How Soil Reaction Affects the Supply of Plant Nutrients

Two tons of ground limestone per acre made the difference between the alfalfa on the left and weeds on the right.

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How Soil Reaction Affects the Supply of Plant Nutrients[1]

The effect of soil acidity or alkalinity on the availability[2] of plant nutrients together with the relation between lime and fertilizers, is one of the most widely discussed subjects in agriculture. It is a subject which holds the interest of farmers, teachers, extension workers, and investigators alike. It is of interest to the grain and livestock farmer, to the vegetable growers, to the lime and fertilizer industries, to landscape gardeners, to the golfer and others. It is a subject about which a great deal of information has been accumulated, yet many phases of the problem are not well understood. They must be studied further by scientists, but the facts now available should be given wider dissemination and clearer explanation by teachers and extension workers.

Many changes take place when a soil becomes acid or when it is limed. The degree to which a soil has become acid or alkaline often determines the use which crops are able to make of the supply of plant nutrients in the soil. The state of reaction markedly affects the availability to crops of most plant nutrients, but others are affected to a lesser degree. The causes of the change in availability of plant nutrients with change in soil reaction are complex and in most cases indirect.

Whether the reaction is direct or indirect, however, is of secondary importance to the farmer. The important fact is that there is a change in the availability of plant nutrients to the crop as the soil reaction changes. If the reaction is known, a great deal of other information about the remainder of the soil system automatically becomes known, because of the close association between soil reaction and certain soil conditions. Hence the soil reaction may be thought of as one of the "pulses" which indicate the "state of health" of the soil, in the same sense that the temperature of the body is an indicator of the state of health in animals. Certain variations in the temperature of the body occur under conditions of normal health, but if the tem-

[1]This bulletin is a revision of one prepared by the late N. A. Pettinger entitled, "A Useful Chart for Teaching the Relation of Soil Reaction to the Availability of Plant Nutrients to Crops," published in March, 1935. The revision was made by members of the Agronomy, and Plant Pathology and Physiology departments of Virginia Polytechnic Institute.

[2]The term "availability" is necessarily used in its broadest sense. It embraces proper use within the plant and all of its antecedent processes. Nutrient availability may involve either wholly or in part the processes of solution, ionization, absorption, membrane permeability, ion antagonism and balance, and many others.

perature becomes either higher or lower than these limits, the animal is not well.

In soils, assuming other factors to be favorable for the growing of crops, a certain range in reaction indicates that the soil is "well," but beyond this range the state of health is not good. As the state of health is good or bad, soil conditions for the availability of plant nutrients will be favorable or unfavorable, respectively. Soil reaction may, therefore, indicate whether the farmer may expect an efficient use of the fertilizer he applies to the soil or whether much of the plant nutrients added will be lost or made very slowly available to the crop because soil conditions are not suitable for keeping the nutrients in forms that are usable by plants.

The importance of soil reaction is obvious, and its relation to liming and fertilizing crops is a matter that deserves not only a great deal of study and thought but wider dissemination and clearer presentation.

The information available on this subject is so widely scattered and much of it so well buried in technical literature that it has not been readily accessible to extension workers, teachers and other agricultural workers. In order to give this important subject wider and clearer presentation, it seems desirable to attempt a summary and simplification of the facts as they are now known and to make an effort to present the story in such a way as to interest non-technical groups.

The Colored Chart

The chart is composed of a series of bands of color representing the availability of some of the 15 plant nutrient elements[3] and a scale showing the range of reaction. The changes in width of the color bands represent changes in the availability of the different plant nutrients to crops over the range of soil reaction shown by the scale. As the bands become narrower the nutrients are less available and as they become wider the availability is increased.

As now constructed, the chart has certain limitations. At first it was hoped that the bands could be drawn so that their widths would represent the quantities of the various nutrients available to crops in the average soil. It was soon found, however, that this would be impossible. The quantities of phosphates, manganese, and iron available to plants are usually so small in comparison with calcium, magnesium, and potassium, that the idea of proportionate representation had to be abandoned. As a result, the differences in the widths of the various

[3]Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N), Phosphorus (P), Potash (K), Calcium (Ca), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), Copper (Cu), Boron (B), Zinc (Zn), Iron (Fe), and Sulphur (S).

bands have no significance when compared with each other. The important feature is the changes in width within the bands.

