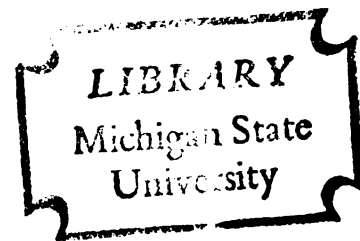


THE EFFECT OF CALCIUM CARBONATE,
CALCIUM SULPHATE, AND MAGNESIUM
CARBONATE ON THE YIELD OF
SEVERAL CROPS GROWN ON
ORGANIC SOIL

Thesis for the Degree of M. S.
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THESIS



ABSTRACT

THE EFFECT OF CALCIUM CARBONATE, CALCIUM SULPHATE, AND MAGNESIUM CARBONATE ON THE YIELD OF SEVERAL CROPS GROWN ON ORGANIC SOIL

by Eugene Grennan

A greenhouse study was undertaken to determine the relationship between CaCO_3 , $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ and MgCO_3 applied to an organic soil and the growth of alfalfa, corn, oats, barley, beans and sugar beet. The response of alfalfa and corn to CaCO_3 with and without fertilizer N was also investigated.

Rifle peat with a pH value of 3.8 was the soil used. CaCO_3 at rates of 3, 6, and 9 tons/acre, $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ at 4.35 tons, and MgCO_3 , at 2.52 tons, applied alone and in various combinations, were the treatments used. The 3, 6, and 9 ton rates of CaCO_3 were applied with and without fertilizer N for alfalfa and corn. A check treatment receiving basic fertilizers only was included. The basic fertilizer included P, K, Cu, B, Mo, Mn and N except where N was a treatment.

Crop yields and root weights of alfalfa were recorded. The pH, percent organic matter and ash, total exchange capacity, exchangeable bases, percent base saturation and exchangeable Na, K, Ca, Mg and H were determined on the

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untreated soil. Available P, K, Ca, and Mg and pH and percent base saturation were determined on the treated soils.

All crops responded to CaCO_3 . Three tons per acre was sufficient for most crops supplied with N fertilizer, but sugar beet and alfalfa without N fertilizer required 6 to 9 tons.

Crops varied in their response to MgCO_3 , the order of increasing response being: corn, beans, oats, barley, alfalfa and sugar beet. CaCO_3 and MgCO_3 were equally effective for sugar beet but CaCO_3 was superior for most of the other crops.

$\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ depressed the pH and the yield of all crops.

A pH of 4.4 for the crops responding to 3 tons of lime and pH 5.0 to 5.8 for those needing the higher rate of lime, was satisfactory for normal growth. This corresponded to a base saturation of 34 to 42 percent for the former and 53 to 70 percent for the latter. On average, pH 5.5 or 65 to 70 percent base saturation was satisfactory for all crops grown.

Nodulation of alfalfa was best at the highest rate of liming in the absence of fertilizer N.

The effects of the treatments on root growth of alfalfa were similar to their effects on top growth.

The severe N deficiency in corn not fertilized with N was not relieved by heavy liming.

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Symptoms resembling Ca deficiency developed in corn on soil treated with MgCO_3 without CaCO_3 .

There was a high correlation between pH and exchangeable H, and between pH and percent base saturation for this soil.

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INTRODUCTION

The application of lime to acid soils is an ancient practice. The value of chalk or marl is said to have been recognized by the prehistoric Greeks, notably in Aegina, "where their use became a theme of mythology." (24) Yet it is only in recent times that the nature of soil acidity has been more clearly understood and chemical tests for accurately predicting the lime requirement of soils have been developed.

The responses of crops to lime generally have been attributed to changes in the soil environment with regard to: (a) solubilities of toxic substances, Al and Mn being those implicated most frequently; (b) availabilities of Ca and Mg; (c) availabilities of P and K; (d) solubilities and availabilities of trace elements; or (e) populations and activities of soil microorganisms (12). The particular factors likely to be encountered causing injury and limiting plant growth in an acid soil depends on the chemical composition of the soil, the soil pH, and the crop grown. It is possible that the acidity factor of greatest importance under strongly acid conditions differs from that predominating at a higher pH.

Soil pH is regarded by some as a practical measure of the lime needs of an organic soil. There are instances, however, of crops growing normally at a pH considerably below that usually considered a minimum for optimum growth. Other workers consider the percent total or exchangeable Ca in the soil a better measure of lime need than is soil pH. Percent base saturation may also be used as a measure of the lime status of the soil.

The following study was conducted to investigate the response of several crops to CaCO_3 , $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$ and MgCO_3 , in different combinations, the response to CaCO_3 with and without fertilizer N, and to relate the responses obtained to some chemical properties of the soil.

LITERATURE REVIEW

Current ideas on the nature of acid soils and their ion-exchange chemistry have little resemblance to those in vogue less than two decades ago. Jenny (35) reviewed the theories of soil acidity from early conceptions to modern times.

Soil Acidity and Hydrogen Ion Toxicity

Natural soils differ considerably in their reaction or pH, and these differences are reflected in the vegetation or crops they carry. For a long time it was not clear whether these differences were due to the sensitivity of plant roots to the H ion concentration of the soil or soil solution in which they were growing, or to secondary effects brought about by the reaction. Gallagher (25) referred to the then prevalent idea that the relative infertility of acid soils is due to the direct action of acid on the plant itself. He considered this unlikely since the acidity of the sap of the average healthy plant lies between pH 4 and pH 6. Moreover, a plant will usually grow quite well in a culture solution which is much more acid than the average acid soil. He cited work of Magistad (47) who found that at acidities less than pH 5, red clover and alfalfa suffered

greatly from mere acidity, while barley, corn, oats and rye suffered much less, but still appreciably. Magistad concluded that since the pH of most soils is between 5 and 7, the practical benefit of liming in the case of clover, oats, rye and alfalfa is due to a decrease in acidity, in the case of corn and barley, the benefit is due both to decrease in acidity or H-ion concentration and to precipitation of Al, while the benefit derived from liming soybeans is due to precipitation of Al.

Salter and McIlvaine (65) found that germination in a range of plants was not affected by acidity, as such, down to pH 4, while the subsequent growth of the seedlings was best under definitely acid conditions (from pH 5 to 6). At greater acidity than pH 5, growth rapidly diminished. Bryan (9) noted that cereals are less sensitive to acids than are legumes. Oats gave a maximum yield at pH 6, and wheat at between pH 6 and 7. At pH 4 and 5, oats grew much better than did wheat. Albrecht (2,3) contended that the H ion attached to the colloidal fraction was not in itself injurious. If the degree of Ca saturation increased, with a corresponding increase in both pH and Ca level, he assumed that the increasing Ca level was responsible for better growth. Gedroiz (27) suggested that two factors prevented plant growth on a soil fully saturated with H ions and which was given no CaCO_3 : the absence of available Ca, and the acid reaction. He pointed to the injurious effects of the

acid reaction, since the introduction of CaSO_4 in place of CaCO_3 in a H saturated soil failed to produce good growth. Albrecht (2) suggested that in such cases the sulphuric acid formed from the introduction of CaSO_4 into a H saturated soil could be the cause of plant growth failure. In other words, the H ion in an acid soil is not necessarily the injurious factor.

Arnon and Johnson (5) found that a range of pH fluctuations, from 4 to 8, is tolerated by plants, provided an adequate supply of nutrient elements is maintained. Arnon et al (4) also found that such diverse plants as tomatoes, lettuce and bermuda grass absorbed P from culture solutions ranging in pH from 4 to 8. Hewitt (30) reported that sugar beet, cauliflower, savoy cabbage, swede, oat, barley and potato were not appreciably affected by pH values of 4.5 in the nutrient solution as applied, but the plants usually caused the pH to rise to 5.5 to 6.0. Where nutrient solutions with pH values as low as 3.5 were applied, sugar beet was the first to show injury; cauliflower was next in sensitivity. Except for a tendency to chlorosis or red tinting of leaf margins in sugar beet, no symptoms suggestive of the acidity complex were observed.

Peech and Bradfield (58) stated that despite numerous studies on the effect of H ion concentration on plant growth, it is very difficult to evaluate the true ecological significance of soil reaction in the presence of other complicating and associated variables. However it is

generally held that the harmful effects of soil acidity are due to secondary causes, except in rare cases, and pH per se is generally not regarded as an important factor, at least in the range usually encountered in soils (12, 26, 37, 64). Coleman et al. point out, however, that the H ion appears to decrease the active absorption of metal cations by competition for carrier sites, so that a higher external concentration of a given ion is necessary to support a given rate of absorption at low pH rather than at high.

Soil Acidity and Calcium, Magnesium Deficiency

Perhaps the most controversial aspect of crop response to lime has been that of toxicity of Al and Mn versus availability of Ca and Mg. The difficulty is that the addition of lime to soils simultaneously increases the quantity of Ca (and usually Mg) in the soil, increases the availabilities of those ions by raising percentage base saturation, and lowers the amount of exchangeable Al and Mn. Al concentration is lowered by precipitation or conversion to nonexchangeable hydroxy-ions, and Mn concentration is lowered by precipitation and/or oxidation (12).

Gallagher (25) stated that the aim in liming is not, except in very exceptional circumstances, to furnish the soil with Ca as a plant food, but rather to correct an undesirable physico-chemical condition which exists in certain soils. In support of this he refers to the fact that the application of CaSO_4 to an acid soil usually

provides no improvement in the symptoms of soil sourness. He quoted Truog who held that certain plants require relatively large quantities of CaCO_3 as such to neutralize organic acids formed in the course of metabolism.

Gardner and Garner (26) thought Ca deficiency to be a probable cause of crop failures in the case of extremely acid light soils which were low in exchangeable Ca. Collings (15) stated that, except on highly leached soils, the supply of Ca in the soil was sufficient for non legumes, although the supply is often insufficient for the legumes. Peech and Bradfield (58) disagreed with the theory that the beneficial effect of liming acid soils is due to the increased supply of Ca as a plant nutrient, since many mineral soils that must be limed for optimum growth may contain several thousand pounds of exchangeable Ca per acre. The degree of Ca saturation is emphasized as an important factor determining the Ca supplying power of the soil (50).

Albrecht (3) has been an outstanding and outspoken proponent of the viewpoint that "soil acidity" is nutrient deficiency, particularly of Ca. He defended the thesis (a) that an acid reaction of most soils is not a hindrance, but rather a help, to plant nutrition via the provision of essential nutrient ions; (b) that it is only under significant H ion activity that the process of mineral breakdown, clay formation, and fertility delivery can be carried on, and (c) that the respiration of plant roots and microbes generates active H to maintain the flow of nutrient cations from the soils rocks and minerals. Some authors appear to

agree, at least to the extent that a major result of liming is increased Ca availability (8, 50).

Hewitt (30) studied the effects of Ca on a range of crops in sand culture. Ca deficiency symptoms were produced in several crops. Symptoms included wilting, marginal browning, and death of the growing point. Cereals were particularly resistant and only showed chlorotic rolled terminal leaves or tip die-back with severe deficiency. He suggested that Ca deficiency may occur in sugar beet where magnesium limestone is used instead of carboniferous limestone.

Bohl (8) found that neutralizing the substrate with NaOH produced insignificant increases in yield or none at all, of yellow lupin, while neutral salts such as CaSO_4 or CaCl_2 improved yields without affecting soil reactions.

Coleman et al (12) concluded that Ca and Mg are bound more tightly to permanent charges on soil particles than to various kinds of weakly acidic exchange spots, so that availabilities of these ions should be greater in nearly neutral than in acid soils. Melsted (52) found definite Ca deficiency in corn in certain Illinois soils where quantities of exchangeable Ca were low. Krackenberger et al (41) considered the general matter of Ca and Mg deficiency, concluding that most soils contain sufficient quantities of these ions to support adequate plant growth.

