conditions, have a low solubility. Phosphorus contained in compounds of low solubility is present in a slowly available form.

Cation Exchange--An Important Process

Cation exchange is considered to be an extremely important reaction occurring in soils. Certain of the elements, such as calcium, magnesium, and potassium can occur as cations in soils. Cations possess a positive charge Clay and humus particles in the soil are usually negatively charged and therefore attract positively charged cations to their surfaces. Cations which are adsorbed in this manner are called exchangeable cations. These cations are made readily available to plants through a process known as cation exchange.

DYNAMICS OF NUTRIENTS IN THE SOIL

Removal of Nutrients

Nutrient elements in the soil are continuously being removed from and added to the soil system. Nutrients are removed by plants and are leached out of the soil by percolating water. Overirrigation can be a serious loss of plant nutrients due to excess leaching. Available plant nutrients can become "fixed" by soil components and thereby converted to a much less readily available form. Under some conditions, nutrients can assume gaseous forms and be given off as a gas into the atmosphere. We refer to such a process as volatilization. Under conditions of poor drainage and poor aeration, for instance, sulfur can be converted into hydrogen sulfide, which is a gas. Also under certain conditions, nitrogen can be lost as gaseous ammonia.

Addition of Nutrients

Nutrients are added to the soil through the weathering and decomposition of minerals and organic matter or washed out of the atmosphere in rainfall or added to the soil in irrigation water. Fertilizers are also used as a source of nutrient elements.

Nutrient Balance

It is also important that the soil contain a correct balance of nutrients. A high level of potassium can reduce the uptake of magnesium. Magnesium deficiencies can therefore occur where the potassium to magnesium ratio in soils is out of balance. Likewise, phosphorus can interfere with the uptake of zinc. It is, therefore, important that we adopt the multinutrient approach to soil fertility rather than the single element approach. As previously defined, a fertile soil is one which contains, among other things, a proper balance of nutrient elements.

The "Law of the Minimum"

One of the basic rules of soil fertility is known as the "Law of the Minimum." The "Law of the Minimum" states that the growth of plants is controlled by the nutrient element present in the most limiting amount. A deficiency of available phosphorus in the soil, for instance, will retard plant growth, even though all other nutrient elements are present in adequate amount.

The "Law of Diminishing Returns"

The "Law of Diminishing Returns" states that additional growth increments tend to decrease as additional increments of a nutrient element are added. Fifty pounds of nitrogen may result in a yield of 60 bushels. Seventy-five

and 100 pounds of nitrogen may give yields of 80 and 90 bushels, respectively. The first 25-pound increment of nitrogen, therefore, increased the yield by 20 bushels, and the second 25-pound increment increased the yield by a further 10 bushels. The yield increase from the second 25-pound nitrogen increment was, therefore, only one-half of the yield increase resulting from the first 25-pound nitrogen increment. This type of response to additions of nutrient elements is frequently, but not always, observed.

Some Nutrients are Mobile

The mobility of nutrient elements in soils varies considerably. Nitrogen in the form of nitrate and sulfur in the form of sulfate usually are highly mobile as they are not adsorbed or "fixed" by the soil particles. The mobile nutrient elements can move readily in the soil solution to the plant roots. Also, they can be readily leached out of the soil in percolating water. Losses of such nutrient elements are sometimes severe due to overirrigation.

Some Nutrients are Not Mobile

Other nutrient elements are considered to be "immobile" in the soil. Nutrients such as potassium and magnesium are adsorbed by clay and humus particles and thus do not move freely in the soil solution. Phosphorus is another "immobile" nutrient element. Its mobility is reduced due to the fact that it forms chemical compounds of low solubility. For the uptake of "immobile" nutrient elements by plants, root growth is of particular importance as the root must move to the nutrient rather than the nutrient moving to the root. Also, banding or placement of "immobile" nutrient elements in the vicinity of roots is important.

NUTRIENT SUPPLY TO PLANTS

Uptake of Nutrients

Most of the nutrients are taken up by plants through their root systems, through the process of ion exchange. Plant roots give off materials which result in the formation of hydrogen ions. These hydrogen ions exchange with nutrient elements, such as calcium and magnesium, which are in turn absorbed by the plant roots. The plant nutrients are largely removed from the soil solution, which is one reason why soil moisture is so essential to the growth of plants. The uptake of nutrients by plants can be affected by many factors such as temperature, soil aeration, and an adequate supply of other nutrients. Adequate nutrient uptake is only possible in the case of a healthy growing plant. Zones of active nutrient uptake in plant roots are the root tips and root hairs. Root tips and root hairs are associated with actively growing roots.

Sources of Nutrients

There are many ways in which nutrients are supplied to plants. Three of the major sources of nutrients to growing crops are nutrients released by the soil, residual nutrients from previous fertilizer, and nutrients supplied to the crop in fertilizers. This is illustrated in the following equation.

Nutrients in Soil	+	Nutrients from Previous Fertilizer	+	Nutrients Applied in Fertilizer	=	Nutrient Supply

It can be seen that if the soil releases adequate amounts of nutrients that further fertilizer applications are not necessary. Some soils, for instance, have a high natural fertility in such nutrients as calcium, phosphorus, or potassium. Additional applications of these nutrients will not result in increased yields and may under certain conditions even prove to be harmful.