A second limitation is the fact that the chart is designed to illustrate only the changes which take place in well-drained mineral soils of the humid regions. No claims are made for its applications to the alkali soils of semi-arid regions nor to swampy or highly organic soils, although many of the relations shown also may apply wholly or in part to some of these soils. Furthermore, it cannot be guaranteed that the facts as represented in the chart will apply to any particular soil that may be selected. The changes indicated may be very mild and relatively unimportant in some soils, but in others they may be larger and of great practical importance. The chart is designed to illustrate basic principles involved in the availability of plant nutrients as associated with changes in soil reaction, rather than to portray the situation in a quantitative or absolute manner for any particular soil.

You should understand that not all of the changes in plant nutrient availability are caused by the changes in soil reaction. In some instances the degree of availability is determined directly by soil reaction, but in other instances availability is controlled largely by other processes which may or may not be related to soil reaction. Where changes in availability follow changes in soil reaction but the evidence is not clear that availability is a function of reaction, the situation should be referred to as one of association rather than as one of cause and effect.

Not all of the ideas represented in the chart meet with universal approval. Some investigators contend that in certain cases the trends of availability are somewhat different from those shown on the chart. Nevertheless, as now constructed, the chart represents the facts as shown by most of the evidence available and is the consensus of a number of authorities whose judgment has been solicited. When the discovery of new evidence makes it necessary to discard present beliefs either wholly or in part, or when better methods of representing the facts are developed, the chart will be revised.

Soil Reaction and the Meaning of pH

Soils, like many other things, are either acid, neutral, or alkaline (basic) in reaction. They become acid when there is an excess of acidic materials over those which are basic. They become alkaline when there is an excess of basic constituents over those which are acidic. When the acidic and basic materials are present in equal[4] proportions, the soil is neither acid nor alkaline and is said to be neutral.

[4]Equivalent.

The present method of measuring and expressing degrees of acidity or alkalinity in soils is in terms of pH values, very much like heat and cold are expressed in degrees Centigrade or Fahrenheit. The Centigrade temperature scale is centered around zero degree or the freezing point of water, and thermometers are used to measure intensities of heat and cold above and below this point. The scale of measuring acidity and alkalinity contains 14 divisions known as pH units. It is centered around pH 7, which is neutral. Values below 7 constitute the acid range of the scale; values above 7 make up the alkaline range. These relations are shown graphically in Figure 1.

From this it might be inferred that the acidity values below pH 7 measure the total amount of excess acid constituents and that the values above pH 7 measure the excess alkaline constituents. However, this is not true. Two acid soils with the same pH value, one a clay and the other a sand, require widely different amounts of lime for neutralization. It happens that the acid and alkaline materials exist in two forms, namely, (1) free[5] and (2) combined.[6] The former is always small compared to the latter. The pH scale measures only that portion of the excess acid or alkali which is in the free form. It gives no indication of the amount of combined acids or alkalies. The acidity scale below pH 7 is therefore a measure of the intensity of acidity rather than the quantity, and the scale above pH 7 measures the intensity of alkalinity rather than the quantity.

As shown in Figure 1 and in the accompanying color chart, the intensity of acidity increases tenfold with each unit decrease in pH below pH 7. Thus the free acidity is ten times more intense at pH 5 than at pH 6, ten times more intense at pH 4 than at pH 5, and so on. The intensity of acidity at pH 4 is 10 x 10 or 100 times the intensity at pH 6, and the intensity at pH 4 is 10 x 10 x 10 or 1,000 times that at pH 7. These tenfold increases in the intensity of free acidity are shown in the left half of the color chart by the portion in pink. The blue portion in the right half of the chart indicates the same relations with reference to alkalinity.