Schmehl et al (66) studied the effect of limestone and gypsum, alone and in combination, on the growth and Ca

content of plants on acid soils. The general finding that CaSO_4 accentuates rather than relieves poor plant growth has been interpreted as proving that Ca deficiency was not a factor. Coleman et al (12) disagreed with this conclusion since the addition of any neutral salt to an acid soil displaces Al, Mn and other exchangeable ions, possibly building soil solution concentrations to a point at which toxicity occurs.

Fried and Peech (23) compared lime and gypsum on the growth and composition of several crops. Gypsum produced much lower yields of crops, yet resulted in a much greater concentration of Ca in the soil solution. They concluded that the reasons for the poor growth with gypsum, and the inability of the plant to absorb Ca from the relatively soluble gypsum are quite obscure.

Fielding and Cummings (20) offered an explanation. In soils with colloid of the 2:1 type, a higher degree of Ca saturation is required than on soils of the 1:1 type of colloid. It is suggested that competition with the H ion is much more pronounced in soils of the 2:1 colloid type than in soils of the 1:1 type. It is conceivable, then, that with soils of the 1:1 type, response to Ca would occur at 20 percent Ca saturation, whereas no such response would be obtained with soils of the 2:1 type of colloid at the same degree of saturation. These authors concluded that we may expect beneficial results from the use of soluble sources of Ca under three conditions; (a) in soils of very low exchange

capacity where the possibilities of building up levels of exchangeable Ca are limited; (b) in soils of moderate acidity where it is desirable to keep soil reaction fairly low, and yet supply Ca for plant growth; (c) in soils of either low or high exchange capacity where the crops have a high Ca requirement at certain stages of growth, or where it is necessary to supply Ca to certain soil zones.

Russell (64) pointed out that while the harmful effects of acidity can always be corrected by the judicious use of CaCO_3 , two of the harmful effects of acidity - low available Ca and sometimes high available Mn - can be mitigated by adding a soluble calcium salt such as CaSO_4 which has no effect on the pH of the soil. It increases the available Ca, and decreases the relative ease of uptake of Mn by the plant roots. Potatoes, the brassica crops and legumes would be expected to respond to CaSO_4 for this reason.

Adams and Pearson (1) suggest that it is only in the absence of toxic levels of H, Al or Mn ions that Ca saturation can be considered a good measure of Ca availability in soil.

Barber (7) developed the concept that plant nutrient availability in a soil is principally governed by the rate at which nutrients move through the soil to the root surface. The principal mechanisms by which the nutrient ions reach the root-soil interface are by mass-flow with the soil water that moves to the root and by diffusion. The concentration

of P and K in soil solution is often low and diffusion is the mechanism by which many of these ions reach the root surface. The concentration of Ca, Mg, S and N is usually high enough for mass-flow to be the dominant factor for the transport of these nutrients to the plant root. A soil test procedure which gives a measure of the concentration at the root and the rate at which the concentration gradient at the root decreases with continued uptake of the ion in question should come the nearest to providing a method to predict availability of those nutrients whose availability is dependent upon diffusion. Determination of the content in the solution which flows to the root should be the most suitable method of determining availability of nutrients supplied mainly by mass-flow.

Soil Acidity and Aluminum, Iron, and Manganese Toxicity

Several workers indicate that Ca deficiency is of less importance than is toxicity of Al and Mn. Ideas concerning Al toxicity are based in part on earlier findings that Al concentrations in displaced soil solutions, while very small at pH near 6, sometimes are as high as 0.5 ppm in the pH range 5-5.5 and may become very large at more acid reactions (12). It was shown at an early stage that culture solution concentrations of 2 ppm are toxic to plants, and it appears that levels at least this high exist in many acid soils. Miyake (54) demonstrated the toxic effect of 1.2 ppm of solution Al on rice and suggested the possibility of a relationship between Al and the infertility of acid soils.

Gallagher (25) refers to the presence of soluble Al in acid soils and to its toxic effect on some plants.

Connor (16) concluded that Al salts are the prime cause of acidity in certain soils. He noted that the acidity in certain soils could be overcome by treatment with phosphate. Hartwell and Pember (29) noted that liming greatly increased the yield of barley but not of rye. In solution cultures, Al was more toxic to barley than to rye. They concluded that the benefit of liming was due to precipitation of Al salts from soil solution, while a heavy dressing of acid phosphate or superphosphate had similar beneficial effects. Gallagher (25) recognized that Al was toxic; the question in dispute then was whether acid soils contain soluble Al in sufficient concentrations to completely explain soil sourness.

Magistad (47) found a definite correlation between the H-ion concentration of the soil and Al present in soil solution. At pH near 7 the solubility of Al was almost zero; at pH 5, he found 1-2 ppm in solution and the solubility increase rapidly at lower pH. Gallagher (25) cited Line who disputed the Al theory and attributed the toxic action of Al to P deficiency, P being precipitated with Al.

Fried and Peech (23) showed that Mn is very toxic to such lime-responsive crops as alfalfa, and its presence in excessive amounts interferes with Ca uptake by plants. Schmehl et al (66) found that not only Mn but Al and H in solution reduced absorption of Ca by alfalfa. They concluded that the low Ca content usually observed in plants grown on

acid soils may be due to the antagonistic effect of Al, Mn and H on the absorption of Ca, as well as to the restricted root growth, rather than to the low Ca supply in the soil.

Vlams (73) showed that Al toxicity was entirely responsible for the poor growth of barley on an acid soil. If the soil pH is below 5.5, and if the soil contains more than 1 ml of exchangeable Al, root growth is largely inhibited. The concentration of Al ions in soil solution will depend on the amount present, the complementary ions, the water content and the electrolyte concentration. The general observation is made that the addition of CaSO_4 intensifies rather than helps soil difficulties due to Al (and perhaps Mn) toxicity, because increasing the salt concentration shifts the exchange equilibrium so that more Al ions are in soil solution (23, 67). The addition of 1000 lb CaSO_4 per acre increased the Al content of the soil solution by 50 percent, while 4000 lb more than doubled it. Plant yields decreased on the addition of CaSO_4 to acid soils (pH 4.8) but not to one limed to pH 6.3 (23). In fact it was shown that CaSO_4 supplied Ca to plants more readily than did CaCO_3 when the soil pH was above 6 (34).

Hewitt (30), using sand culture, showed that most brassicas were highly susceptible to injury by excess Mn. Celery, oat, carrot, flax, and especially sugar beet were relatively tolerant to Mn toxicity, and these crops, together with most legumes, do not appear to be affected greatly by the Mn excess factor in acid soils. Tolerance to Al also

varied greatly. Sugar beet and barley were very sensitive; celery, carrot and flax were less sensitive, while oat and most brassicas were relatively tolerant to Al toxicity. Barley showed symptoms of acute P deficiency with high levels of Al.

Foy (22) studied the effects of the acidity of 17 soils on the growth of lucerne. On 9 soils growth was limited by Mn toxicity; on 1 soil by Al toxicity; on 1 soil by Ca deficiency; on 3 soils by two of these factors together; all responded positively to liming. In 2 cases the toxic effect of a high Mn level was probably counteracted by a high level of exchangeable Ca. In one case the high content of organic matter probably reduced the effect of a high level of Al: these latter 3 soils did not respond to lime.

Hourigan (32) found that barley grown in sand culture was limited by 11, 6 and 300 ppm of Al, Mn and Fe respectively. In soils of various pH values and various Al, Mn and Fe concentrations, Mn and Fe caused no adverse effects, but additions of 7 and 14 me Al per 100 grams of soil produced toxicity. Plant (59) grew brassicas and lettuce on acid soils treated with limestone, dolomite, calcium sulphate and sodium molybdate. On the least acid soils (pH 4.8) only Mo deficiency was apparent; at pH 4.6 a mixed syndrome of Mo deficiency and Mn toxicity appeared, and on the most acid soil (pH 4) the syndrome also included Al toxicity.

Russell (64) considered the secondary effects of high acidity or low pH in a soil to be a shortage of available Ca

and sometimes P on the one hand, and excess of soluble Al, Mn and perhaps other metallic cations on the other. The relative importance of these factors depends on the composition of the soil insofar as it affects the level of available Ca, P, Al, and Mn, and on the susceptibility of the crop to a deficiency of Ca, or an excess of Al or Mn. Since crops differ in their susceptibilities to these consequences of acidity, it is impossible to draw up any table showing the critical pH at which a given crop begins to suffer severely from acidity. He expressed the view that there is no necessary close connection between the pH of a soil and its suitability for a given crop in the moderately acid range.

Hewitt (30) stated that different crops react differently when exposed to a single particular factor of the acidity complex and a characteristic order of tolerance can be assigned for each factor. The relative tolerance of crops to soil acidity described by Russell (64) probably reflects their tolerance to a number of factors in the acidity complex. The familiar order of tolerance observed in acid soils is closely reproduced when certain combined factors, e.g. Al and Mn excess with low Ca supply are tested and the visual responses of most crops are fully explained by the effects of these factors, and of deficiencies of Mo in sensitive crops, of Mg in oats and of certain complex combinations of K with Mn or Fe status in potato.

Aluminum Toxicity

Mode of action: While accepting that Al is an important factor in the acidity complex, the mechanism of Al toxicity is not known (12). Wright (77) believed that Al interferes with the uptake and translocation of P and that this is the primary cause for Al toxicity. Pratt (60) found that when soils with large amounts of basic Ca phosphates were acidified from neutrality to pH 3.5, Ca phosphate was converted to Al and Fe phosphate, thereby preventing Al toxicity until pH dropped below 4.7. Randall and Vose (62) reported that high Al levels depressed P uptake, and that P may be bound to Al after uptake, causing the symptoms of P deficiency characteristic of Al toxicity. MacLeod and Jackson (46) found that Al taken up by the plant was concentrated in the roots, and the levels in the tops increased only with levels of 2 ppm or more in solution. Al application increased the P level in the roots where it was immobilized by Al.

An alternative explanation of the mechanism of Al toxicity is given by Schmehl et al (67) who observed that nutrient solution Al decreased Ca uptake. Coleman et al. (12) considered this an attractive possibility in view of the essentially of Ca for root growth, and since a primary symptom of Al toxicity is a stunting of the root system. However these authors found that raising the Ca concentration of the substrate did not counteract the effects of Al. MacLeod and Jackson showed that increasing concentrations of Al increased the percent Ca in roots and decreased it in tops (46).

The inhibiting effects of Al on root growth seems to be a major factor in soil acidity. Root growth in rice was inhibited by 1 to 2 ppm water soluble Al (18). Less than 1 ppm of Al restricted root growth of legume seedlings, while 2 ppm was toxic to root growth (46). In a soil rich in Al barley roots were twisted and confined to the surface layer (40). Root growth of sorghum and sweet corn was inversely related to the amount of exchangeable Al in the soil (61). The seedling stage may be the most critical period for a plant in relation to Al toxicity. Rorison (63) reported that if seedlings can grow rapidly through the seedling stage, the effect of Al decreases. The direct effect of acid soil on barley was the same when plants were grown in it for the first 20 days of their life as when they were grown in it all the time (39).

Al has been shown to inhibit isocitric dehydrogenase and malic enzyme activities in soybean plants, so perhaps we should look to the effects of Al on enzyme systems in efforts to explain its deleterious effects (11).