Applications of fertilizer to some preceding crop may have resulted in a large residue of nutrients in the soil. Under such circumstances, additional fertilization would not result in an increased yield. Very often, a soil test will tell us when the soil will provide sufficient nutrition for plants, either from natural sources or from residues of previous fertilizer applications. When the soil does not supply adequate amounts of nutrients, then fertilization would be required for maximum yields.

THE ROLES OF NUTRIENTS IN PLANTS

Nitrogen

Nitrogen is a component of many of the substances found in plants. It is an essential component of amino acids and proteins, a large number of which are found in plants and are essential to their growth. Nitrogen is essential to the formation of chlorophyll, which imparts the green color to plants. As a result, deficiencies of nitrogen result in a restricted formation of chlorophyll and a resulting light green or yellowish color. Also, nitrogen is so essential to the growth of plants that when its supply is inadequate, plant growth is restricted, and the plant becomes small and stunted. Because nitrogen enters into so many of the essential components of plants, it is required by plants in comparatively large amounts. Plants well supplied with nitrogen have a dark green color, make abundant vegetative growth, and are succulent. Excessive vegetative growth and succulence resulting from an oversupply of nitrogen can result in lodging and other undesirable plant characteristics.

Phosphorus

Phosphorus is essential to proper cell division in plants and is therefore related to plant growth. Phosphorus deficiency results in the stunted

growth of plants, including poor development and growth of lateral and fibrous roots. Proper flowering, fruiting, and seed formation are dependent on an adequate supply of phosphorus. Phosphorus deficiencies can cause delayed maturity of crops, reduced crop quality, and a lower resistance to disease. In some plants, phosphorus deficiency causes a purplish discoloration of the older leaves.

Potassium

Potassium does not appear to be an essential component of any particular plant part. It is, however, essential to the translocation of sugars within the plant and in the synthesis of starch. Plants deficient in potassium exhibit poor root development and often have weak stems. Plants are capable of accumulating potassium to much higher concentrations than are actually needed for optimum growth. This excessive accumulation of an element is called luxury consumption. Some plants such as alfalfa and clover exhibit chlorotic spots around the edges of the leaves when potassium is deficient. Other plants such as cereals and grasses exhibit scorched areas on the margins and tips of the leaves.

Sulfur

Sulfur is an essential component of many substances important to plants. It is an essential component of many proteins and is necessary to the formation of chlorophyll in plants. As a result, sulfur deficiencies are very similar to nitrogen deficiencies--namely, yellowish coloration and stunted growth.

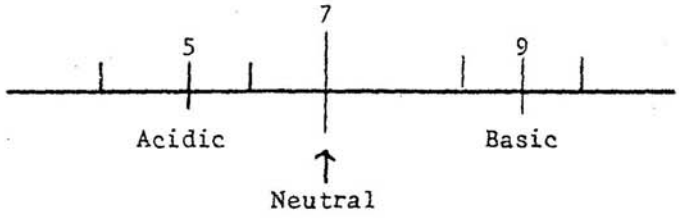
Calcium

Calcium is essential to several plant growth properties. It plays a role in the translocation of carbohydrates and proteins and prevents the toxic accumulation of such substances as aluminum, manganese, and oxalic acid. It is necessary to the normal development of leaves, roots, and root hairs. In some plants, a deficiency of calcium causes distortion on the terminal growing regions of the shoot and root.

pH

What is pH

The pH of a soil indicates whether the soil is acid or alkaline and is sometimes referred to as the soil reaction. A pH value of seven indicates that the soil is neutral and is neither acidic or basic in reaction. The hydrogen ion is the chemical component which causes acidity, and alkalinity is caused by the hydroxyl ion. Where hydrogen ions and hydroxyl ions are equal, the reaction is neutral and the pH is seven. Such would be the case with pure water which consists of equal numbers of hydrogen ions and hydroxyl ions.



pH and Nutrient Availability

The availability of many of the nutrient elements in soils is greatly affected by the pH of the soil. The availability of phosphorus, for instance, is the greatest between the pH 6.5 and 7.5. Under acid soil conditions, phosphorus combines with soluble iron and aluminum to form insoluble compounds. Under basic soil conditions, phosphorus combines with calcium to form insoluble calcium phosphate.

Microorganisms React to pH Changes

pH affects the properties of soils in many other ways. It influences the activity of microorganisms in the soil and is thus related to such things as nitrogen fixation by bacteria and the decomposition of organic residues.

pH is Related to Toxicities in Soil

Soil pH sometimes affects soil toxicity. In strongly acid soils, for instance, some of the elements, such as aluminum, manganese, and iron become comparatively soluble, and are sometimes absorbed by plant roots in such large amounts as to be toxic to the plants.

Plant Tolerance to Soil pH Conditions

Plants vary considerably in their tolerance to soil acidity. The following table groups plants on the basis of their tolerance to soil acidity.

Low Tolerance:	Garden beets, lettuce, sweet corn, cauliflower, spinach, cabbage, peas, carrots, asparagus, alfalfa, white clover, bluegrass, red clover, sugar beets.
Mod. Tolerance:	Meadow fescue, timothy, tall fescue, orchardgrass, alsike clover, crimson clover, vetch, soybeans, small grains, millet, corn, tomatoes.
High Tolerance:	Blueberries, cranberries, strawberries, potatoes, redtop, bentgrass, red fescue, rhododendrons, azaleas.