The pH Range of Soils

Soils in the eastern part of the United States are usually acid in reaction. The reason for this is that the soil retains certain acidic constituents while the basic materials are being removed by leaching and by cropping. The acidity of mineral soils in humid regions is usually between pH 5 and pH 6, sometimes below pH 5, but rarely as low as

[5]Ionized $H+$ and $OH-$.

[6]Molecular $H+$ and $OH-$: hydrogen in mineral and organic acids, acid salts, and hydrogen clays and humates, and hydroxyl ions in hydroxides.

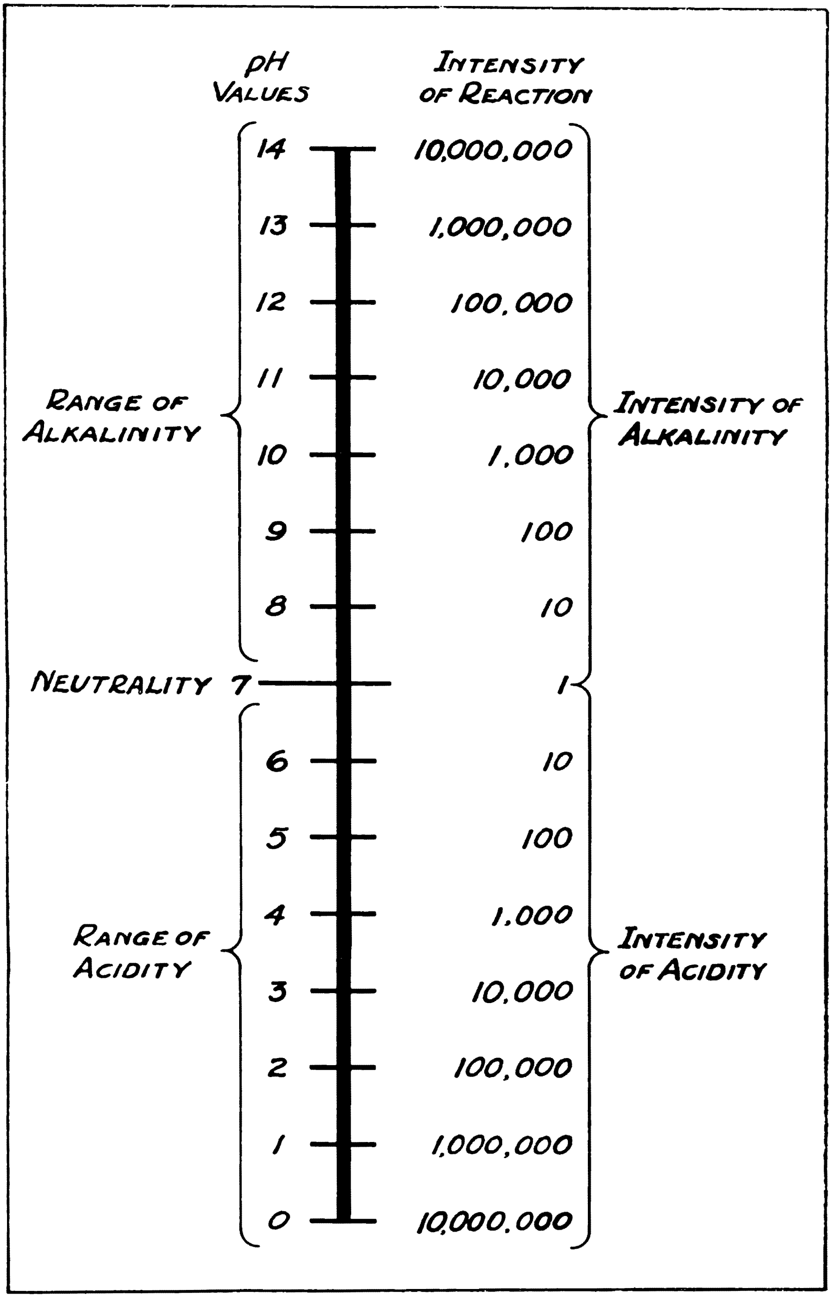


Figure 1

The relationship between pH and intensity of acidity or alkalinity. The intensity of acidity is not proportional to lime needs. (See Text.)

pH 4. Acidities between pH 6 and 7 are not uncommon, especially where lime has been applied in recent years. Neutral or slightly alkaline soils are seldom encountered and are found only where large quantities of lime have been applied very recently or where marl or other lime deposits are located near the surface. In the latter case the soil may have an alkalinity of the order of pH 8.