Soil Acidity and Microbial Activity

The behavior of microorganism in acid soils and their response to liming is an important factor in soil acidity. Establishment and efficiency of a symbiotic relationship require a narrower range of soil reaction than is necessary for growth of plants not relying on N fixation. Lime applications therefore are often required for establishment of

leguminous crops on many acidic soils (33).

Microbial growth and survival:

The growth and survival of many strains of rhizobia are strongly influenced by soil acidity. The general tendency is for alfalfa rhizobia to be more sensitive than clover strains to acid conditions. Byron (9) for example noted that soybean rhizobia were able to survive in soils down to about pH 4, red clover rhizobia to pH 4.5, and alfalfa rhizobia to about pH 5. The detrimental effects of soil acidity on rhizobial survival and growth may result from one or more of the many causes which affect plant growth. However the direct effect of H ion concentration appears to be more crucial for rhizobia than it is for higher plants (33). The Ca requirements of rhizobia are not large and are considerably less than the requirements of the host plants. In several studies, the low Ca requirements, the abrupt and large depression of growth with acidity and the failure of Ca to ameliorate the effects of low pH, all suggest that the failure of rhizobia to thrive in acid soils is largely accounted for by direct H ion effects (43, 56).

NODULATION:

Poor nodulation in acid soils may be due to a direct effect of acidity on infection of the host and subsequent nodulation, or to a lack of viable organisms in the substrate. Poor root growth may contribute either directly or indirectly. Fletcher (20) found nodulation of red clover very much impaired at pH 4.2 although the plants grew very well when

N was added. Amounts of Mn which were toxic to the plants depressed the number and total volume of nodules on three varieties of white clover (74). In general the evidence suggests that Ca is specifically required either for inoculation of the host or for nodule development, that the amount of Ca required for effective nodulation exceeded the requirement of the host, and that some of the detrimental effects of soil acidity on nodulation come about as a consequence of altered Ca contents of the host (33).

Nitrogen fixation

Once root nodules are established, their N-fixing function is especially sensitive to acidity and to deficiencies of Ca and Mo. Efficiency of alfalfa nodules in N fixation was restricted at pH 5 or less, whereas subterranean clover nodules still functioned well (36). Data available indicate that the Ca requirement for N fixation was greater than the requirement for growth of clover and this was due to an insufficient supply of metabolites from the tops for efficient nodule functioning when the Ca supply was moderately low (33). In contrast to Ca, Mo seems not to be involved in infection and nodulation processes but rather to be directly involved in the N fixation process (33).

Organic Matter and Soil Acidity

Soil organic matter is composed of an extremely complicated array of products arising from the partially decomposed remains of plants. Partial decomposition of

organic matter under water or in swamp conditions usually results in an acid environment, although the mineral content of the water is an important factor (42). Davis and Lucas (19) attribute the acidity of organic soils to the presence of organic compounds, exchangeable hydrogen, iron sulfide and silicic acid.

There is general agreement that the acidic functional groups of organic matter are carboxyls, phenols, enols and perhaps other alcoholic hydroxyls. The relative amounts of these groups appear to vary both with the soil and with the fraction of organic matter. The carboxyl groups (pKa 4 to 5) ionize largely between pH 4 and pH 7 while the other groups (pKa 7) ionize only at alkaline reaction, though it is suggested that some polyphenols and substituted phenols may contribute at pH less than 7 (13, 14). It has been estimated that 55 percent of the CEC of organic matter from soil is accounted for by carboxyls; phenolic and enolic groups contributed another 35 percent and imide nitrogen, 10 percent. The density of carboxyl groups, and thus the CEC which can develop under acid conditions, varies from one soil or horizon to another. Values for the humic and fulvic acid fractions vary from 200 to 900 meg/100 g. Carboxyl group concentration for whole organic matter has been found to range between 100 to 200 meg/100 g. Because of the chemical nature of organic matter, it probably has only pH-dependent charge. Soil organic matter is weakly acidic by nature. Thus, effective CEC, as deduced from titration curves, is nearly a linear function of pH, being near zero at pH 3 to 4 and increasing

regularly to pH 8. In most acid soils, organic matter behaves as if it has a pKa of around 6. Generally, the CEC of organic matter $\text{[BaCl}_2\text{-TEA at pH 8.2]}$ is of the order of 200 meq/100 g. It is around one-half of that at pH 6 (13, 14).

Much attention has been given to establishing relationships between soil pH, and percentage base saturation. Differences in the pH at which the CEC was determined has lead to wide differences in the relationships reported, especially for organic soils. Basing calculations of percent base saturation on CEC at pH 8.2, as determined with $\text{BaCl}_2\text{-TEA}$, Mehlich (48,49) concluded that soils dominated by organic matter reached pH 7 when 30 to 50 percent base saturated. When the functional groups of organic matter are complexed with Al and Fe^{3+} , a pH between 6 and 7 appears characteristic of half-saturation of CEC at pH 8.2 with Ca and Mg (12,13). Lucas and Davis (44) report that a H saturated organic soil has a pH of about 3.0 and a Ca-saturated soil a pH of 7.2 to 7.8. pH 4.5 corresponds to about 50 percent base saturation and pH 5.5 to about 70 percent. Shickluna and Lucas (69) determined CEC by summation of exchangeable K, Ca, Mg, and H. Soils with high exchange capacities contain larger amounts of exchangeable Ca than soils with the same pH but with lower exchange capacity values. It is stated by these authors that fertile organic soils are generally 50 to 65 percent saturated with Ca.

Titration curves of soil organic matter sometimes are consistent with the presence of carboxylic groups with

apparent pKa around 4. More often these curves indicate pKa's of around 6, reflecting weaker-acid character than would be expected for the carboxyl groups known to be present. Recent studies suggest that the weak acid character of organic matter results from the fact that metal ion complexes, primarily Al^{3+} and Fe^{3+} rather than free carboxyl groups are present. Reaction of soil organic matter from acid soils with base involves the hydrolysis of bound trivalent metal ions rather than ionization of carboxyl groups. The buffer capacity of an Al-saturated peat to pH 7 is appreciably smaller than for a H-saturated peat. In soils where the organic matter never has been acid, it appears that little Fe^{3+} or Al^{3+} is bound on the organic matter (14).

In soils high in organic matter, Yvan (78,79) concludes that a higher proportion of the exchange acidity is H rather than Al. Coleman and Thomas (14) question this conclusion suggesting that the H apparently exchangeable from organic soils may arise from the hydrolysis of difficultly exchangeable Al. Presumably in blanket peats containing only 2.4 percent ash, and low in Al, the greater proportion of the exchangeable acidity is H.

PROCEDURE

Experiments were conducted in the greenhouse to investigate the response of several crops to CaCO_3 , $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ and MgCO_3 , with and without fertilizer N, on an acid organic soil.

Soil from the top 12 inches of a Rifle peat profile, in the vicinity of Capitol Airport, Ingham County, Michigan, was obtained in August 1967. The soil was air dried to an apparent optimum moisture content and sieved through a 1/4 inch screen. After uniform mixing, five 100-gram samples were oven dried to determine the moisture content. Lots of 3920 grams of moist soil (40 percent dry matter), equivalent to 1568 grams of oven-dry soil, were weighed for each of the 100 pots.

A basic fertilizer treatment of 300 lb/acre P_2O_5 (as monocalcium phosphate, $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$), 900 lb K_2O (as KCl), 20 lb Cu (as $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$) and 2 lb sodium molybdate ($\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$) was added to all the treatments. The basic treatment of Mn (as $\text{MnSO}_4 \cdot \text{H}_2\text{O}$) and B (as $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$) was varied with the crop and the rate of liming, as shown in Tables 4 and 5. N (as NH_4NO_3) was added at 100 lb/acre to all treatments except C, G and L (Table 4) and additional N was applied in solution as needed for individual crops as indicated below.

The liming materials used were precipitated calcium carbonate (CaCO_3), calcium sulphate ($\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$) and magnesium carbonate (MgCO_3), and the treatments are given in Tables 4 and 5. $\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$ supplied Ca equivalent to that contained in 3 tons of CaCO_3 while the quantity of MgCO_3 used was equivalent in neutralizing value to 3 tons of CaCO_3 .

Soil, lime, fertilizers and micro nutrients were thoroughly mixed, placed in 2 gallon jars, moistened to field capacity and allowed to incubate for 7 to 10 days before sowing crops.

The quantity of lime and fertilizers required per pot was calculated on a volume basis. From the known weight of soil used, this was equivalent to the same rates per acre, 400,000 lb. wt.

Experiments with alfalfa and corn

Alfalfa

The 14 lime and N treatments, and the basic Mn and B rates, are given in Table 4. Vernal alfalfa was inoculated and seeded 1/4-1/2 inch deep on Sept. 7th and thinned to 40 plants per pot on Sept. 20th. N at 100 lb/acre was applied in solution on Oct. 5th, Oct. 25th, and Nov. 30th, excepting treatments C, G, L which received no N. Three harvests were taken, on Oct. 21st, Nov. 30th and Dec. 21st.

After the 3rd harvest, the roots were examined and a visual appraisal made of the degree of nodulation. Roots, collected by sifting through the soil by hand, were washed, oven dried and weights recorded.

Nodules were absent where heavy N rates were applied but increased with the rate of liming where no N was used. Accordingly 2 of the 4 replications used in this experiment were re-sown with alfalfa to investigate the response to liming materials at a lower level of available soil N. No additional N was applied with the plants, the plants being dependent on residual soil N or that fixed symbiotically.

Alfalfa was inoculated and seeded on Jan. 1st, thinned to 20 plants per pot on Feb. 1st and harvested on Feb. 24th. After harvesting the roots were examined for nodulation.

Corn:

The remaining 2 replications used for the first alfalfa crop were sown to corn on Jan. 12th at 14 seeds per pot, thinned to 12 plants/pot on Jan. 28th, and harvested on Feb. 21st. N at 100 lb/acre was applied in solution on Jan. 20th and again on Feb. 11th. No N was added to treatments C.G.L. (Table 4), so that the response to lime with and without fertilizer N could be compared.

Experiments with oats, barley, beans and sugar beet

The 11 lime treatments, and the basic Mn and B rates are given in Table 5. These 4 crops were grown in succession in the same pots.

Oats: Garry oats was sown on Sept. 12th, thinned to 30 plants/pot on Sept. 18th, and harvested on Oct. 21st. N at 100 lb/acre was applied, in solution, Oct. 5th.

Barley: Barley, variety Trail, was sown Oct. 21st, thinned to 25 plants/pot, Nov. 2nd and harvested Nov. 30th. N at 100 lb/acre was applied at sowing.

Beans: The Sanilac variety of beans was sown on Nov. 30th, thinned to 10 plants/pot on Dec. 9th and harvested Dec. 30th. N was added at 100 lb/acre at sowing and the seeds were not inoculated.

Sugar beet: Sugar beet was sown on Jan. 5th, thinned to 5 plants per pot, Feb. 3rd, and the whole plants harvested on Feb. 21st. N at 100 lb/acre and 300 lb K_2O /acre were applied in solution after sowing. Soil tests after the bean crop had indicated the need for extra K.

A completely randomized design was used for all experiments. All treatments were replicated 4 times, except the corn and 2nd crop of alfalfa which had 2 replications.

The soils were maintained at optimum moisture conditions by periodically bringing the jars up to weight with distilled water. Notes were recorded and photographs taken of the plants to show the differences that developed.

After harvesting, the plant material was placed in paper bags, dried in a forced draft electrical oven at $174^{\circ}F$ and weights recorded.

Soil analysis

The untreated soil was chemically analyzed for the following constituents: Exchangeable Na, K, Ca, Mg, and readily available P, K, Ca and Mg. In addition the following properties were determined: Organic matter and total ash,

pH, total exchange capacity, exchangeable H, exchangeable bases and percent base saturation.

