The Liming of Soils

by EMIL TRUOG

ABOUT three-fourths of the cultivated land in our humid regions needs lime. What would happen if farmers stopped applying it? Just this: Yields on lands where more than half of our agricultural crops are now produced would start to go down. For a few years we would not notice the decline very much. In a decade it would become quite pronounced. In 30 years or so the yields might be cut in half; in 50 years the result would certainly be hunger and disaster. And not only would harvests drop; control of soil erosion would become increasingly difficult.

In recent years American farmers have become well aware of the need for liming: In 1944 they used nearly 25 million tons of agricultural lime, four times the amount applied just 8 years earlier and seven times more than in 1929. Calculations by C. E. Carter of the Department indicate that about 40 million tons of lime annually should be used for the next decade on our arable and pasture lands. That a usage approaching that figure may be attained in the near future seems quite probable.

Extensive educational work on liming by the State and Federal agencies, including hundreds of thousands of tests for acidity and numerous field demonstrations of results, has brought about a general and thorough realization among farmers of the widespread need for lime and its benefits. Because liming of acid soils has been shown to have a favorable effect as regards fertility on the physical, chemical, and biological properties of soils, farmers now appreciate, as never before, why liming of land is often referred to as the backbone of profitable and permanent agriculture in humid regions.

Occasionally the application of lime has reduced crop yields, and some farmers naturally doubted its value. Now we know why: For the most part, it turns out to be a lowered availability of boron and manganese. Sometimes the application of too much lime, especially to sandy soils that are low in active organic matter, makes the boron and manganese in the soil less available. In this country, James A. Naftel, of Alabama, was the first to demonstrate the relationship of overliming to a deficiency of available boron. His early investigations, made with a number of crops, notably cotton grown on Norfolk loamy sand, emphasize the great importance of carefully regulating the amount of lime added in accordance with needs as indicated by soil tests.

Boron is a nutrient element required in small amounts—a ton of alfalfa hay may contain about an ounce—by all crops for normal growth. The amount present in fertile soils in available form (that is, extractable with hot water) is usually not more than 1 to 5 pounds per acre plow layer. In some soils, particularly those that are low in organic matter and have been severely leached and exhaustively cropped, as is the case with many sandy soils of the South and Southeast, the content of available boron is so low that a slight reduction in availability, such as may be effected by liming, greatly reduces crop yields. The application of 25 to 50 pounds of borax to the acre remedies the condition, so that the lime needed to grow satisfactory crops of alfalfa, clover, and other crops may be added.

The relation of the availability of manganese to liming is much like that of boron. It has been known for 20 years or more that high pH (alkalinity) or heavy liming sometimes induces a deficiency of available manganese, but not until recent years was the frequency of the occurrence established by means of controlled experiments. Plants need but little manganese—a ton of alfalfa hay usually contains about 1 pound—but that amount is greater relatively than the requirement of boron.

The supply of available manganese in sands and loams that are low in organic matter and in certain peats that have little manganese-containing minerals is frequently too small for crop needs when their pH rises above 7 and—more important—when they are calcareous. The explanation for this is now quite clear. As long as the soil is acid (that is, the pH is below 7), a considerable part of the manganese tends to be in the divalent (reduced or manganous) form. In that form it acts like calcium or magnesium, particularly as an exchangeable cation, and is readily available because it is brought into solution as a bicarbonate through the action of the ever-present carbonic acid. As the pH rises to 7 and higher, there is a greater tendency toward the oxidation of divalent manganese to the tetravalent form by the oxygen dissolved in the soil solution, in accordance with the following reaction: $2Mn(OH)_2+O_2=2MnO_2+2H_2O$. Tetravalent manganese in the form of manganese dioxide (MnO_2) is insoluble in carbonic acid, and is, therefore, not readily available for crop use.

Because oxygen is required in the reaction for the formation of the highly insoluble manganese dioxide, we would expect that the excessive aeration of the soil would also favor the formation. That is the case. Thus, a combination of high pH and excessive aeration is the condition under which a lack of available manganese most frequently occurs. Because sands and loams that are low in organic matter and water-holding capacity are often over-aerated, it is these kinds of soils that are most subject to a lack of available manganese when the pH is high. Some peaty and very sandy soils are so low in total manganese and so severely leached that even when they are strongly acid they lack an adequate supply of this element in available form.