Under arid conditions, soils are predominantly alkaline. The pH is usually between 7 and 8, although alkalinities between pH 8 and 9 are not uncommon. Alkalinities above pH 9 have been observed in soils but are exceptionally rare.

Availability of Nitrogen

Nearly all plants absorb the bulk of their nitrogen in the form of nitrates. Some crops are known to make use of ammonia nitrogen, but under field conditions the quantity used by crops in this form is small compared to the amount of nitrogen absorbed as nitrates. There are, of course, many other forms of nitrogen present in soils, but crops apparently make very little use of them.

Over the usual pH range in soils, nitrates are apparently as available to plants at one pH value as at another. Hence, in special cases where crops receive all of their nitrogen from nitrate fertilizers, soil reaction probably exerts no appreciable influence on the availability of the nitrogen supply.

However, very few crops receive all of their nitrogen in the nitrate form. Practically all of them must obtain all or a part of their nitrogen from the soil organic matter, stable manures, ammonia fertilizers, urea, cyanamid, or such organic fertilizers as cottonseed meal, tankage, and fish meal or scraps. The nitrogen in these materials is slowly available to plants as it must be changed to a water soluble form before it can be used by crops. This change is made by microscopic organisms which live in the soil, and of which bacteria are the most important group. Since bacteria are living organisms they are affected by much the same conditions that influence crops. Therefore, when conditions are unfavorable for the activity of bacteria, the organic materials are not readily decomposed, and the nitrogen is not converted to an available form. When conditions are favorable to them, the bacteria decompose the organic matter more readily, the nitrogen is changed into available forms.

In acid soils nitrate formation is markedly reduced below pH 5.5. This is indicated on the color chart by a narrowing of the band labeled "nitrates." Above pH 5.5, other conditions being favorable, nitrate formation proceeds quite favorably until an over-supply of lime again reduces the activity of the bacteria. In humid-region soils, the harmful effect of too much lime on nitrate formation is seldom experienced.