Sources of Acidity

There is a tendency in many cropped soils for acidity to increase. This is because many of the biochemical and chemical processes occurring in soils result in an increase in the number of hydrogen ions. Plant root activities result in the production of hydrogen ions. When organic matter decomposes in the soil, organic acids which give off hydrogen ions are formed. Many fertilizer materials react with the soil to form hydrogen ions. Ammonium nitrogen is a good example of this. Hydrogen ions tend to be strongly adsorbed by clay and humus particles in the soil and tend to replace basic ions, such as calcium and magnesium. The hydrogen ions tend, therefore, to be retained against the leaching action of percolating water.

Sources of Alkalinity

Certain factors in soils tend to increase or create alkalinity. Many of the soils in arid regions contain calcium carbonate or dolomite. These materials weather in soils, and their weathering products tend to create an alkaline soil pH. Certain alkali soils contain relatively large amounts of sodium carbonate which gives a particularly high pH, sometimes in excess of pH 10. Certain soil amendments such as applications of ground limestone or dolomite will increase the pH of acid soils.

The Acidity Effect from Fertilizers

Many fertilizer materials, particularly those supplying nitrogen, have an acidifying effect on soil. This is because the fertilizer material reacts with the soil to produce hydrogen ions. This reaction normally involves chemical and biological processes and is dependent upon such factors as irrigation, moisture supply, and soil temperature. The following reaction shows how ammonia reacts in the soil to produce hydrogen ions:

$$NH_3 + O_2 + \text{microbes} \longrightarrow NO_3 + H^+$$

The following reactions involving elemental sulfur and aluminum sulfate also show how these two materials increase acidity in soils:

$$S + H_2O + O_2 + \text{microbes} \longrightarrow SO_4 + H^+$$

$$Al_2(SO_4)_3 + H_2O \longrightarrow Al(OH)_3 + SO_4 + H^+$$

Equivalent Acidity of Fertilizers

Fertilizers create varying amounts of acidity in soils. Actually some fertilizer materials, such as calcium nitrate, increase the basic properties of soils rather than the acid properties. The following table gives

the equivalent acidity of several fertilizer materials. The acidity is expressed in terms of the amount of pure calcium carbonate or pure lime required to neutralize the acidity created by the fertilizer material. The first figure in the table gives the equivalent acidity per 100 lbs of nutrient element, whereas the second figure is the acidity per 100 lbs of actual fertilizer material. The first figure is probably the more meaningful one as we are really interested in the amount of acidity created per unit of nutrient applied.

Equivalent Acidity or Basicity of Fertilizer Materials

	% Nutrient	Equivalent Acidity[1] or Basicity per 100 lbs[2]	
		Nutrient	Fert.
NITROGEN FERTILIZERS			
Ammonium Nitrate	33.5	185	62
Ammonium Sulfate	20.5	535	110
Urea	46	182	84
Anhydrous Ammonia	82	180	148
Aqua Ammonia	20	180	36
Calcium Nitrate	15	133B[3]	20B
Calcium Cyanamid	22	292B	63B
Sodium Nitrate	16	181B	29B
NP FERTILIZERS			
Ammonium Phosphate	11-48	500(114)[4]	55
Amm. Phos. Sulfate	16-20	550(440)	88
Amm. Phos. Sulfate	13-39	530(177)	69
Diammonium Phosphate	21-53	357(141)	75
PHOSPHORUS FERTILIZERS			
Single Superphosphate	19	0	0
Concentrated Super	45	0	0
POTASSIUM FERTILIZERS			
Muriate of Potash	60	0	0
Potassium Sulfate	50	0	0
Potassium Nitrate	44	0	0
OTHERS			
Magnesium Potassium Sulfate		0	0

[1]Equivalent acidity or basicity is expressed as pounds of pure calcium carbonate or pure lime.

[2]Equivalent acidity or basicity is expressed in two ways--the first column is the pounds of $CaCO_3$ required to neutralize the acidity when enough fertilizer to supply 100 lbs of the nutrient is applied.

The second column is the lbs of $CaCO_3$ required to neutralize the acidity when 100 lbs of the actual fertilizer material is applied.

A sample calculation for a 200 lb. application of ammonium nitrate would be:

This can be calculated in 2 ways.

a) 100 lbs ammonium nitrate requires 62 lbs of $CaCO_3$ to neutralize acidity, therefore, 200 lbs would require

$$\frac{200}{100} \times 62 = 124 \text{ lbs of } CaCO_3$$

b) 200 lbs of ammonium nitrate contains

$$\frac{200}{100} \times 33{,}5 = 67 \text{ lbs of N}$$

100 lbs of N as ammonium nitrate requires 185 $CaCO_3$ to neutralize acidity,
therefore, 67 lbs of N requires,

$$\frac{67}{100} \times 185 = 124 \text{ lbs } CaCO_3$$

[3]The letter "B" means that the fertilizer material increases alkalinity rather than acidity.
A 100 lb application of calcium nitrate, for instance, would increase soil alkalinity equal to 20 lbs of $CaCO_3$.

[4]The figures in brackets represent the amount of acidity per 100 lbs of P_2O_5. The non-bracketed figures give the acidity values per 100 lbs of N.

CATION EXCHANGE AND CATION EXCHANGE CAPACITY

What is Cation Exchange

Cation exchange is the process whereby certain plant nutrient ions such as calcium, magnesium, potassium, and ammonium are attracted to and held on the surface of the very small clay and humus particles in the soil. This attraction occurs because these nutrients, when in the ionic form, possess a positive electrical charge, and the fine soil particles possess a negative charge. Through electrical attraction these nutrient ions or cations become attached or adsorbed to the surface of the clay or humus particles. In this state of attachment or adsorption they are referred to as exchangeable cations.