On the other hand, the heavier soils and those containing considerable organic matter hold much more water and do not easily become over-aerated; in fact, a lack of aeration often occurs in the heavier soils, especially during periods of heavy rainfall. Such soils are usually also better supplied with organic matter, which, on decomposition, releases its manganese in available form and favors the transformation of manganese minerals to the available type. A lack of available manganese at high pH, therefore, occurs much less frequently in the heavier soils than in the lighter ones. In either case the lack is usually remedied by an application of 25 to 100 pounds of manganese sulfate to the acre.

The discovery of the relationship between liming and the availability of boron and manganese and the remedy is one of the reasons for the recent rapid increase in the use of lime in some sections of the South and Southeast where the soils are generally very acid. This greater use of lime is a great boon there; it makes possible the production of good crops of the more valuable legumes, which, in turn, add badly needed nitrogen and organic matter to the soils.

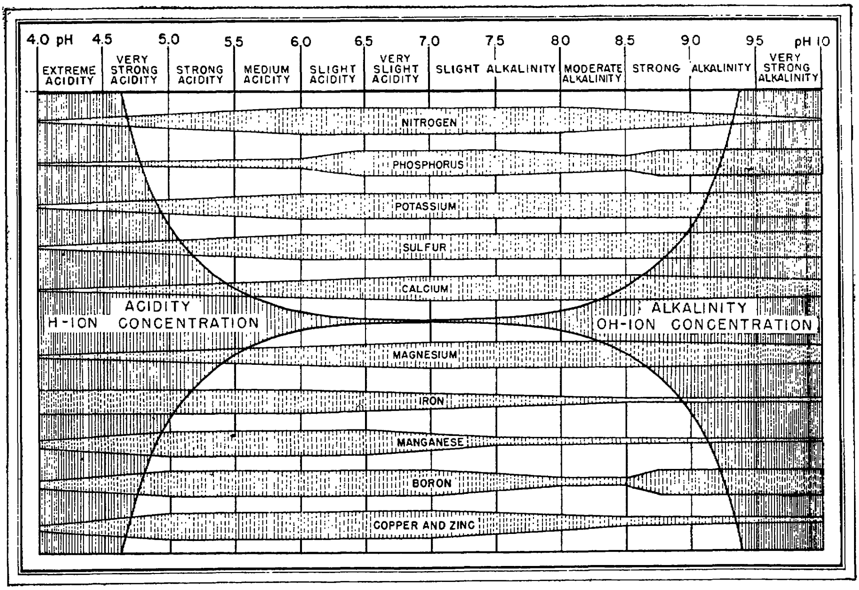
It is of interest to note what Edmund Ruffin wrote about reduced yields that occasionally follow the application of lime (marl) in excessive amounts to acid soils: "There are many practices universally admitted to be beneficial—yet there are none, which are not found sometimes useless, or hurtful, on account of some other attendant circumstance, which was not expected, and perhaps not discovered. Every application of calcareous earth to soil is a chemical operation on a great scale; decompositions and new combinations are produced, and in a manner generally conforming to the operators' expectations. But other and unknown agents may sometimes have a share in the process, and thus cause unlooked-for results. Such differences between practice and theory have sometimes occurred in my use of calcareous manures (as may be observed in some of the reported experiments) but they have neither been frequent, uniform, nor important."

Possibly the reduced yields of which Ruffin wrote more than a hundred years ago were caused by a lack of available boron or manganese, or both; prophetically, his words carry the inference that the cause of the reduced yields would some day be elucidated so that proper remedial measures could be taken. He found that sandiness and paucity of organic matter accentuate the overliming injury, that clover was less affected than other crops, and that its growth with attendant addition of organic matter would in time overcome the unfavorable condition for other crops. These observations are in accord with ours today. Possibly the reason that legumes that persist for more than one season, like red clover and alfalfa, are less affected by overliming than certain annuals is because by the second year their well-established root system are feeding to advantage for nutrients, such as manganese, below the limed layer. Also, by feeding throughout the growing season, they are able to take advantage of more favorable periods when there is abundant moisture.