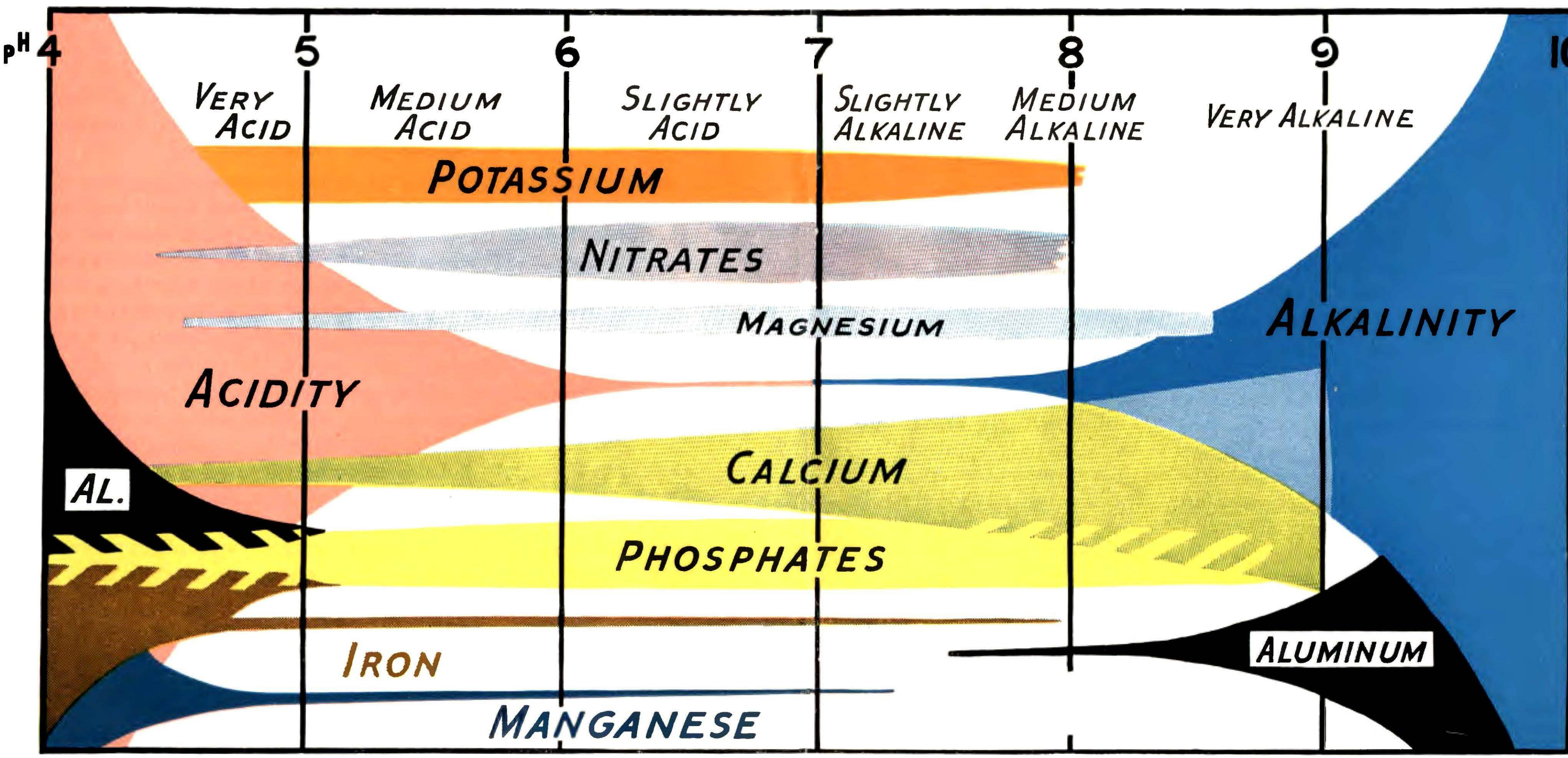
Availability of Phosphates

Phosphates are one of the most deficient plant nutrients in cultivated soils. Where it has become necessary to apply commercial plant nutrients, phosphates are usually the first to be added. Hence, anything which affects the availability of phosphates in soils is of tremendous importance. Processes which decrease their availability to crops must be reduced to a minimum; processes which increase their availability should be encouraged as much as possible.

Experiments have shown that soil reaction has a pronounced effect on the availability of phosphates. They are most available between pH 5.5 and pH 7.5. Above and below this range phosphates are partially fixed by other materials and their availability is reduced. Below pH 5.5 the fixation is thought to be accomplished largely by aluminum and iron, probably to a greater degree by aluminum than by iron. These two materials are relatively insoluble between pH 5.5 and pH 7.5, but below pH 5.5 they are more soluble. Their solubility is still low, however, until the pH drops to about 4.8 or 5, when they come into solution abundantly. As iron and aluminum come into solution they tend to unite with the phosphates to form iron phosphate and aluminum phosphate, considered to be very slowly available to crops. Their presence really indicates that phosphates which were once available have been converted to a form which crops cannot immediately use. Hence, the poor growth which plants often make on very acid soils may be due as much to phosphate starvation as to any other cause.

Above pH 7.5 phosphates again become less available, but for a different reason. Aluminum comes into solution again above pH 7.5 in increasing quantities, but in the alkaline range it is not able to fix phosphates as it did in the acid range. The availability of phosphates is reduced in over-limed soils by the high calcium content.

In the accompanying color chart the available phosphates are shown by the solid yellow band. The fixation of phosphates by aluminum is shown by alternate bands of yellow and black, thus indicating the formation of the unavailable aluminum phosphate. The fixation by iron is shown by the alternate bands of yellow and brown, indicating the union of iron and phosphate to form the unavailable iron phosphate. In the alkaline range, the reduction in phosphate avail-



General Relationship Between Soil Reaction (pH) and Availability of Mineral Elements to Plants.

ability is shown by alternate bands of the colors representing phosphates and calcium.