Readily available P, K, Ca, and Mg, and pH were determined on the soils after treatment with lime and fertilizers. Exchangeable cations and percent base saturation were also determined. These samples were taken about 4 months after the treatments were applied and just prior to sowing the final series of crops.

METHODS OF SOIL ANALYSIS

Soil reaction was determined by the glass electrode. The pH of the untreated soil was determined using moist soil at 1 to 1, 1 to 2 and 1 to 4 soil to water ratios, and oven dried soil at 1 to 2 and 1 to 4 ratios. Oven dried soil, at a 1 to 4 soil to water ratio, was used for the treated soils.

Exchangeable bases were determined by the ammonium acetate extraction of the soils as outlined by Chapman (11). Exchangeable Na, K, Ca, Mg were determined on the leachates from the ammonium acetate extractions of the soils, Na and K being determined with a Coleman flame emission spectrophotometer, Ca with a Beckman Model Du flame emission spectrophotometer, and Mg with a Perkin Elmer Model 290 atomic absorption unit.

Available Ca, K and Mg was extracted with neutral, 1 normal ammonium acetate at soil to solution ratios of approximately 1 to 20. P was extracted with Bray P₁ solution at the same ratio and determined colorimetrically.

Organic matter and ash content were determined by loss of weight on ignition.

Exchange capacity was determined by the Conductometric titration method outlined by Mortland and Mellor (55), and by summation of exchangeable bases plus exchangeable H.

Exchangeable H was determined by the Barium acetate procedure of Mehlich (51), and also by subtracting the sum of the exchangeable metallic cations from the cation exchange capacity as determined by the method of Mortland and Mellor (55).

The CEC of organic matter is mainly pH dependent, and the quantity of exchangeable H depends on the pH at which it is measured. A curve was prepared for the titration of an S.M.P. buffer with standardized HCl. Suspensions of acid soil and distilled water were prepared, with the quantity of soil varying from 0.1 to 6.0 grams, and 20 ml of buffer solution was added to each suspension. The mixture was stirred, allowed to come to equilibrium for 30 minutes and the pH recorded. The pH ranged from 7.25 to 3.6. From the depression in pH of the buffer, the quantity of soil used and the equilibrium pH, the quantity of hydrogen exchanged at each pH over the pH range 3.6 to 7.25 was determined. This method gave an estimate of exchangeable hydrogen as a function of pH. If exchangeable bases are added to the figures for exchangeable hydrogen so obtained, an estimate of "effective" exchange capacity is obtained. Percent base saturation was calculated as follows:

$$\frac{\text{Total bases}}{\text{Total exchange capacity}} \times 100 = \text{percent base saturation}$$

RESULTS AND DISCUSSION

SOIL ANALYSIS

Some chemical characteristics of the acid organic soil used in the study are given in Table 1. The pH varied with the soil to water ratio used. Oven dried soil gave a somewhat lower value than moist soil and pH 3.8 is the value obtained by the routine procedure at the Michigan State University soil testing laboratory.

The exchangeable cations appeared in the following order of decreasing magnitude—Ca, Mg, Na and K, and this is the normal order for organic soil in this locality (68).

Total exchange capacity, exchangeable H, and percent base saturation varied with the method of determination. The exchange capacity of organic soils is mainly pH dependent, and conductometric titration of a barium saturated soil (at pH 8.1) with MgSO_4 gave the highest value. Summation of exchangeable bases, and exchangeable H by the barium acetate method, gave a much lower value.

Exchangeable hydrogen, as determined directly by the barium acetate method, was much lower than the value obtained by subtracting exchangeable bases from the exchange capacity at pH 8.1.

TABLE 1. Some chemical characteristics of the acid organic soil used in the investigation

	<u>Soil to water ratio</u>		
	<u>1:1</u>	<u>1:2</u>	<u>1:4</u>
pH moist soil	3.90	4.10	4.15
oven dried soil	-	3.6	3.8
Percent organic matter			91.6
Percent ash			8.4
Exchange capacity M.E./100 grams (a)			146
" " M.E./100 " (b)			110
Exchangeable hydrogen, M.E./100 grams (c)			91.4
" " " " (d)			127.6
Exchangeable bases M.E./100 grams			18.6
Percent base saturation (e)			12.7
" " " (f)			16.9
Exchangeable Ca M.E./100 gram			13.8
Mg			3.6
Na			0.7
K			0.3

(a) At pH 8.1 by conductometric titration (55).

(b) Summation of exchangeable bases and exchangeable hydrogen (66).

(c) Barium acetate method of Mehlich (51).

(d) Exchange capacity (55) minus exchangeable bases.

(e) Exchange capacity = 146.

(f) Exchange capacity = 110.

TABLE 2. Content of iron, aluminum and manganese in the soil used. (1)

Total iron	1900 ppm
Total aluminum	2300 "
Total manganese	27 "
Exchangeable manganese	3.7"
Easily reducable manganese	2.5"
Inert manganese oxides	20.8"
Exchangeable iron	4.7"

(1) Chemical analysis of a similar soil in the same locality.

Data extracted from M.S. thesis, 1951 by J.C. Shickluna,
Michigan State College.

The percent base saturation depends, naturally, on the value for exchange capacity used in the calculation, and results are given for two estimates of the exchange capacity.

Chemical analysis of a similar soil in this area (68) showed that these elements occurred in the following order of magnitude - Al, Fe and Mn (Table 2). The levels of these elements differed but little in four organic soils with similar ash content.

The relationship between pH and exchangeable H was studied in more detail using an SMP buffer solution. The titration of this buffer with HCl shows an almost linear depression in pH over the range 7.5 to 3.8. Increments of

acid organic soil, from 0.1 to 6.0 grams, also depressed the pH of the buffer, but the relationship is not linear. Small quantities of soil caused a relatively large depression in pH, while the larger increments had a relatively small effect. The relationship between the weight of soil used, the pH of the soil-water-buffer mixture and the quantity of H exchanged is shown in Table 3.

With small quantities of soil, for example 0.1 to 0.2 grams, the pH at equilibrium is 6.95 to 7.25. At this pH all the carboxyl groups and some polyphenols and substituted phenols are dissociated (12,13). This causes a relatively large depression in pH, and gives a high value for exchange capacity, as calculated from the titration curve of the buffer with HCl.

With a larger quantity of soil, such as 1.5 grams, the pH at equilibrium was 5.00. At this pH only a fraction of the carboxyl groups are dissociated, causing a relatively small depression in pH per unit weight of soil, and giving a low value for exchangeable hydrogen.

The relationship between the pH and exchangeable H in Table 3 is shown graphically in Fig. 1. There is a very high correlation between pH and exchangeable H, ($r = .995$). The graph cuts the x axis at pH 2.8, indicating that at this pH the soil is 100 percent H saturated. At pH 7.3 [obtained with 0.1 grams soil in Table 3] the exchangeable H predicted from the graph is 93 me/100 grams. This is in close agreement with the value of 91.4 obtained by the barium acetate

method of Mehlich (51). Quantities of soil greater than 0.2 grams depressed the pH of the buffer below 7.0 and gave lower values for exchangeable H. This method could be used to estimate the exchangeable H in these soils at various pH values. The addition of exchangeable bases and exchangeable H would give an estimate of "effective" exchange capacity as a function of pH.

Available P, K, Ca, and Mg

The lime and N treatments and basic Mn and B rates are given in Tables 4 and 5. Levels of available P, K, Ca and Mg in the soil after cropping with alfalfa are shown in Table 6. In general, the lime and fertilizer treatments are reflected in the soil analysis. P was very low on the untreated soil and increased by P application. Levels were highest on treatments A and D, where yields were lowest, resulting in lower removal of P. Liming appeared to have little direct effect on available P.

K showed similar trends, being very low on the untreated soil, and highest on treatments A, C and D where yields were lowest due to low lime or N application.

Ca levels increased with all rates of CaCO_3 and $\text{CaSO}_4 \cdot 1/2 \text{H}_2\text{O}$, while the latter generally gave higher values for available Ca. However, pH was lowered where $\text{CaSO}_4 \cdot 1/2 \text{H}_2\text{O}$ was applied although "available" Ca was increased.

Mg levels increased from about 200 to 800-900 lb/acre with the application of MgCO_3 .

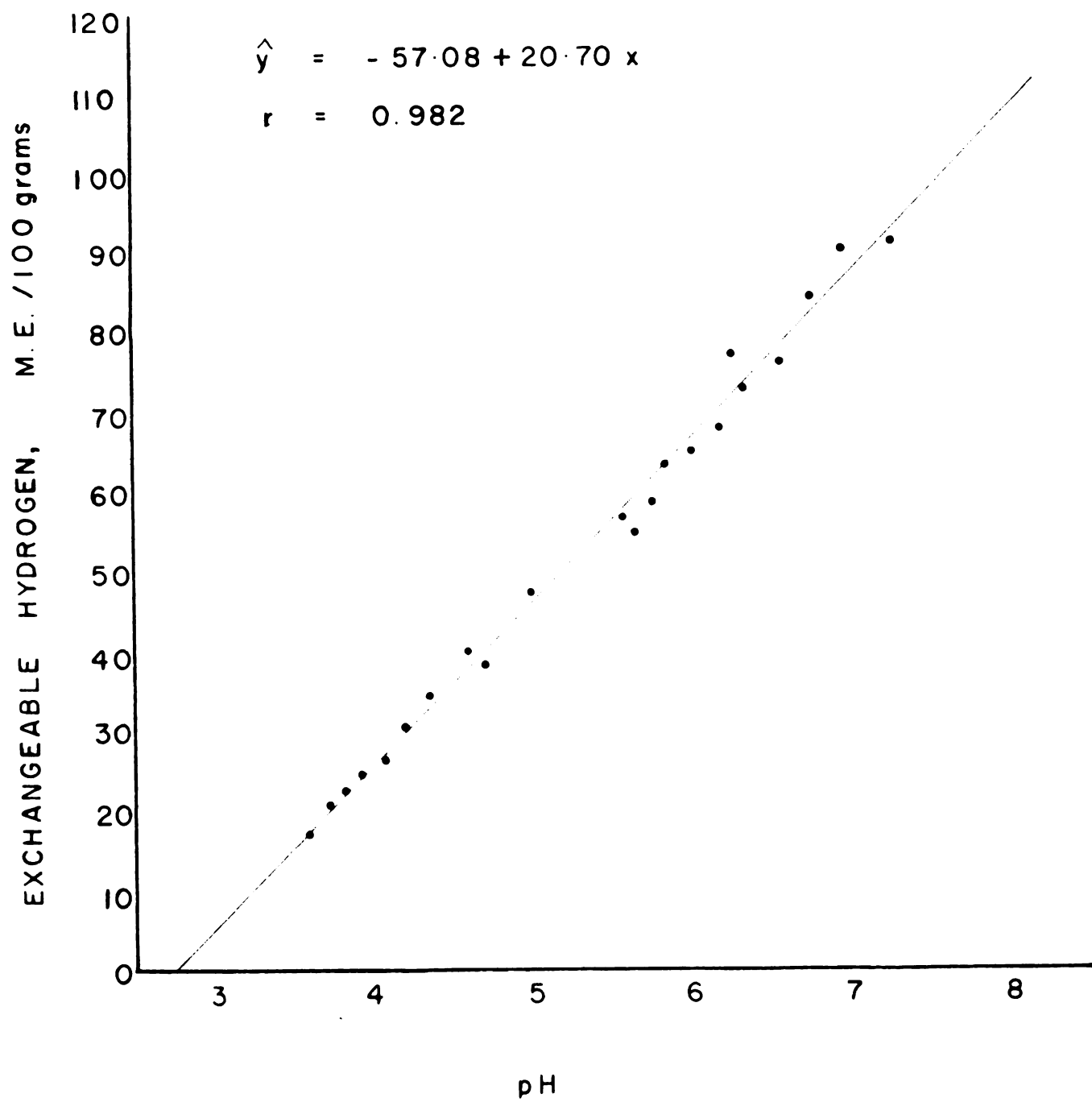
TABLE 3. Hydrogen exchanged from the acid organic soil at various pH values as determined by the S.M.P. buffer solution. (1)

Air dry soil (grams)	pH of soil-water buffer mixture	Hydrogen exchanged ME/100 gram soil
0.1	7.3	91.8
0.2	7.0	90.7
0.3	6.7	85.0
0.4	6.5	76.5
0.5	6.3	73.4
0.6	6.2	68.0
0.7	6.0	65.5
0.8	5.8	63.7
0.9	5.7	58.9
1.0	5.6	55.1
1.5	5.0	47.6
2.0	4.7	38.7
2.5	4.4	34.7
3.0	4.2	30.2
3.5	4.1	26.8
4.0	3.9	24.5
4.5	3.8	22.4
5.0	3.7	20.6
6.0	3.6	17.5

(1) SMP buffer (pH 7.5) as used for the determination of lime requirement by the Ohio method.