Liming and the Availability of Plant Nutrients

The influence of reaction and accompanying conditions on the availability of the plant nutrients obtained from the soil proper is shown diagrammatically on page 570, which is simpler in form but more complete in several respects than that published by N. A. Pettinger. Reaction is expressed in terms of the pH scale. The reader is reminded that on this scale, a pH value of 7.0 (the middle vertical line in the diagram) represents the neutral point, while values to the left and progressively less than 7 express increasing acidity, and values to the right and progressively greater than 7 express increasing alkalinity. Also, a change in pH of one unit expresses a tenfold change in reaction; thus, pH 5 expresses acidity which is 10 times as intense as that at pH 6; likewise, at pH 9 the alkalinity is 10 times as intense as at pH 8. This change in intensity of acidity and alkalinity is shown in the diagram by the change in width of the heavily cross-hatched area between the curved lines.

In the drawing the influence of reaction and accompanying conditions on the availability of each nutrient element is expressed by the width of the band (the wider the band the more favorable the influence) carrying the name of the respective element. Thus, for the maintenance of a satisfactory supply of available nitrogen, a reaction or pH range of 6.0 to 8.0 is the most favorable. This does not mean that if the reaction of a soil falls in this range that a satisfactory supply of available nitrogen is assured. All it means is that as far as reaction is concerned, the conditions are favorable for a satisfactory supply of available nitrogen. Also, the narrowed band for nitrogen at pH 5 does not necessarily mean that a deficiency of this element will prevail at that pH; it means that as far as reaction is concerned, the conditions are not favorable for an abundant supply of available nitrogen; other factors than reaction and the usual accompanying conditions may even promote the presence of an abundant supply; moreover, certain crops having a low requirement may be fully satisfied with a low supply. What I have said about nitrogen holds also for the other nutrient elements.



This chart illustrates the general trend of the relation of reaction (pH) and accompanying conditions to the availability of plant-nutrient elements.

At both strong acidity and strong alkalinity, the conditions as regards the fixation of nitrogen by legumes and the transformation of organic nitrogen to forms available to plants become increasingly less favorable.

In the case of phosphorus, you will note that in the pH range of 6.5 to 7.5 conditions are most favorable for high availability. Below pH 6.5 the influence as regards availability rapidly become less favorable. That is an important reason why acid soils should be limed to pH 6.5. In fact, if lime produced no other benefit than its favorable influence on phosphate availability, it would usually pay to use it. At pH 6.5, lime is sufficiently abundant and available to keep a considerable portion of the phosphorus in the form of calcium phosphate, which is soluble in carbonic acid and hence is readily available to crops. This holds for both the phosphorus naturally present in soils and that applied as manures and fertilizers.

When lime is present or added in amounts so as to raise the pH beyond 7.5, the influence on phosphate availability gradually becomes less favorable, although this is usually not serious until the pH goes beyond 8 and there is present 2 to 3 percent and more of free calcium carbonate. The reason for this is explained by these reactions:

$$CaCO_3 + H_2CO_3 = Ca(HCO_3)_2$$

$$Ca_3(PO_4)_2 + 2H_2CO_3 = Ca_2H_2(PO_4)_2 + Ca(HCO_3)_2$$

The action of carbonic acid on calcium carbonate is expressed by the first reaction, and on calcium phosphate by the second reaction. The solubility of all the products is low, but adequate for plant nutrition.

You will note that calcium bicarbonate is formed in both reactions. Now, if a great abundance of calcium carbonate is present in a soil, the action of carbonic acid on it will keep the soil solution saturated with calcium bicarbonate, and this will greatly retard or even stop the second reaction, because it also involves the formation in solution of calcium bicarbonate. In other words, when the soil solution is once saturated with a certain product, such as calcium bicarbonate, all reactions involving the formation of this product are brought to a standstill until some of the product is removed by leaching or plant feeding. The explanation coincides with the principle of chemistry usually referred to as the law of mass action. Our observations indicate that usually a soil must contain several parts per hundred of calcium carbonate—that is, enough to permeate all the minute areas of a soil—in order to retard seriously the availability of phosphate. Of course, since 1 percent of calcium carbonate in a soil represents 10 tons of lime to the acre, a condition of this kind is seldom, if ever, produced by liming.