Soils Vary in Cation Exchange Capacity

Cation exchange capacity is an expression of the soils' capacity to adsorb cations. A soil which can adsorb a large number of cations per unit mass is said to have a high cation exchange capacity. As only the very fine particles in soils, namely the clay and humus particles, possess a negative charge, the cation exchange capacity of a soil high in clay and humus is normally greater than the cation exchange capacity of a coarse sandy soil which has little humus content. For this reason, coarse-textured sandy soils low in humus have a lower affinity to adsorb and retain such nutrients as calcium and magnesium than do soils with a relatively high clay and humus content.

How is CEC Expressed

The cation exchange capacity of a soil is expressed using a chemical term, namely milliequivalents per 100 grams of soil (meq/100g). A sandy soil might have a cation exchange capacity of 7 meq/100g, whereas a loam might have a value of 40 meq/100g. Humus has a relatively high cation exchange capacity and some muck soils, which are very high in humus, might have a cation exchange capacity of 200 meq/100g or more.

Converting from me to Pounds

To give some idea as to the meaning of milliequivalents in terms of pounds of nutrients, let us calculate the pounds of calcium in an acre six inches of soil, having a calcium content of 5 meq/100g. Referring to our chemistry tables, we find that one me of calcium is equal to 0.02 grams. 100 grams of soil, therefore, contains 5 x 0.020 or 0.10 grams of calcium. Using the same ratio, 100 pounds of soil would contain 0.10 pounds of calcium. An acre six inches of soil weighs approximately two million pounds. If 100 pounds of soil contains 0.10 pounds of calcium, two million pounds of soil would contain $\frac{2,000,000}{100} \times 0.10 = 2,000$ pounds of calcium. We could, therefore, say that a soil with a soil test value of five milliequivalents of calcium per 100 grams of soil would contain 2,000 pounds of exchangeable calcium per acre six inches. The use of milliequivalents to express the amounts of certain nutrients in the soil might seem unnecessarily complicated. There are, however, very good reasons from a chemical point of view, such as the calculation of cation exchange capacity and percent base saturation, for expressing some of the nutrients in this way. Similar calculations show that 1 meq/100g of potassium equals 780 lbs of potassium per acre six inches and that 1 meq/100g magnesium equals 240 lbs of magnesium per acre 6 inches.

Plant Uptake of Exchangeable Nutrients

Exchangeable cations such as potassium and calcium, which are attached or adsorbed to the surface of clay or humus particles in the soil, are available to plant roots. The uptake of these exchangeable cations by plants is brought about by a process known as cation exchange. In this process, positively charged hydrogen ions are given off by the plant roots and exchange with ions such as calcium and magnesium on the surface of clay & humus particles. The exchangeable cations which are thus released from the exchange complex of the soil can then be absorbed by the plant roots. This process of cation exchange is one of the most important processes which occurs in nature. Exchangeable cations are not readily removed from the surface of the fine soil particles by water and are, therefore, fairly resistant to leaching and other losses. They are, however, readily available to plants. The process of cation exchange is a major reason why clay and humus are important components of soils. Low cation exchange capacity is strongly related to the relative infertility of sandy, coarse-textured soils.

PERCENT BASE SATURATION

Definition of % Base Saturation

The percent base saturation of a soil is the percentage of the cation exchange capacity which is occupied by basic cations, namely calcium, magnesium, potassium, and ammonium. In most soils exchangeable cations which are found to be present in significant amounts are calcium, magnesium potassium, hydrogen and aluminum. The sum of all of these cations will normally equal fairly closely the cation exchange capacity of the soil. In most soil, the sum of calcium plus magnesium plus potassium, divided by the cation exchange capacity times 100 will equal the percent base saturation of the soil.

Thus, $\frac{\text{Exchangeable (Ca + Mg + K)}}{\text{CEC}} \times 100 = \%$ Base Saturation.

Base Saturation and Plant Growth

Normally, the higher the percent base saturation of the soil, the higher will be the pH. An average figure for a relationship between percent base saturation and pH would be about pH 5.5 for 50 percent base saturation and pH 7 or slightly higher for 100 percent base saturation. For crops with a high base requirement, such as alfalfa, it might be desirable to have a percent base saturation value of 90 percent. This figure, however, will vary with soils and with crops. Many workers have found that there is a better relationship between percent base saturation and lime requirement than there is between pH and lime requirement. For most soils and crops, for instance, liming is probably necessary whenever the percent base saturation is lower than 60. The figure would be much higher than this for some crops and soils.

CATION EXCHANGE CAPACITY AND FERTILITY MANAGEMENT OF SOILS

CEC and Fertilizer Application

Soils with a high cation exchange capacity have a greater ability to adsorb and retain nutrients. This has several implications. One is that nutrient cations, such as calcium, magnesium, and potassium, do not tend to be as mobile in the soils with a high cation exchange capacity as they are in sandy soils. Surface applications of these nutrients to soils with high cation exchange capacities result in the retention of the nutrient in the soil near the surface. The nutrients, therefore, may not move downwards into the rooting zone. This is the reason why band or plowdown applications of potassium are often recommended and why it is important to mix lime to as great a depth as possible when it is applied.