FIG. 1. The relationship between pH and exchangeable hydrogen as determined with the S.M.P. buffer.



In general, the available nutrient levels in the soil after cropping with oats, barley and beans followed a similar pattern (Table 7). However the total dry matter produced by these 3 crops was about double that produced by 3 harvests of alfalfa (Tables 8 and 10). This would lead to a greater removal of nutrients and probably accounts for the lower nutrient levels in the soil after growing these crops. In particular, K levels were much lower, and luxury uptake may have been an important factor.

pH and percent base saturation:

The effects of liming materials on soil pH are given in Tables 8 and 10, and the relationship between pH and percent base saturation is shown in Figs. 2,3,4 and 5.

Fertilizers, without lime, depressed the pH below that of the untreated soil. CaCO_3 gave an approximately linear increase in pH, and the pH was higher where no N was applied. Substitution of 2.52 tons of MgCO_3 for 3 tons of CaCO_3 caused little change in pH, indicating that these materials were about equally effective in neutralizing the acidity. Assuming this linear relationship between pH and rate of liming to hold, approximately 15 tons of CaCO_3 would be required to raise the pH to 7.0.

$\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ depressed the pH, whether applied alone, or with CaCO_3 . This differs from results obtained under field conditions on blanket peat, where $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$, supplying 3600 lb Ca per acre did not affect the pH (57). It is generally considered that $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ has little effect on

TABLE 4. CaCO_3 , MgCO_3 , $\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$, and N treatments, and basic Mn and B rates for alfalfa and corn experiments

Treatment No.	Tons per acre			lb per acre		
	CaCO_3	$\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$	MgCO_3	N	B	Mn
A	0	0	0	100	2	0
B	3	0	0	100	2	0
C	3	0	0	0	2	0
D	0	4.35	0	100	2	0
E	0	0	2.52	100	2	0
F	6	0	0	100	3	5
G	6	0	0	0	3	5
H	3	4.35	0	100	3	5
I	3	0	2.52	100	3	5
J	3	4.35	2.52	100	3	5
K	9	0	0	100	4	10
L	9	0	0	0	4	10
M	6	4.35	0	100	4	10
N	6	0	2.52	100	4	10

TABLE 5. CaCO_3 , MgCO_3 , $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ treatments and basic Mn and $\frac{1}{2}$ B rates for oats, $\frac{1}{2}$ barley, beans and sugar beet

Treatment	Tons per acre			lb per acre	
	CaCO_3	$\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$	MgCO_3	B	Mn
A	0	0	0	1	0
B	3	0	0	1	0
C	0	4.35	0	1	0
D	0	0	2.52	1	0
E	6	0	0	2	10
F	3	4.35	0	2	10
G	3	0	2.52	2	10
H	3	4.35	2.52	2	10
I	9	0	0	2	20
J	6	4.35	0	2	20
K	6	0	2.52	2	20

TABLE 6. Available P, K, Ca and Mg, in lb/acre (400,000 lb wt), in soil fertilized and cropped with alfalfa

Treatment	P	K	Ca	Mg
Untreated soil	4	29	420	115
A	72	668	520	184
B	52	524	1624	173
C	61	676	1702	186
D	76	721	2062	200
E	60	568	359	882
F	53	533	2844	191
G	62	610	2726	178
H	53	551	3709	200
I	50	603	1628	928
J	54	559	2888	891
K	52	541	4062	221
L	47	541	3866	176
M	45	480	4376	186
N	55	506	2422	832

TABLE 7. Available P, K, Ca, and Mg in lb/acre (400,000 lb wt), in soil fertilized and cropped with oats, barley, beans and sugar beet

Treatment	P	K	Ca	Mg
Untreated soil	4	29	420	115
A	52	533	500	124
B	34	153	1388	124
C	58	525	1742	136
D	37	235	520	706
E	27	123	2333	119
F	32	191	2785	128
G	31	154	1506	721
H	32	165	2412	649
I	30	130	3198	126
J	31	153	3591	128
K	28	187	2156	596

soil reaction (64, 70). The contrasting results obtained on two acid organic soils may be explained by the fact that products such as H_2SO_4 formed are leached out under field conditions in an area of high rainfall, while such would not occur in the greenhouse.

Percent base saturation was highly correlated with pH, the r values lying between 0.955 and 0.986. The regression lines indicate that base saturation is zero at pH 2.8 to 3.0, and this is in close agreement with the value of pH 3.0 reported for a H saturated organic soil (44). The pH at 100 percent base saturation depends on the method of determining exchange capacity, and also differed somewhat between the two series of experiments. When exchange capacity is estimated at 110 M.E./100 grams, pH 6.5 to 6.9 represents 100 percent base saturation. The corresponding figures for 146 M.E./100 grams are pH 7.7 to 8.2. Lucas and Davis (44) reported that a Ca saturated organic soil has a pH of 7.2 to 7.8, and that pH 4.5 and 5.5 correspond to about 50 and 70 percent base saturation respectively. Data in Figs. 3 and 5 indicate that pH 4.5 corresponds to 38 to 45 percent base saturation, and pH 5.5 to 64 and 72 percent. If exchange capacity is estimated at 146 ME, the percent base saturation at these pH values is reduced proportionately.

FIG. 2. The relationship between pH and percent base saturation of soil cropped with alfalfa and corn (CEC = 146 ME/100 grams).

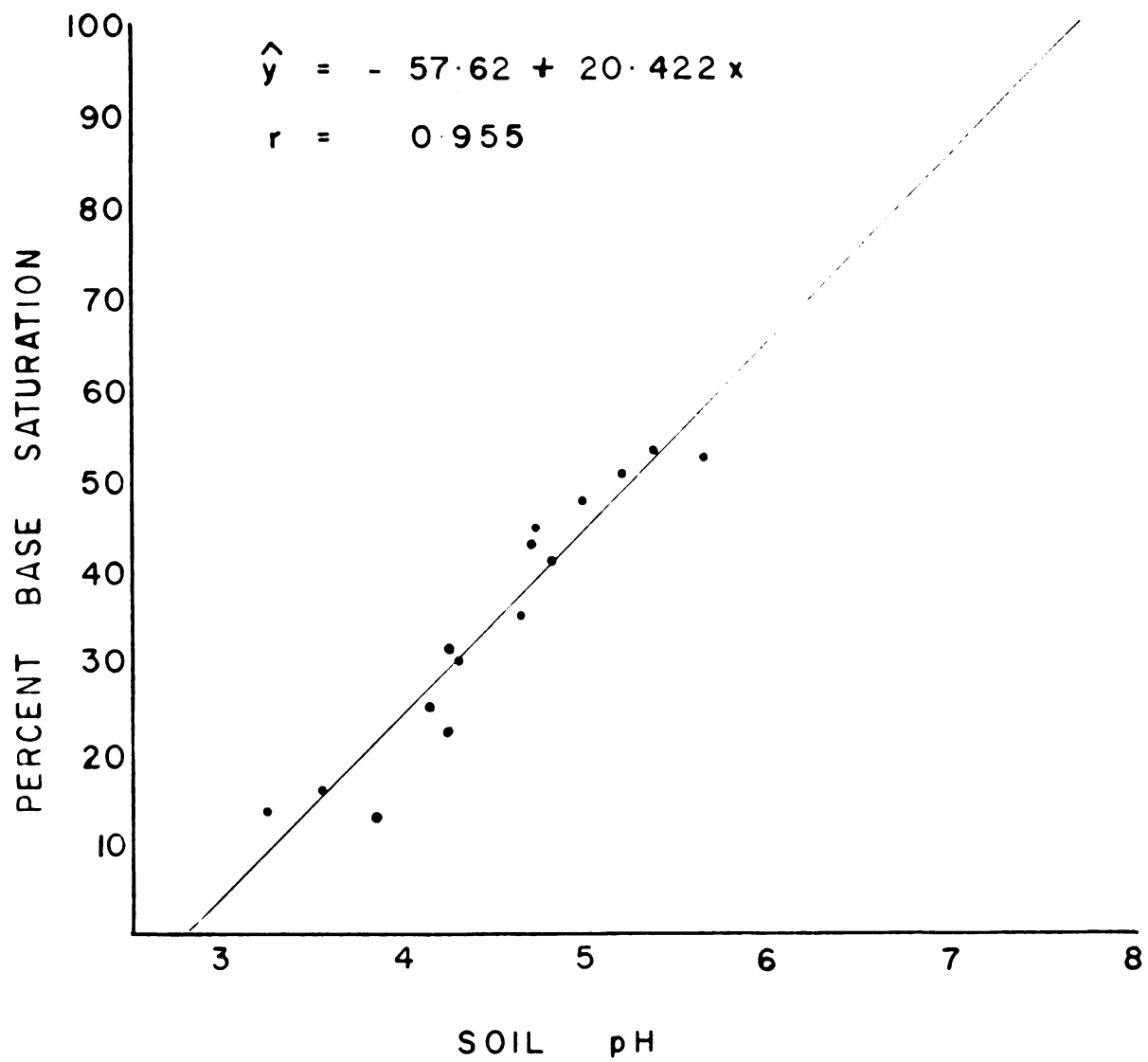


FIG. 3. The relationship between pH and percent base saturation of soil cropped with alfalfa and corn (CEC = 110 ME/100 grams).