Toxicity of Aluminum

When the acidity becomes very high in some soils (pH 4 to 5) more aluminum is present than is used in the fixation of phosphates. Since aluminum is brought into solution by soluble fertilizers, the toxic effects of aluminum are made worse by high fertilizer applications to acid soils.

Recent investigations indicate that this free aluminum is very harmful to the roots of plants because it prevents proper development and nutrient uptake. Aluminum is probably the chief factor which inhibits growth of plants in most of our acid soils.

Availability of Potassium

Very little is known concerning the relative availability of potassium to crops in humid soils of different pH values. Some evidence has been accumulated which indicates that in heavily limed soils, potassium is somewhat less available than where liming has been light or moderate. This may be due in part to the competitive action between potassium and calcium. There is no conclusive evidence available concerning the relative changes in the availability of potassium in acid soils, but many agronomists believe that there is very little change in availability in the usual acid range of soils.

Very acid soils have often been observed to be deficient in available potassium. However, this is usually due to continued removal by cropping and leaching and in some cases to erosion, which means that the deficiency is not due to factors affected by the soil reaction. When available potassium is added to such soils it apparently remains in a form available to crops.

Available Supply of Calcium and Magnesium

Calcium is the principal constituent of importance in liming materials. It usually is considered synonymously with lime and commonly is referred to as lime. Even where dolomitic lime is used to introduce magnesium, calcium is added in large quantities. Lime adds calcium as a weak base which, over a period of time, reacts with the soil and replaces the acidity. Liming, therefore, would be expected to increase the supply of available calcium and raise the pH in a soil. The accompanying colored chart shows this to be true. The quantity of calcium available at pH 4 usually is very small but as the pH of the soil is raised by adding lime, more and more calcium is held by the soil. In addition, the calcium which is there becomes more available as the pH is raised.

The quantity of magnesium available to plants usually is smaller than that of calcium. Its relative abundance at different pH values tends to parallel calcium although this may not always be true. For example, in very acid soils, magnesium often is present in larger quantities than is calcium. This is because magnesium is a part of some clay minerals; whereas, calcium is not. Also, magnesium deficiencies may occur on sandy soils where no dolomitic limestone has been used even if the pH is quite high. As an average, however, the chart shows magnesium to increase in availability with increasing pH until pH 8.0 is reached.

In very acid soils the quantity of available calcium and magnesium is often too small for a satisfactory growth of crops, and is unquestionably one of the factors contributing to the poor growth of crops on such soils. Calcium deficiencies are often unobserved because of the lack of definite symptoms in the growing plants, but acute deficiencies of magnesium are sometimes observed in sandy soils by a failure of the plants to develop normally the green coloring matter in their leaves. These troubles usually occur in very acid sandy soils where the basic constituents have been reduced to a low level by cropping and by excessive leaching. A few crops, such as watermelons, cranberries, and strawberries, apparently require very little basic materials and make a satisfactory growth at low pH values. Potatoes and tomatoes are also usually grown at relatively acid reactions, but this is done to help control diseases which are encouraged by lime. Most crops, however, require at least a fair supply of basic elements, and make their best growth when the soil is only slightly acid. Some of the leguminuos crops like alfalfa and sweet clover prefer large quantities of available calcium, and soils are usually limed to near neutrality where these crops are to be grown.

Availability of Manganese and Iron

The elements manganese and iron are quite similar chemically and behave alike in the soil with respect to pH. Their solubilities are high at pH 5 and below and decrease in less acid soils. Whether or not sufficient quantities of manganese and iron are available for normal plant growth depends in part on the quantity and forms of the elements present in the soil. The presence of excess calcium, and probably other elements, also affects their uptake. Moreover, there is evidence that the presence of easily decomposed organic matter often increases the availability of these elements, particularly in heavier soils and where the soil contains abundant moisture. Thus, it may be seen that the availability of manganese and iron is complex and is relatively easily varied by cultural practices, liming, and weather conditions.