CEC is Related to Frequency of Fertilizer Application

Soils with low cation exchange capacity, such as sandy soils, cannot retain as many nutrients, particularly cations, as can clay loams. For this reason, more frequent fertilizer applications are often required on sandy soils and leaching losses are frequently greater by comparison with loams and clay loams.

Liming Rate and CEC

Soils with a high cation exchange capacity normally have a higher buffering capacity, that is, they tend to have a greater resistance to pH changes. They therefore require heavier applications of lime to significantly exchange pH or percent base saturation than do sandy soils. For this reason, higher rates of lime are usually recommended for clay soils than for sandy soils.

NITROGEN

Organic Matter as a Source of N

A major natural source of nitrogen in most soils is from the decomposition of organic material. Organic material normally contains some protein and one of the essential constituents of protein is nitrogen. When the organic material is decomposed due to the activity of microorganisms in the soil, nitrogen is released in a form in which it is available to plants. In some soils, which are high in organic matter, this can serve as a fairly substantial source of nitrogen for plant

growth. Organic nitrogen is, however, not readily available, as decomposition of the organic matter is required to convert organic nitrogen into an available form. The rate of decomposition of organic matter is dependent on adequate soil temperature, moisture, and aeration and the microorganisms must be adequately supplied with nutrients such as calcium, potassium, in order for them to actively decompose the organic material.

Organic Material Varies in N Content

The organic material in soils contains varying amounts of nitrogen depending upon the kind of plant from which the material originated. Leguminous plants, for instance, supply organic material which is relatively high in nitrogen, whereas grain straw is high in cellulose and lignin but has a relatively low nitrogen content. If we were to average across a large number of soils, we would probably find that the organic matter in these soils contained about five percent nitrogen. We could not, however, use this figure as the amount of nitrogen which these soils would supply to a growing crop. Probably only a relatively small proportion of this organic nitrogen would be made available to a crop during any single growing season. Certainly, however, other factors being equal, a soil high in organic matter could be expected to release more nitrogen to a growing crop than a soil which is low in organic matter. Under warm, moist soil conditions the nitrogen released due to the decomposition of organic matter would be very quickly transformed into the nitrate form.

Legumes Supply N

Another important source of nitrogen in soils is the N produced by legumes. Properly inoculated and nodulated legumes are capable of transforming the nitrogen in the atmosphere, which is not available to plants, into a form of nitrogen which is available to plants. This process is brought about by small organisms called rhizobia which infect the roots of legumes and produce a small swelling known as a nodule. The rhizobia live in these nodules, obtaining their nutrition from the plant and at the same time transform atmospheric N into an available form. This relationship between the host plant and the rhizobia is called symbiosis.

Inoculation of the Seed is Important

In order for legumes to fix nitrogen, the roots must be infected with with an effective strain of the rhizobia microorganims. Sometimes an effective strain is present in the soil, but frequently this is not the case. It is therefore good insurance to inoculate legume seed with a culture of rhizobia prior to seeding. The inoculum is cheap.

Good Inoculum Should Be Used

Certain precautions are required when inoculating legume seed. The correct strain of inoculum for the legume in question should be used. Different legumes require different strains of rhizobia. The inoculum should be fresh and should have been stored under proper conditions. Sunlight and heat will reduce the effectiveness of rhizobia. As a result, the rhizobia should be stored under darkened, cool conditions, preferably in a refrigerator.

How to Inoculate the Seed

Seed should be inoculated immediately prior to seeding. Inoculated seed should not be left in the sun or heat. The seed should be dampened with milk or a sugar solution prior to mixing with the inoculum. This increases the sticking of the inoculum to the seed coat. The moistened seed and the inoculum should be thoroughly mixed and as soon as possible the seed should be planted, preferably into warm, moist, soil. The broadcasting of inoculated seed on the surface of dry, hot, soil will greatly reduce the effectiveness of the rhizobia.

Some Nodules are Ineffective

The presence of nodules on the roots of legumes does not necessarily mean that nitrogen is being effectively fixed by these legumes. Some strains of rhizobia which are capable of producing nodules in legume roots are relatively ineffective as nitrogen fixers. If alfalfa plants are yellow and stunted and respond to applications of nitrogen fertilizer, the chances are pretty good that the alfalfa plants are not effectively inoculated even though nodules may appear on the roots.

Availability and Mobility of Organic Nitrogen in Soils

Organic nitrogen is relatively immobile and is only slowly available to plants. Organic nitrogen does not become available to plants until the organic material decomposes and the nitrogen is released in a form available to plants. The nitrogen is initially released in the ammonium form, which is a cation and is adsorbed onto the surface of clay and humus particles. The ammonium form of nitrogen is, therefore, fairly immobile. Ammonium nitrogen, under warm, moist, well aerated soil conditions, or under soil conditions where plants make good growth, is quickly converted over to the nitrate form of nitrogen. Nitrogen in the nitrate form moves fairly easily in the soil.

Availability and Mobility of N Fertilizers

Fertilizer materials contain nitrogen in various forms, including the ammonium, nitrate, and urea forms. Each of these forms can be utilized

by plants but most of the nitrogen is absorbed by plants as nitrate. Urea moves freely in soils but it is chemically fairly unstable under normal growing conditions, being converted rather readily, first to the ammonium form and then to the nitrate form. Nitrate is mobile in soils but is chemically fairly stable, although it can be reduced to gaseous forms of nitrogen under wet, poorly aerated conditions. The ammonium form of nitrogen is not mobile in soil, as it is adsorbed onto the exchange complex of soils.