$$\hat{y} = -77.75 + 27.39x$$

$$r = 0.964$$

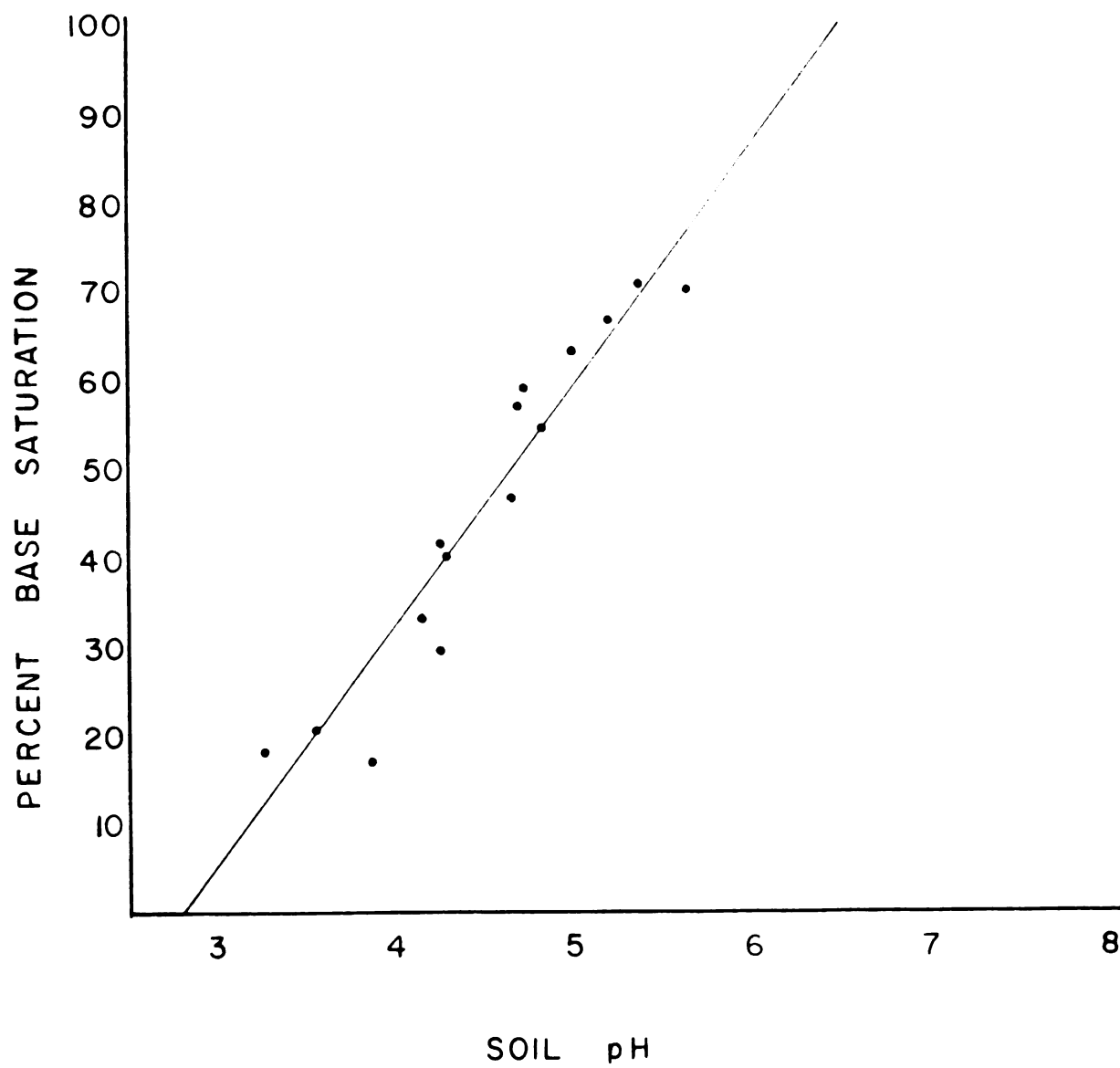


FIG. 4. The relationship between pH and percent base saturation of soil cropped with oats, barley, beans and sugar beet (CEC = 146 ME/100 grams).

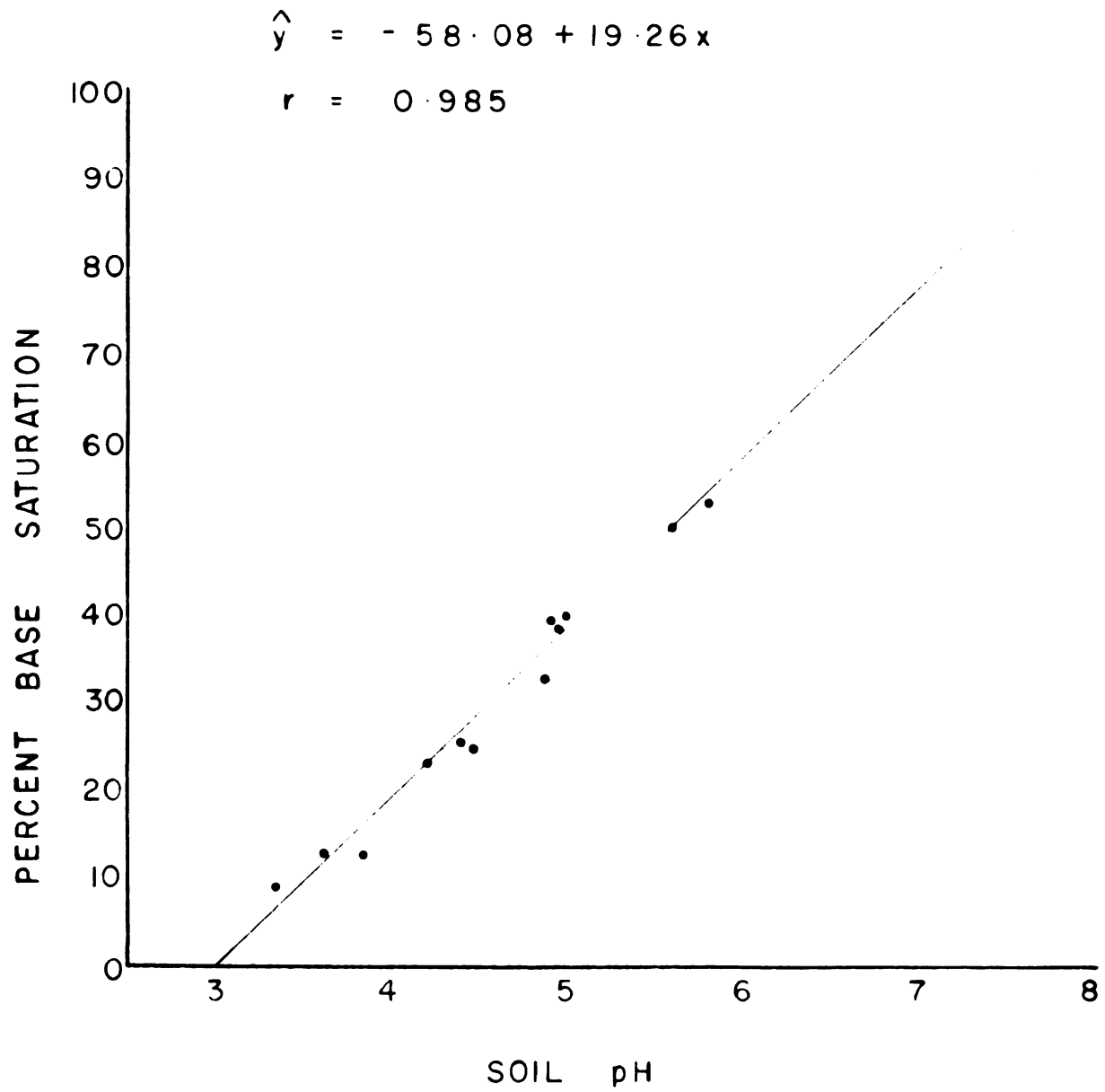
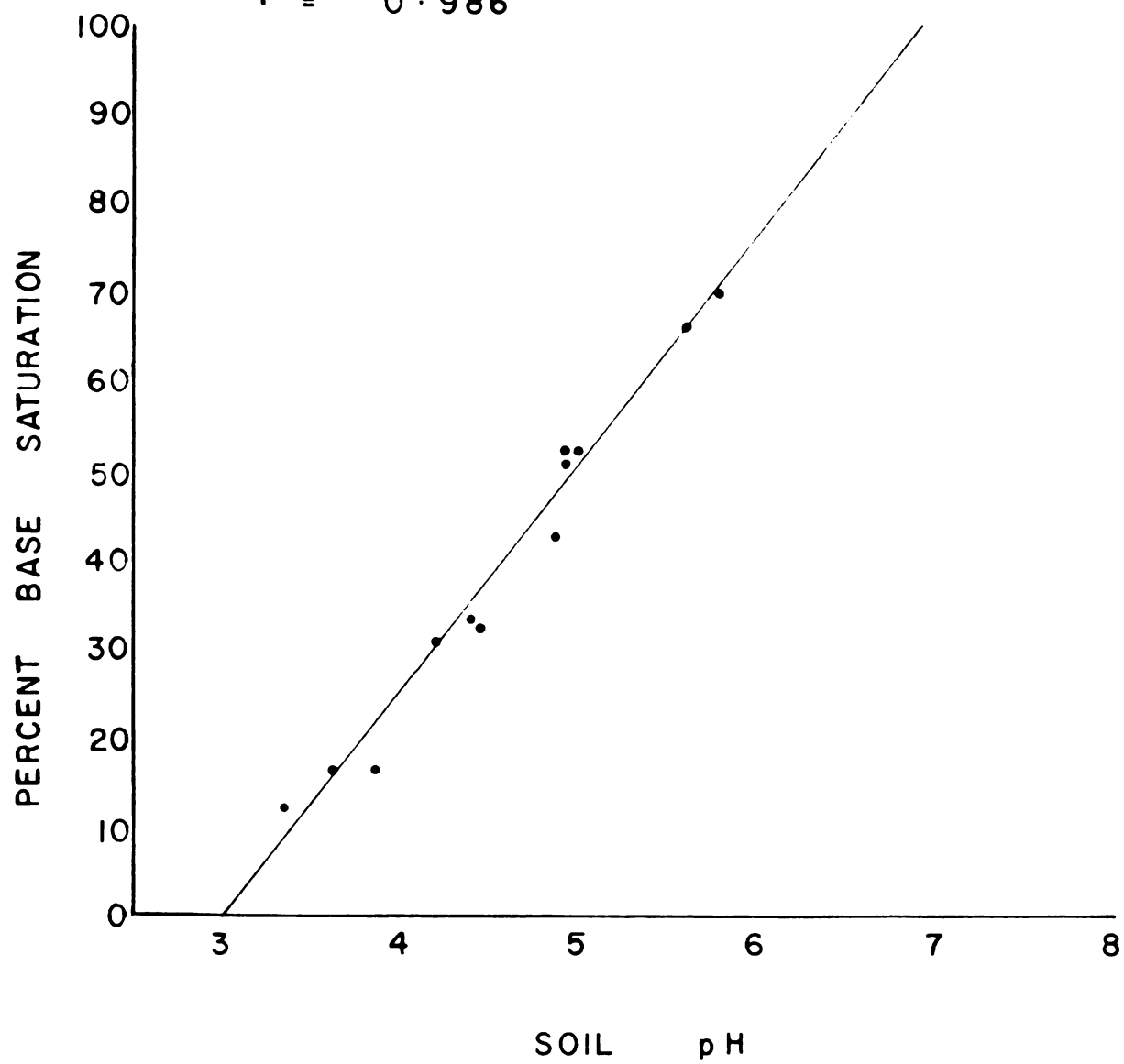


FIG. 5. The relationship between pH and percent base saturation of soil cropped with oats, barley, beans and sugar beet (CEC = 110 ME/100 grams).

$$\hat{y} = -77.10 + 25.568 x$$

$$r = 0.986$$



Crop yields as affected by treatments

Alfalfa, 1st harvest: The various treatments had a marked effect on the yield of alfalfa (Table 8). Yields were very low without lime but were reduced to zero where $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ was applied, the plants having died shortly after germination. This was probably due to the very low pH associated with the latter treatment. Where N was applied, yield was not increased by liming in excess of 3 tons of CaCO_3 per acre. In the absence of N, a yield response was obtained up to 9 tons of CaCO_3 . MgCO_3 alone gave a marked response in yield and was as effective as 3 tons of CaCO_3 .