It is to be noted that when the pH of soils goes higher than 8.5, the availability of their phosphorus tends to increase again. This is because in this higher pH range the soil solution contains small amounts of sodium hydroxide which reacts with insoluble soil phosphates and forms small amounts of the highly soluble and available sodium phosphate. Since little or no leaching usually accompanies this high alkalinity, most if not all of the sodium phosphate thus formed is available for use by such crops as will grow at this high alkalinity.

It will be noted in the chart that conditions associated with acidity, especially of a pronounced degree, are unfavorable as regards the availability of sulfur, potassium, calcium, and magnesium. At strong acidity, the conditions for both the accumulation of sulfur in organic matter and its subsequent transformation to sulfate for plant use are not favorable. With increasing acidity, the amounts of the other three elements in exchangeable or readily available form usually decrease because of the attendant severe leaching; furthermore, the elements are held more tightly by the excess of insoluble acids against solution and plant feeding.

The availability of the other nutrient elements, iron, manganese, boron, copper, and zinc (often referred to as the minor nutrient elements), is influenced greatly by reaction. The influence on boron and manganese has been discussed. It should be noted that beyond pH 8.5, the influence of reaction is again in the direction of making boron more available; that is due to the presence of sodium hydroxide in the soil solution, which forms soluble salts of boron that are available for plant use.

The influence of reaction on the availability of iron is similar in nature to that of manganese, but due to the great abundance of iron in soils compared to manganese, deficiency of the former in available form does not occur nearly so often as of the latter. Below pH 6.5, small amounts of iron tend to exist in the ferrous state. In that form the iron is soluble in carbonic acid, and so is readily available. In fact, at extreme acidity and restricted aeration, toxic concentrations of ferrous iron sometimes exist. Also, at strong acidity, the ferric oxide, which is always present, dissolves in sufficient amounts to supply crop needs. As the pH rises above 6.5, soluble ferrous iron tends to become oxidized to ferric oxide, which is so insoluble under neutral and alkaline conditions that a deficiency for crop growth sometimes occurs under such conditions. As is the case with manganese, a good supply of active organic matter tends to overcome a lack of available iron at high pH because it not only carries and furnishes available iron, but also produces local reducing areas where iron is kept in the readily available ferrous state.

Crops need only minute amounts of copper and zinc. But, even so, deficiencies sometimes occur, particularly under calcareous and highly alkaline conditions, which greatly lower the solubility and availability of the two elements. Also, in strongly acid soils the amount present in readily available forms may be too low for crop needs because of depletion by leaching during the development of the acidity and strong retention by the soil acids of the other portions which exist as exchangeable bases.

A most important point to note is that pH 6.5 is a very favorable reaction as regards the availability of all of the elements listed and obtained by plants from the soil proper. That is why for general farming it is usually recommended that acid soils be limed to pH 6.5. Of course, for the control of potato scab and the culture of certain ornamental plants that need a lower pH, that condition may not be feasible or advisable. I also emphasize that the chart is a generalized diagram. Because adequate and precise data relating to certain aspects of the subject are still lacking, I had to make some assumptions in its preparation and so there are undoubtedly some inaccuracies in it. There will be cases that do not conform to the diagram because of the inaccuracies, or special and peculiar conditions that are involved, e. g., conditions that are associated with orchard crops. But in the main, especially in the reaction range of pH 5.5 to 8.5, I believe the diagram presents a fairly reliable picture. It should be added that where rather pure calcium lime is used, a deficiency of available magnesium may be created at pH 6.5 or any other pH value.

Loss of Lime by Leaching and Cropping

Fortunately, scientists are discovering that the rate of loss of lime by leaching is much less than was formerly believed to be the case; some of us used to assume that the annual loss was 500 to 1,000 pounds an acre. Recent data obtained by R. S. Stauffer in Illinois and Victor J. Kilmer, Orville E. Hays, and Robert J. Muckenhirn in Wisconsin show that when silt loams in their area are kept in crops, very little soil water percolates beyond a depth of 4 feet and that very little leaching of lime beyond the root zone can therefore occur. Their data were obtained with lysimeters that allowed natural surface drainage.