Nitrogen Losses from Soil Due to Reduction

In addition to plant removal, which normally accounts for a considerable portion of the nitrogen loss from soils, nitrogen is also lost by leaching, as mentioned above, and also losses due to other phenomena sometimes occur. Under wet, poorly drained soil conditions, nitrate nitrogen can be converted, by a process known as reduction, to gaseous forms of nitrogen, such as nitrogen gas and nitrous oxide. These nitrogen gases can move to the surface of the soil and be given off into the atmosphere.

The Loss of Nitrogen as Ammonia

Another form in which nitrogen is lost from soils is as ammonia gas. Anhydrous ammonia consists of ammonia gas and if this nitrogen fertilizer material is not injected to a sufficient depth in the soil, it can be lost into the atmosphere from the surface of the soil. Applications of urea to the surface of the soils can sometimes result in nitrogen losses as urea is converted to ammonia by biochemical processes in the soil. Losses of ammonia can be serious where relatively large applications of urea are made to the surface of moist soil. Mixing the urea with the soil or washing the urea into the soil through irrigation or rain will substantially reduce these losses. Losses of nitrogen following applications of urea are normally more serious on neutral to alkaline soils, but can also occur on soils with a pH below 7. Nitrogen can also be lost as ammonia gas following surface applications of ammonium sulfate or ammonium nitrate to soils which are alkaline in reaction. These losses can be reduced by mixing the fertilizer with the soil as ammonia is adsorbed by the fine soil particles.

PHOSPHORUS IN SOILS

Phosphorus in Organic Matter

Phosphorus occurs in several different forms in soils. In some soils which are high in organic matter, organic phosphorus is an important source of this nutrient. Organic phosphorus is not readily available

to growing plants, as the organic matter must be decomposed before phosphorus is released in a plant-available form. Phosphorus is a constituent of plant and animal remains in soils.

Chemical forms of Phosphorus

The form of phosphorus in soils is frequently related to the pH of the soil. Under acid soil conditions, much of the phosphorus is present as iron and aluminum phosphates and under alkaline soil conditions, as calcium phosphates. These compounds are relatively insoluble and therefore tend to release plant-available phosphorus at rather slow rates. The availability of phosphorus, however, tends to be higher in the pH range 6 to 7.5. Liming an acid soil can increase the availability of phosphorus by raising the pH of the soil. When plant-available phosphorus is added to soils in the form of fertilizers, a considerable proportion of the phosphorus normally gets converted into low solubility compounds such as iron, aluminum, and calcium phosphate. The degree to which these insoluble compounds are formed depends on soil pH. If the soil is extremely acid, for instance, insoluble iron and aluminum phosphates may be formed to the point where very little of the added phosphorus is available to plants. For this reason it is frequently recommended that phosphorus fertilizer not be applied to strongly acid soils until they have been limed.

POTASSIUM IN SOILS

Most of the Potassium is in the Mineral Form

Nearly all mineral soils contain large amounts of potassium. Normally most of this potassium is contained in rocks and minerals and is not readily available to plants. As these rocks and minerals weather or break down in the soil, the potassium is released slowly in a plant-available form. Some of the potassium-bearing minerals in soils such as micas release potassium relatively rapidly and where soils contain large amounts of this type of mineral, they have a high potassium fertility and normally potassium fertilization is not required for optimum plant growth.

Soils Supply Varying Amounts of Potassium

Many of our soils, however, do not possess this natural ability to supply potassium and potassium must be applied in the form of fertilizer for optimum production of many crops. As mentioned earlier under cation exchange, the potassium ion possesses a positive charge and is therefore adsorbed onto clay and humus particles, in which form it is farily resistant to leaching and yet readily available to the plants.

"Fixation" of Potassium in Soils

Certain clay minerals in the soil, such as vermiculite, possess the ability to "fix" potassium. These small clay particles are plate-like in structure and under certain circumstances possess the ability to trap potassium between the platelets which make up the clay particles. This trapped potassium is referred to as "fixed" potassium and it is not readily available to plants. Sometimes when relatively small amounts of potassium fertilizer are applied to soils high in these potassium-fixing clays, the applied potassium becomes "fixed," thus reducing the response of the plants to the applied potassium.

Mobility of Potassium

Due to the adsorption of potassium by the exchange complex of soils and the fixation of potassium in some soils, the potassium ion does not have a high mobility in soils possessing clay or humus particles. For this reason, potassium which is applied to the surface of the soil does not readily move downwards into the rooting zone. For this reason, band or plowdown applications of potassium are frequently recommended.

Organic Matter Contains Potassium

As most plants contain relatively large amounts of potassium, organic matter or plant remains in the soil are a source of potassium for plant growth. Potassium in plant material is fairly water soluble and is thus readily available.

CALCIUM IN SOILS

Calcium is Abundant in Most Soils

Calcium is a constituent of many minerals such as calcite, limestone, dolomite, and gypsum, which are commonly found in soils. Most mineral soils contain substantial amounts of calcium, particularly when the pH is neutral or alkaline. Even most acid soils contain enough Ca for the nutritional needs of plants.

Calcium is Required to Neutralize Acidity

In most soils Ca is the main basic element and thus is important in neutralizing soil acidity. Additions of Ca in the form of lime are frequently made to acid soils as a means of raising the pH of the soil. The response to lime is usually indirect, being due to the increased availability of other nutrients, such as phosphorus or nitrogen.