2nd harvest: The response to treatments followed a similar pattern to that of the 1st harvest. Three tons/acre of CaCO_3 or MgCO_3 was adequate for maximum yield with N, though MgCO_3 seemed slightly less effective. Alfalfa responded to the maximum rate of liming, without N. The application of $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ with 6 tons of CaCO_3 seemed beneficial, though the yield was not significantly greater than with 3 tons of CaCO_3 .

3rd harvest: Plants grown without lime had died at this time, so no yield was obtained with this treatment. Apart from this treatment, the responses were similar to earlier harvests. $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ applied with 6 tons of CaCO_3 was better than all other treatments. The yield with 9 tons of CaCO_3 , without N fertilizer, was equal to that obtained with N at lower rates of liming.

Total yield: Data for total yield reflect the treatments and show similar trends to those of individual harvests. In summary, 3 tons of CaCO_3 with N, and at least 9 tons without N were required for maximum yield. MgCO_3 could be substituted for CaCO_3 and was only slightly less effective. $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ depressed plant growth without CaCO_3 , had no apparent effect with 3 tons of CaCO_3 and gave a positive, though insignificant response with 6 tons of CaCO_3 .

Weight of roots: The weights of roots, taken after the 3rd harvest, reflect the treatments applied, and approximate rather closely the yield of top growth at the 3rd harvest (Table 8). Root growth was severely restricted where no lime, or $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ only was applied. In general, 3 tons of CaCO_3 , or its equivalent as MgCO_3 , with N, was sufficient for normal root growth, while up to 9 tons of CaCO_3 was beneficial without N fertilizdr.

Alfalfa - 2nd crop: As indicated earlier, no additional N was applied for the 2nd crop of alfalfa, the plants being dependent on the residual soil N or that fixed symbiotically. The responses obtained differed to some degree from those of the 1st crop (Table 9). Yields without lime, or with $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ only, were again very low. MgCO_3 was somewhat less effective than CaCO_3 , though the differences were not significant. A heavier rate of liming, 6 tons of CaCO_3 or its equivalent, was required where N fertilizer had been applied, whereas 3 tons was sufficient for the 1st crop. This same rate, 6 tons, was also satisfactory where no N had

TABLE 8. Effect of liming materials and nitrogen fertilizers on the yield of alfalfa, weight of roots, and soil pH

Treatment No.	N lb/acre	Liming materials and rates of application (tons/acre)	1st harvest	2nd harvest	3rd harvest	Total yield	wt.of roots	pH
A	100	0	0.82	0.39	0	1.19	.07	3.6
B	100	3 CaCO ₃	7.12	7.08	2.83	17.03	2.88	4.3
C	0	3 CaCO ₃	2.72	1.76	0.90	5.38	0.78	4.3
D	100	4.35 CaSO ₄ ·½H ₂ O	0	0	0	0	0	3.2
E	100	2.52 MgCO ₃	7.52	5.53	2.06	15.11	1.99	4.2
F	100	6 CaCO ₃	6.40	7.18	2.62	16.20	2.57	4.7
G	0	6 CaCO ₃	3.25	3.01	1.63	7.89	1.50	5.0
H	100	3 CaCO ₃ +4.35CaSO ₄ ·½H ₂ O	7.85	5.89	3.04	16.78	2.18	4.1
I	100	3 CaCO ₃ +2.52MgCO ₃	7.65	7.10	3.28	18.03	3.25	4.8
J	100	3 CaCO ₃ +2.52MgCO ₃ +						
		4.35 CaSO ₄ ·½H ₂ O	6.50	5.93	2.52	14.95	2.30	4.6
K	100	9 CaCO ₃	6.82	6.87	3.20	16.89	2.54	5.4
L	0	9 CaCO ₃	5.25	5.72	2.91	13.88	2.67	5.7
M	100	6 CaCO ₃ +4.35CaSO ₄ ·½H ₂ O	6.98	9.06	5.14	21.18	3.54	4.7
N	100	6 CaCO ₃ +2.52 MgCO ₃	6.35	6.72	3.46	16.53	2.64	5.2
		L.S.D. (5% level)	1.46	2.22	1.10	4.35	1.26	

been applied. $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ depressed the yield significantly, not only in the absence of CaCO_3 , but also when applied with 3 and 6 tons of CaCO_3 .

The differences in the responses of the two crops of alfalfa can be accounted for when the level of soil N and degree of nodulation of the legume is considered.

Nodulation: A visual examination of the roots of alfalfa, after the 3rd harvest was taken from the first crop, showed that nodules were present only where CaCO_3 was applied, without fertilizer N. The nodules were small and scarce with 3 tons of CaCO_3 and increased in number and size with 6 and 9 tons of CaCO_3 . Apparently the heavy rate of N applied, a total of 400 lb/acre, prevented nodulation in the remaining treatments, while the low pH on the unlimed soil, and that receiving $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ only, was an additional factor preventing nodulation. The improved nodulation with increasing rates of CaCO_3 would account for the response obtained to heavy liming where no N was applied.

The level of fertilizer N in the soil should be appreciably lower for the 2nd crop of alfalfa, since no additional N was applied. This was reflected in the degree of nodule development. In the absence of applied N, some nodules formed with the 3 ton CaCO_3 treatment but the number and quality were better at higher rates of liming. Nodules also formed where N had been applied for the previous crop. These were scarce at low lime rates and increased where the equivalent of 6 and 9 tons of CaCO_3 was applied.

TABLE 9. Effect of liming materials and nitrogen fertilizer on the yield of alfalfa (second crop) and corn, and on soil pH

Treatment No.	N lb/acre	Liming materials and rates of application (tons/acre)	Yield of D.M. (grams/pot)		
			Alfalfa	Corn	pH
A	100	0	0.97	27.26	3.6
B	100	3 CaCO_3	3.18	39.92	4.3
C	0	3 CaCO_3	2.58	15.15	4.3
D	100	4.35 $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$	0.17	11.13	3.2
E	100	2.52 MgCO_3	2.06	26.86	4.2
F	100	6 CaCO_3	5.05	40.28	4.7
G	0	6 CaCO_3	4.28	13.37	5.0
H	100	3 CaCO_3 + 4.35 $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$	2.16	35.95	4.1
I	100	3 CaCO_3 + 2.52 MgCO_3	4.30	38.73	4.8
J	100	3 CaCO_3 + 2.52 MgCO_3 + 4.35 $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$	2.12	36.19	4.6
K	100	9 CaCO_3	4.60	38.11	5.4
L	0	9 CaCO_3	3.47	7.75	5.7
M	100	6 CaCO_3 + 4.35 $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$	2.27	36.52	4.7
N	100	6 CaCO_3 + 2.52 MgCO_3	4.67	41.13	5.2
		L.S.D. (5% level)	1.59	8.28	

The response to heavy liming could also be attributed to increased mineralization of organic soil N. That this was not the case in this soil is evident from the response of corn to heavy rates of lime where no fertilizer N was applied (Table 9).

Corn:

The yield of corn was not increased by liming in excess of 3 tons/acre of CaCO_3 (Table 9). $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ depressed the yield where no CaCO_3 was applied, but had little effect when combined with 3 or 6 tons of CaCO_3 . In contrast with alfalfa, MgCO_3 did not increase the yield of corn, although it was as effective as CaCO_3 in raising soil pH. This would suggest that Ca deficiency, or an imbalance of cations in the soil, rather than factors associated with the low pH per se, was limiting plant growth on the unlimed soil. Ca deficiency symptoms have been observed on corn grown on the very acid Cisne soil in Illinois (53). In corn a shortage of Ca prevents the emergence and unfolding of the new leaves, whose tips are almost colorless and are covered with a sticky gelatinous material which causes them to adhere to one another (70). Similar symptoms were observed on corn in the greenhouse where MgCO_3 was applied without CaCO_3 but the symptoms were less pronounced where no Ca or Mg was applied. Apparently Mg accentuated the symptoms of Ca deficiency.

$\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ alone would not be expected to correct the deficiency and improve growth since it depressed the pH to 3.24.

Symptoms of N deficiency were very pronounced where no N was applied, and increasing the rate of CaCO_3 from 3 to 9 tons per acre reduced the yield by about 50 percent. The reason for this is not quite clear. Turk (71) showed that the nitrifying capacity of two soils with pH of 4.3 and 3.4 was increased fourfold by liming. Kaila and Soini (38) found that liming acid peats increased the nitrification of NH_4 nitrogen in some samples and increased NH_4 nitrogen concentration in others. Ammonia volatilization, denitrification, or temporary microbial immobilization of N interfered with the effects of liming on mineral - N accumulation. When the pH is above 5.2, there is little further improvement in N availability from lime additions (44).

Oats: Although normally considered acid tolerant, oats showed a large response to lime (Table 10). The 3 and 6 ton rates of CaCO_3 were equally effective, while the 9 ton treatment gave a small additional response. MgCO_3 was also beneficial, though less effective than CaCO_3 . The yield with 2.52 tons of MgCO_3 was 78 percent of that obtained with an equivalent amount of CaCO_3 . It appears that the response of oats was due to the increase in pH and to the added Ca, rather than to Mg, since the addition of MgCO_3 to the 3 or 6 ton treatments of CaCO_3 was without benefit. $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ alone depressed the yield, but had little effect when applied with CaCO_3 . The lack of response to $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ is attributed to the low pH resulting from this treatment.

Barley: The response of barley to the treatments was very similar to that of oats (Table 10). Although less tolerant for acidity than oats (51), 3 tons of CaCO_3 per acre was sufficient for maximum yield. MgCO_3 was nearly as beneficial as CaCO_3 , the former, applied alone, yielding 91 percent of that obtained with an equivalent amount of the latter. $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ alone depressed the yield slightly, but was without effect when applied in conjunction with CaCO_3 .

Beans: The response of beans differed to some extent from that of cereals (Table 10). $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ tended to depress the yield when applied in combination with CaCO_3 , or with CaCO_3 and MgCO_3 . The depression in pH caused by $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ would not entirely account for the reduction in yield, since growth was normal at pH 4.4 with 3 tons of CaCO_3 , but was stunted at pH 4.9 when $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ was applied. It is probable that sulphate levels in the soil had reached a toxic level since they were not leached from the closed containers (16).

The response to MgCO_3 alone was not significant and yield with this treatment was about 73% of that obtained with an equivalent amount of CaCO_3 .

Sugar beet: This crop is considered to be slightly acid tolerant and is in the same category as alfalfa (53). The response to liming materials was very similar to that of alfalfa grown without fertilizer N (Table 10). The heaviest lime treatment - 9 tons/acre of CaCO_3 - produced the highest yields. MgCO_3 , applied alone or with CaCO_3 , was about as

TABLE 10. Effect of liming materials on soil pH and yield of oats, barley, beans and sugar beet

Treatment No.	Liming materials, and rates of application. (tons/acre)	Yield of dry matter, in grams/pot			
		Oats	Barley	Beans	Sugar beet pH
A	0	4.42	3.56	3.42	4.36 3.6
B	3 CaCO ₃	16.55	9.42	5.55	6.68 4.4
C	4.35 CaSO ₄ ·½H ₂ O	3.08	2.68	3.72	0.91 3.3
D	2.52 MgCO ₃	12.88	8.60	4.07	7.43 4.5
E	6 CaCO ₃	16.53	9.68	5.71	8.35 4.9
F	3 CaCO ₃ +4.35 CaSO ₄ ·½H ₂ O	16.08	9.09	4.24	3.14 4.2
G	3 CaCO ₃ +2.52 MgCO ₃	15.38	9.98	5.56	8.97 5.0
H	3 CaCO ₃ +2.52 MgCO ₃ +4.35 CaSO ₄ ·½H ₂ O	15.28	8.85	4.17	3.06 4.9
I	9 CaCO ₃	18.68	8.72	6.08	10.92 5.8
J	6 CaCO ₃ +4.35 CaSO ₄ ·½H ₂ O	15.12	9.37	5.45	5.10 4.9
K	6 CaCO ₃ +2.52 MgCO ₃	16.85	9.14	5.62	10.26 5.6
	L.S.D. (5% level)	1.91	1.07	1.29	2.15

effective as an equivalent quantity of CaCO_3 . $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ depressed the yield significantly at all rates of liming. This is attributed to the lower soil pH, as well as possible toxic sulphate levels in the soil (17).