In some of the older lysimeter experiments, surface drainage was not provided, and all the rainfall was forced to enter the soil. Under such conditions, the amount of drainage water causing loss of lime may be multiplied several times, because it is that excess of water beyond a certain amount that the soil can hold or is used by crops that eventually drains out and causes leaching. With an annual rainfall of about 30 to 35 inches, the excess or percolation under cropping of the better soils when surface runoff is allowed may amount to only 2 or 3 inches annually; without runoff, it may amount to 8 to 10 inches.

That lime is not lost by leaching as rapidly as we once believed is substantiated by a consideration of the amount found present in many virgin soils. In eastern Wisconsin, for example, there exists a red clay loam soil which either contains lime carbonate throughout the soil profile, or is, at the most, only slightly acid in the surface layer. Geologists estimate that the parent material of this soil (lacustrine clay with some calcium carbonate) was laid down by glacial action about 25,000 years ago. If the annual loss of lime over that period had averaged 500 pounds an acre, the total loss for the whole time would amount to about 3 feet of powdered limestone. Obviously, nothing like that has taken place, otherwise the soil to a considerable depth would now be decidedly acid. Undoubtedly the native vegetation, a mixture of hardwoods and conifers, markedly retarded the net loss of lime by providing annual returns from the deeper layers to the surface in the form of deposits of tree leaves. I think that under these conditions the annual loss of lime carbonate by leaching was not more than a hundred pounds to the acre.

Investigations by J. W. White and F. J. Holben, carried on in connection with the old soil fertility test plots on Hagerstown clay loam at the Pennsylvania Agricultural Experiment Station, give information bearing directly on the leaching of lime under cropping. From a plot which had received lime (CaO) at the rate of 35,200 pounds an acre in 40 years, they calculated from their soil analyses that 4,353 pounds of CaO were leached out of the surface soil layer (0–7 inches) during the period. On an annual basis, that amounts to 109 pounds of CaO, or 195 pounds of $CaCO_3$. Because the loss occurred in a soil that was kept very heavily limed (maintained at a pH well above 7), it is higher than would be the case under most farming conditions (soil at pH 6.5 or less) in a similar climate. Moreover, some of the lime that was removed from the surface soil layer was retained by the soil below and so was not lost for soil improvement and crop use.

For the northern States of the humid region, an average annual removal by leaching and cropping of 200 pounds of calcium and magnesium carbonates an acre would seem to be a conservative estimate. In farming, as usually carried on, much of the lime removed by cropping can be returned and should be returned in the form of manure and crop residues. If that is done, the annual net removal would be less than 200 pounds in many cases. Even with an annual net removal of 200 pounds an acre, an application of a ton of lime to the acre will resupply what is removed in 10 years.

As one goes from north to south in the humid region of this country, the rainfall, temperature, and character of soil in many places become much more conducive to loss by leaching. Possibly the average net loss by cropping and leaching in the Southern States may be 25 to 50 percent higher than that estimated for the Northern States. A ton of lime an acre should, on the average, put back at least what is lost in the Southern States in a period of 7 or 8 years. It may be considerably longer in certain cases, depending on type of soil and cropping system.

The Cost of Maintaining the Lime Supply

What does it cost to provide and maintain a proper supply of lime in the soil?

Obviously the cost varies with conditions. I give one computation. In the North Central States, where about two-thirds of the country's agricultural lime is used, lime delivered at the farm frequently costs about $3 a ton. If 3 tons an acre are needed to bring the soil to a pH of 6.5, a capital investment of $9 is required; at 4-percent interest that represents an annual carrying charge of 36 cents. If the annual net loss or depletion of lime is 200 pounds an acre, it will take 30 cents annually to cover this. Thus, under these conditions, the total annual cost per acre of providing and maintaining a satisfactory supply of lime in a soil that needs 3 tons of lime an acre to start with is only 66 cents. The annual returns, as revealed by numerous field tests, from this investment in terms of increased yields of crops of higher quality, and soil improvement and conservation may easily amount to 10 or 20 times the annual cost. In fact, in time, it may mean the difference between complete crop failure with soil ruination, and bumper crops with permanent soil fertility and conservation. In these considerations it is understood, of course, that the lime would be supplemented with fertilizers as needed.