Calcium is an Important Exchangeable Cation

Calcium is normally the most abundant exchangeable basic cation in mineral soils and in neutral or alkaline soils Ca usually occupies over 50 percent of the cation exchange capacity. In acid soils acidifying cations, usually mostly aluminum with some hydrogen, will often be more abundant on the exchange complex than Ca. Usually calcium plus magnesium will account for over 80 percent of the basic exchangeable cations in soils. Nearly all of the plant-available Ca in soil is in the form of exchangeable calcium. Ca is relatively immobile in soil.

MAGNESIUM IN SOILS

Sources of Magnesium

Magnesium is a constituent of several minerals such as dolomite and serpentine, which are found in soils. Similar to calcium, it is an important basic cation and thus neutralizes soil acidity. It is usually less abundant than calcium, both on the basis of total and available forms. Some soils are deficient in magnesium and Mg fertilizer is required to provide Mg for the nutrition of plants.

Magnesium Fertilization is Sometimes Necessary

Magnesium is sometimes added to soil in a liming material called dolomite. This material neutralizes acidity and also provides magnesium and calcium. It is used on acid soils which are deficient in magnesium. Most of the plant-available Mg in soils is in the exchangeable form. Mg is relatively immobile in soil.

SULFUR IN SOILS

Sources of Sulfur

Some minerals, such as gypsum, which are found in soils, contain sulfur. Minerals like gypsum, however, are fairly soluble and are, therefore, absent from soils in high rainfall areas where leaching occurs. Sulfur is a fairly important constituent of plant tissue and is present in organic matter in soils and becomes slowly available as the organic matter decomposes. In some areas considerable amounts of sulfur are added to the soil from the atmosphere. The sulfur is normally carried down out of the atmosphere in rainfall. This source of sulfur is most prevalent in the vicinity of industrial development where smoke and fumes containing sulfur are given off into the atmosphere. This source of sulfur has been reduced in recent years through the substitution

of electrical, natural gas, oil, and nuclear power and heat for coal and coke. In some areas, considerable amounts of sulfur are contained in irrigation water. This situation exists in some areas of eastern Oregon where responses to sulfur fertilizer are not obtained.

Forms of Sulfur

Various forms of sulfur exist in soils but under active growing conditions all forms of sulfur tend to convert to sulfate sulfur, which is the form taken up by plants. In most soils, sulfate sulfur is highly mobile and is thus readily leached from soils. For this reason, applications of sulfate sulfur are recommended at least every second year. Sulfate sulfur applied to the surface of the soils will move down readily in rainfall or irrigation water into the rooting zone of the plants. Other forms of sulfur, such as the elemental sulfur, are first converted over to sulfate sulfur in the soils prior to being taken up by the plants. Elemental sulfur has a greater residual effect in soil than does sulfate sulfur and its rate of availability is related to the size of the sulfur particle.

Fertilizers Supply Sulfur

Sulfur is a component of many fertilizer materials which are used to supply other nutrient elements. Examples of such fertilizer materials are ammonium sulfate, potassium sulfate, ordinary superphosphate, ammonium phosphate sulfate, and mixed fertilizers containing these fertilizer materials. Other materials commonly used to supply sulfur are gypsum and elemental sulfur.

BORON IN SOIL

Boron in Excess is Highly Toxic to Plants

Boron reponses have been observed in several soils in Oregon, particularly the more acid and highly leached soils in western Oregon. One factor about boron that always should be kept in mind is the fact that a small excess of available boron in soils can be highly toxic to plants and that the range between deficiency and toxicity is very narrow in the case of this nutrient. This has certain implications in the case of boron applications. Boron should never be banded in concentrated bands close to the seed, but it should be evenly applied to the soil. Boron should not be applied in excess of the recommended amount and should not be applied where soil analysis indicates that there is already an adequate amount of available boron in the soil. Some crops, such as beets, have a relatively high boron requirement and, therefore, relatively high fertilizer applications of boron are recommended for beet production. This could have a bearing on the crop to be grown following beets. For instance, beans have a low tolerance to boron and damage to beans has occurred where this crop has followed beets.

Sources of Boron

Organic matter is an important source of boron in soils and as a result much of the boron is often found in the surface soils where organic matter levels are higher. Some soils contain small amounts of boron in certain minerals. Plant-available boron is fairly mobile and boron thus tends to leach out of the soil. Boron deficiencies are sometimes related to high leaching conditions, particularly in sandy soils. In some parts of the United States, boron has been a toxic factor in irrigation water.

MOLYBDENUM IN SOILS

The total amount of molybdenum in most soils is very low and this nutrient is required in very small amounts by plants. Molybdenum in soil is found in both organic and mineral forms with the organic forms being more widely distributed. The availability of molybdenum is greater at higher pH values and as a result liming will frequently increase the uptake of molybdenum by plants. One must be very careful in the use of molybdenum fertilizer, particularly in the case of forages, as slight excesses of molybdenum in forage are highly toxic to animals. For this reason, when molybdenum is recommended, only very small applications are made. It has been found that phosphate in soils increases the availability of molybdenum, whereas sulfate decreases its availability.

Molybdenum deficiencies have occurred on several soils in western Oregon, with such crops as alfalfa, subclover and some vegetable crops.