Manganese is usually less abundant in soils than iron and deficiencies of the former may be related to this fact. Deficiencies usually have been noted on sandy soils high in calcium having a pH 6.0 to 7.0 or above. Often the affected area is confined to sites of former lime piles. These deficiencies may be corrected by dusting or spraying the foliage with soluble manganese compounds, or by applying a large quantity directly to the soil. Large additions of sulphur to the soil are slowly effective in lowering the pH and in reducing oxidized manganese to more soluble forms.

Toxic quantities of manganese may be available to plants under certain conditions: pH below 5.0 and high manganese content. Liming to over pH 5.0 usually corrects this toxicity.

The amount of manganese and, particularly, iron within a plant is not always low when apparent deficiency symptoms occur. High amounts of phosphate within the plant may precipitate iron and make it inactive. High calcium also appears to inactivate the iron within the plant.

Availability of Boron

Within the past ten years extensive studies have been made concerning the boron requirements of plants. They have shown a definite relation between soil reaction and boron availability. A positive correlation between available boron and pH in certain acid soils has been found while other soils do not show this relation. It is generally agreed that boron availability decreases as the pH of the soil increases from pH 7 to 8. Several explanations of this phenomenon have been made. In some soils that are high in organic matter, it has been found that heavy liming greatly reduces the availability of boron because of the fixation of boron in some organic complex. In other soils, the fixation of boron above pH 7 is not related to organic matter. On some heavily limed soils, certain plants may develop boron deficiency symptoms even though the amount of available boron in the soil has not been reduced as a result of raising the pH. The boron requirements of these plants appear to be increased under such conditions and can be supplied by the addition of more boron to the soil.

Availability of Other Trace Elements

Zinc and copper are elements needed by plants in only small amounts, but they are sometimes lacking, particularly in extremely sandy soils and in soils which are high in organic matter. When the soil pH is raised by the addition of lime, the availability of these elements is reduced.

Molybdenum is required in very minute quantities compared to the other elements. For example, an application of one ounce per acre will sometimes correct a deficiency. On the other hand, an excessive amount of molybdenum in forages causes a copper deficiency in animals on pasture; therefore, the supply must be regulated carefully. Molybdenum also is different from the other trace elements because it becomes more available with liming, much as phosphorus does.

Summarizing the Chart

From the chart we may draw the following conclusions:

1. Most crops respond best to soils that are limed to a pH of between 5.5 to 7. Do not go to extremes either way.
2. For a few crops such as potatoes, strawberries, and tomatoes, you will get better results by liming to the lower limit of this range.
3. For such lime-loving crops as alfalfa and sweet clover, you will get better results by liming to the upper limit of this range.
4. Lime is no substitute for fertilizer. However, if the soil reaction is adjusted properly, lime often has the same result as fertilizer where the shortage of plant food is not acute.
5. Where tests show the available plant food in your soil to be low, add fertilizer. Be sure, however, that the soil reaction is as near the desirable range for plant food availability as the requirements of the crop will permit.

Suitable pH Ranges for Various Crops

FIELD CROPS

Alfalfa	6.5 to 7.5
Alsike clover	6.0 to 7.0
Barley	5.5 to 7.0
Buckwheat	5.5 to 6.5
Corn	5.5 to 7.0
Cotton	5.5 to 6.0
Cowpeas	5.5 to 7.0
Crimson clover	6.0 to 7.0
Grasses	5.5 to 7.0
Lespedeza	5.5 to 7.0
Oats	5.5 to 7.0
Peanuts	5.5 to 6.2
Millet	5.5 to 7.0
Red Clover	6.0 to 7.0
Rye	5.5 to 7.0
Sorghum	5.5 to 7.0
Soybeans	5.5 to 7.0
Sweet Clover	6.5 to 7.5
Tobacco (1)	5.0 to 6.5
Velvet beans	5.5 to 6.5
Vetch	5.5 to 6.5
Wheat	5.5 to 7.0
White clover	6.0 to 7.0

(1) Bright 5.0-6.0; Burley 6.0-6.5; Dark fired and sun-cured 5.5-6.5.