Because liming is so important in the humid regions, it is fortunate indeed that an inexhaustible supply of lime exists in most of the areas that need it. Calculations based on analyses of the earth's crust show that enough limestone exists for an application of approximately a half million tons to every acre of the earth's land surface, or close to 10 million tons for every acre of arable land. Moreover, the lime that leaches out of the land forms new deposits, pound for pound. Thus, the use of lime need never be curtailed because of an inadequate or dwindling supply.

We need more information particularly on two points: The loss of lime by leaching and cropping, and the fineness of grinding of limestone. Recommendations on the second point vary greatly. Authorities in several States favor rather coarsely ground material; others prefer finer grinding and have had laws passed that set up standards of purity and fineness.

A product that allows at least 50 percent to pass through a 60-mesh sieve is of high grade and economical as regards fineness for large-scale general use. Very fine material, most or all of which passes a 100-mesh sieve, is on the market; it costs more, but is well adapted for small-scale use, such as gardens, intensive cropping, and special cases where only a small amount of quick-acting material is permissible, as in potato culture.

Differences in recommendations as regards fineness of grinding have probably arisen in some cases because of marked differences in the character of the stone being used. It is well known that the dolomitic stone is much less soluble than the calcium stone, and so probably requires finer grinding if equal activity is desired. But, all in all, the solubility or availability of agricultural lime as influenced by composition and fineness, its subsequent movement, use by crops, and loss by leaching, all deserve much additional investigation.

And Finally

It should be understood that the acids that cause soil acidity are not in themselves undesirable substances to have in a soil. In fact, without them soils would be unreactive and unretentive of the elements of fertility. The acids act as a great reservoir where calcium, magnesium, potassium, and other bases may be stored in a readily available form for crop use and regulation of soil conditions. An acid condition is simply a positive signal that the supply of these bases needs to be replenished. This replenishment is done for the most part by the use of lime, and the more acid the condition the greater the need of the replenishment.

One of the most telling arguments for the liming of soils is an exposition of the relation of liming to the utilization of atmospheric nitrogen. In the atmosphere over every acre of land there are, in round numbers, 35,000 tons of nitrogen, which, if transformed to a fixed (nongaseous) form like ammonium nitrate, would have a commercial value as fertilizer of more than 5 million dollars. It is ironical, then, that many yields are greatly reduced because of a lack of nitrogen in usable form. How can the farmer draw upon this tremendous and inexhaustible supply of nitrogen? He can do so by growing legumes, which, when properly inoculated and grown on land well supplied with lime and mineral nutrients, have the power of fixing atmospheric nitrogen that they can then use for the synthesis of their own proteins, and pass on for use by other plants, as well as animals. Nonlegumes, regardless of how grown, cannot utilize atmospheric nitrogen. They depend for nitrogen on that fixed by the legumes, or supplied in manure and commercial fertilizers.

Now, it so happens that the legumes best in quality of forage and soil building, such as alfalfa and the clovers, like lime; that is, they grow satisfactorily and fix nitrogen efficiently only when the soil is well supplied with lime. A season's growth of alfalfa on an acre under favorable conditions may fix atmospheric nitrogen worth $10 or $20—more than enough to pay the cost of an ordinary application of lime, which usually produces benefits for a decade or more. Yes, the cost of liming land is only a small fraction of the total value of all of the benefits lime produces.

THE AUTHOR

Emil Truog is professor of soils and chairman of the Department of Soils at the University of Wisconsin. His principal contributions pertain to soil testing for lime and fertilizer needs, methods of fertilizer application, availability of plant nutrients, and the training of soil scientists.

FOR FURTHER READING

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ALSO, IN THIS BOOK

Phosphate Fertilizers, by W. H. Pierre, page 554.
Use of Nitrogen Fertilizers, by F. W. Parker, page 561.
The Use of Minor Elements, by Matthew Drosdoff, page 577.