ZINC IN SOILS

Plant-available zinc in soils tends to be rather strongly adsorbed by clay and humus particles and the availability of zinc is reduced by phosphate. As a result, zinc is highly immobile in soils and should therefore be banded or applied in such a way that the plant root can absorb the zinc. Sometimes the zinc is applied foliarly, in which case it is applied directly to the plant leaf. Also, zinc chelates are sometimes applied to the soil. Zinc in the chelate form is more mobile in the soil and thus moves more readily to the plant root.

Several soils in Oregon have been found to be deficient in plant-available zinc. Zinc availability decreases as pH increases and is particularly low in calcareous soils. As a result, zinc deficiencies have occurred on calcareous soils in eastern Oregon, with this condition being particularly prevalent on fields that have been leveled and where calcareous soils have been exposed during the leveling operation. Zinc deficiencies have also occurred on very sandy irrigated soils in the Columbia Basin area, on certain muck soils or high organic matter soils, and one soil type in the Stayton area of Marion County, where zinc deficiencies have been observed on sweet corn, a crop having a particularly high requirement for zinc.

MANGANESE IN SOILS

Many soils contain fairly large amounts of total manganese as it is a constituent of some rather important minerals found in many soils. The availability of manganese in some soils, however, is low, this particularly being the case in alkaline soils and calcareous soils. In acid soils, the solubility of manganese increases greatly and as a result, available manganese is sometimes present in toxic amounts in acid soils. One of the factors seriously limiting crop yields on acid soils in western Oregon, for instance, is a high level of soluble manganese. Toxicity due to manganese can be reduced through liming. Toxic amounts of manganese are sometimes present in soils that are not strongly acid when poor drainage conditions exist. Poor drainage or poor aeration can reduce manganese into a more soluble form.

Manganese deficiencies have not been observed on many soils in Oregon. The possibilities of deficiencies to some crops on calcareous soils in eastern Oregon does exist and manganese fertilization is practiced on irrigated sandy soils in the Columbia Basin area and on certain muck soils.

COPPER IN SOILS

Most soils, particularly some organic soils, are low in copper. The availability of copper is lower in alkaline soils. Copper is not at present considered to be deficient on mineral soils in Oregon. It is, however, applied to certain muck soils.

IRON IN SOILS

Mineral soils normally contain large amounts of total iron as it is one of the major constituents of many minerals found in soils. The solubility of iron is higher in acid soils and soluble iron is sometimes found to be present in toxic amounts in acid soils. Iron deficiencies normally occur in alkaline soils. Available iron is normally strongly adsorbed by the exchange complex.

TOXICITY IN SOIL

Some Soil Conditions Causing Toxicity

Several ways in which toxic conditions can occur in soils have been mentioned in preceding sections. In acid soils toxic amounts of soluble aluminum, manganese, and iron can occur. In poorly drained and poorly aerated soils soluble manganese can create toxic conditions and sometimes, where organic residues are present, toxic levels of reduced sulfur, methane gas or carbon monoxide can reduce plant growth. In alkaline or saline soils toxic conditions due to excess salt or sodium are common and irrigation water sometimes contains toxic levels of boron or salts.

Toxicity from Fertilizers

Fertilizer materials, if improperly used, can cause toxicities in soils. Ammonia is toxic to plants, particularly young plants and germinating seedlings. It is, therefore, recommended that toxic levels of ammonia fertilizers such as anhydrous and aqua ammonia and ammonia-producing fertilizers such as urea should not be banded in excessive amounts close to the seed.

Boron and Molybdenum can be Toxic

The highly toxic nature of boron has already been discussed. Boron in slight excess is very toxic and care should thus be taken to follow the recommendations regarding the application of this nutrient.

Molybdenum is required in very minute amounts by plants. Molybdenum, when present in slight excess in forage plants, can be highly toxic to livestock. The recommendations regarding the application of molybdenum must, therefore, be carefully adhered to.

Salt Injury from Fertilizers

Fertilizer applications increase the salt concentration in soils. The application of excessive amounts of fertilizer can increase the salt concentration to a toxic level. This situation frequently occurs with greenhouse and nursery soils. Also, toxic levels of salt can occur in the vicinity of fertilizer bands with a resulting damage of plant roots in the vicinity of the banded fertilizer. Fertilizer materials vary considerable in their effect on salt concentration in soils.

The Salt Index of Fertilizer Materials

The salt index of a fertilizer is a measure of the tendency of the fertilizer to increase the concentration of salts in the soil solution. The index is based on sodium nitrate which is assigned the index number of 100. The following table lists the salt index of several fertilizer materials.

THE SALT INDEX OF SOME FERTILIZER MATERIALS

Fertilizer Material	Percent Nutrient Content	Salt Index per 100 lbs[1]	
		of Nutrient	of Fert.
Nitrogen Fertilizers			
Anhydrous Ammonia	82	57	47
Ammonium Nitrate	33.5	299	100
Ammonium Sulfate	20.5	325	67
Sodium Nitrate	16	625	100
Urea	46	161	74
Phosphorus Fertilizers			
Single Super	19	39	7
Conc. Super	48	21	10
Mono Amm.Phos.	52	48	25
Diamm. Phos.	54	64	34
Potassium Fertilizers			
Muriate of Potash	60	194	116
Potassium Sulfate	54	85	46
Potassium Nitrate	47	158	74
Mag. Pot. Sulfate	22	197	43

[1]Salt index based on salt effect compared to sodium nitrate which is given a value of 100 for 100 lbs. of material.