GARDEN AND TRUCK CROPS

Asparagus	6.0 to 7.0	Onions	6.0 to 7.0
Beans (large lima)	5.5 to 6.5	Parsnips	5.5 to 6.5
Beans (small lima)	5.5 to 6.5	Peas	6.0 to 7.0
Beans (snap)	5.5 to 6.5	Peppers	5.5 to 6.5
Beets	6.0 to 7.0	Potatoes (Irish)	5.0 to 5.5
Cabbage	5.5 to 6.5	Potatoes (sweet)	5.0 to 6.0
Cantaloupe	6.0 to 7.0	Pumpkins	5.5 to 6.5
Carrot	5.5 to 6.5	Radishes	5.0 to 6.5
Cauliflower	5.5 to 6.5	Rhubarb	5.0 to 6.5
Celery	6.0 to 7.0	Salsify	6.0 to 7.0
Corn (sweet)	5.5 to 6.5	Spinach	6.0 to 7.0
Cucumber	5.5 to 6.5	Squash	5.5 to 6.5
Eggplant	5.5 to 6.5	Strawberries	5.0 to 6.5
Kale	5.5 to 6.5	Tomatoes	5.5 to 6.5
Lettuce	6.0 to 7.0	Turnips	5.5 to 6.5
Mustard	5.5 to 6.5	Watermelons	5.0 to 5.5
Okra	6.0 to 7.0		

Note: These reaction ranges are for soils which are adapted to growing the various crops listed. Thus, the pH values given for garden crops apply to the sandier soil types, because it is on such soils that commercial vegetable growing is concentrated. For fine textured soils and on soils which are very high in organic matter, the pH range for satisfactory production of each crop would be somewhat wider. The pH values given for most of the field crops are for soils which are finer in texture than those devoted to commercial vegetable production.

Since all crops have a suitable pH range, anyone interested in the economical production of plants should have the soil in which they are to grow tested every few years. Soils tend to become more acid under cropping and one should know how rapidly this occurs in order to lime wisely. On the other hand, such information may prevent overliming which, besides being expensive, may greatly reduce crop yields.

Amount of Material Required To Change pH Values

Different soils will require a different amount of lime to adjust the reaction to the proper range. The texture of the soil, the organic matter content, the prevailing reaction, the crop to be grown, the kind of lime to be used, and the soil type are factors which you should consider. Sandy soils require much less lime than heavy or fine-textured soils. Soils low in organic matter require less lime than soils high in organic matter. For practical liming recommendations the following amounts of lime per acre will be found to be satisfactory for changing the reaction of soil 1 pH unit when the organic matter content is average or medium. For soils low in organic matter, these amounts may be reduced 25 percent, but for soils high in organic matter they should be increased 100 percent (doubled).

Soil Class	Pounds per acre required to change reaction from pH 5.0 to pH 6.0		
	Burnt Lime	Hydrated Lime	Ground limestone, Marl, or oyster shells (100 mesh)
Sandy loams	1,120	1,480	2,000
Loams	2,240	2,960	4,000
Silt loams	3,360	4,440	6,000
Clay loams	4,480	5,920	8,000

If your soil has been overlimed, you can do one of three things —wait for the reaction to adjust itself, apply sulphur, or grow crops that tolerate a high pH.

(1) It may require several years for the reaction on overlimed soils to decrease naturally. In the meantime deficient plant nutrients should be supplied, or crops with high feeding power for the deficient elements should be grown. These crops usually are those which grow best at a high pH.

(2) You can bring the soil reaction down to a suitable pH reaction in a few months by adding approximately one pound of sulphur to counteract the effect of three pounds of ground limestone. Apply sulphur in bands in the root zone of the crop to be grown since you will get the same effect this way with less sulphur.

(3) If the soil is otherwise suitable, you can grow such crops as alfalfa or sweet clover, that grow well on soils with high pH.

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