Magnesium in relation to soil acidity: It is unlikely that Mg deficiency was a limiting factor for plant growth on this acid organic soil. Corn and beans showed no significant response to MgCO_3 ; oats, alfalfa and barley gave a large response, while MgCO_3 and CaCO_3 were equally effective for sugar beet. However in no case was the yield increased significantly when MgCO_3 replaced an equivalent quantity of CaCO_3 in the treatments. It is more likely that the responses obtained were due to the increase in pH, base saturation and availability of Mo, and a reduction in the levels of exchangeable Al, Fe and possibly Mn in the soil and reduced uptake of these elements by the plants.

TABLE 11. The optimum pH values at which the highest yields were obtained on the organic soil studied

Crop	pH	Tons of CaCO_3 required to raise soil reaction to optimum pH
Alfalfa, no N	5.0-5.7	6 - 9
Alfalfa, high N	4.3	3
Oats*	4.4	3
Barley	4.4	3
Corn	4.3	3
Beans	4.4	3
Sugar beet*	5.0-5.8	6 - 9

*Yields slightly higher with 9 tons CaCO_3 .

Yield and soil pH: The optimum soil pH varied considerably for the crops grown (Table 11). When alfalfa was supplied with fertilizer N, its lime requirement was similar to that of several non legumes, but when the plant was depending on symbiotic N fixation it required a much higher soil pH. Nodulation improved with increasing rates of CaCO_3 applied and soil pH. This is in agreement with reports showing that rhizobia are adversely affected at low pH, and that more Ca is required for nodulation and N fixation than is required by the host plant (33, 43, 56).

Standards of soil pH for organic soils used by various states of the Mid-western USA indicate an optimum between 5.0 and 5.6 (76). At pH 5.0 or above these soils contain an abundance of available Ca, but do not contain toxic quantities of Mn, Al, and Fe. For wood-sedge organic soils the ideal pH is 5.5 to 5.8, while pH 5.0 is satisfactory for sphagnum peats (44).

pH was not always a reliable indicator of the lime status of the soil in these experiments. MgCO_3 raised the pH but this was not always accompanied by an increase in yield, while $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ often depressed the yield even when the pH seemed sufficiently high. In no case, however, was the yield depressed, even by the heaviest CaCO_3 or MgCO_3 treatment. The availability of certain micronutrients, especially Mn, may be decreased at pH 5.8, the highest value obtained in these experiments (44). An average pH of about 5.5 would appear suitable for the range of crops

grown when the micronutrients Cu, Mo, B and Mn were included in the basic fertilizer.

TABLE 12. Percent base saturation at which the highest yields were obtained on the organic soil investigated

Crop	Percent base saturation	
	Method 1*	Method 2*
Alfalfa, No N	48 - 53	63 - 70
Alfalfa, high N	32	42
Oats	25	34
Barley	25	34
Corn	32	42
Beans	25	34
Sugar beet	40 - 53	53 - 70

*1 = CEC = 146 m.e./100 grams

2 = CEC = 110 m.e./100 grams

Yield and percent base saturation: The percent base saturation and total exchange capacity may be a better criteria than the pH value for estimating the lime needs of crops on an organic soil (66). There was a considerable difference in the optimum base saturation for maximum yield of the crops grown (Table 12). Fertile organic soils are generally 50 to 65 percent saturated with Ca (69). While alfalfa, without fertilizer N, and sugar beet grew best within this range, the other crops tolerated a lower base saturation. It is possible that if the latter crops were allowed to grow to maturity, highest yields would be

obtained at higher pH and base saturation values.

pH, Ca, and soil acidity: The addition of lime to acid soils simultaneously increases the quantity of Ca in the soil, raises the pH, increases the availability of Mo and lowers the amount of exchangeable Al and Mn (12). This causes difficulties in deciding which acidity factors are involved in an individual acid soil. The crops grown differed in their response to CaCO_3 and MgCO_3 .

Corn and beans showed no significant response to MgCO_3 . Symptoms resembling those of Ca deficiency developed in corn when MgCO_3 was applied. This would suggest that Ca deficiency rather than toxicities associated with the low pH was the most limiting factor for growth of these crops on the acid organic soil.

Oats, barley and alfalfa gave large responses to MgCO_3 , though CaCO_3 generally gave somewhat higher yields. In previous studies on this soil CaCO_3 and MgCO_3 were about equally effective for lettuce, but CaCO_3 was best for cauliflower. Both materials increased the availability of Mo (31). Toxicities associated with the low pH, a possible Mo deficiency and, to a lesser extent, Ca deficiency probably account for the acidity injury to these crops.

In the case of sugar beet, CaCO_3 and MgCO_3 were about equally effective as liming materials (Table 10. If Mg was limiting for growth, then substitution of MgCO_3 for part of the CaCO_3 should give an added response, but this did not occur. If Ca deficiency alone, or a combination of

low Ca and low pH were the limiting factors, then 3 tons of CaCO_3 , by raising the pH and supplying Ca simultaneously, should prove better than an equivalent amount of MgCO_3 . This was not the case in these experiments. Apparently the toxic effects of Al, Fe or Mn, and a deficiency of Mo would account for the poor growth of sugar beet without lime on this soil.

Molybdenum: Mo deficiency on this acid peat could be a factor in the poor growth. In previous studies on this soil (31) Mo alone increased the yield of lettuce and cauliflower, crops with a higher Mo requirement (19). Three tons of lime + Mo gave higher yields of lettuce than Mo alone and there was no response to heavier liming. Mo alone was about as effective as 3 tons of lime for cauliflower. Three tons of lime with Mo was better than either applied separately while 6 tons of lime alone gave highest yields. Thus part of the benefit from liming this soil was the increased availability of Mo.

Mo deficiency frequently occurs on organic soils. MacKay and Chipman (45) reported Mo deficiency in vegetable crops on limed sphagnum peat soil. For cauliflower, adjusting the pH with dolomitic limestone had little effect without Mo, but Mo was more effective at pH 5.2-5.7. Van Der Elst (72) found that 2 ozs/acre of sodium molybdate increased pasture production 4 times on a newly reclaimed fibrous peat, white clover showing the greatest response.

Although 2 lb/acre of sodium molybdate was applied on all treatments in this study it is possible that part of the benefit from liming was due to the increased availability of the applied Mo.

Al, Fe, Mn: In previous studies (68) it was found that onions grew best on this soil type at pH 5.3. Liming decreased the exchangeable Mn level in the soil, and the total Mn in tops and bulbs. It was shown that Fe and Al were present in such quantities in the onion tissue harvested from the non-limed treatment, as to be toxic to the plant. The author concluded that Mn was not the toxic element in this soil.

It is generally considered that at pH 5.0 or above organic soils contain an abundance of available Ca, but do not contain toxic quantities of Mn, Al and Fe (76).

Calcium sulphate: On a blanket peat soil, with a pH of about 4.5 in the virgin state, gypsum gave a marked improvement in the growth of oats and barley (29). White clover failed to grow without lime but made good growth and formed nodules at pH 4.7 with 1000 lb/acre of CaCO_3 . Gypsum was also beneficial, and nodules were formed at pH 4.3 with 3600 lbs of Ca, as $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ (57). Gypsum had no effect on soil pH.

The difference in the response to gypsum on the two organic soils may be related to their chemical composition. Blanket peat has a higher pH in the unlimed state, contains

a total of 1000 PPM Mg, 800 PPM Ca, 600 PPM Na, 500 PPM K and 400-600 PPM Fe in the dry matter of the surface layer. Levels of soluble Al and Mn are also low (75). With the levels and ratio of cations, reflecting the maritime influence, the low level of Ca, and low level of Al, Fe and Mn, it is not surprising that a neutral salt such as $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$ would be a useful source of Ca on this soil. The sulphate ion is easily leached out, because of the high rainfall, as H_2SO_4 , if it is formed, or as a salt of sodium which is present at a higher concentration than in Rifle peat. Such leaching did not occur in the greenhouse.

SUMMARY AND CONCLUSION

Experiments were conducted in the greenhouse to investigate the response of alfalfa, corn, oats, barley, beans and sugar beet to CaCO_3 , $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ and MgCO_3 , alone and in combination, on a Rifle peat soil. The response of alfalfa and corn, with and without fertilizer nitrogen, to CaCO_3 was also investigated.

Yields were very low in the unlimed soil and CaCO_3 increased the yields of all crops. Three tons/acre proved sufficient for oats, barley, beans, corn and alfalfa when supplied with fertilizer N but 6 to 9 of CaCO_3 was required for sugar beet (+N) and alfalfa when no N was applied.

The crops varied in their response to MgCO_3 . Corn and beans showed no significant response. For the remaining crops grown the order of increasing response to MgCO_3 was: oats, barley, alfalfa and sugar beet. In the case of sugar beet CaCO_3 and MgCO_3 were equally effective in increasing yield.

$\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ was without benefit for the crops and generally lowered the pH and depressed the yields.

The lowest pH at which maximum yields were obtained varied from about pH 4.4 for oats, barley, corn, beans and

alfalfa when supplied with fertilizer N, to pH 5.0 to 5.8 for sugar beet (with N fertilizer) and alfalfa which received no fertilizer N. The heaviest lime treatments did not decrease the yield of any crop, and an average pH of about 5.5 would appear suitable for the range of crops grown.

The percent base saturation at which maximum yields were obtained was 34 to 42 for those crops which grew satisfactorily at pH 4.4, and 53 to 70 for those requiring the higher pH. If exchange capacity is estimated at 146 M.E./100 gram instead of 110, as used above, the figures for base saturation are correspondingly lower.

N deficiency was very severe in corn not supplied with this fertilizer and heavy liming apparently did not increase the availability of soil N.

Alfalfa produced no nodules when no lime or high N rates were applied, but nodulation improved with increasing quantities of lime in the absence of N fertilizer.

The effects of the various treatments on root growth of alfalfa were very similar to their effects on top growth.

Symptoms resembling Ca deficiency developed in corn when MgCO_3 was applied without CaCO_3 . Ca deficiency may have limited the growth of this crop on the acid soil.

The quantity of exchangeable H in the organic soil depended on the method of determination and was highly correlated with soil pH.

Soil pH and the levels of available P, K, Ca and Mg generally reflected the treatments applied, and soil pH and percent base saturation were highly correlated.

It is suggested that the response to lime on this soil was due to the addition of Ca, a reduction in the levels of exchangeable Al, Fe, and possibly Mn, and increased availability of Mo.

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APPENDIX 1 - PHOTOGRAPHS

No. 1 - Effect of treatments on oats.

Treatments, left to right:-

A = Check - no lime

C = 4.35 tons/acre $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$

B = 3 tons CaCO_3

D = 2.52 tons MgCO_3

No. 2 - Effect of treatments on barley.

A = Check - no lime

B = 3 tons CaCO_3

C = 4.35 tons $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$

D = 2.52 tons MgCO_3

No. 3 - Effect of treatments on beans

A = Check - no lime

B = 3 tons CaCO_3

C = 4.35 tons $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$

D = 2.52 tons MgCO_3

E = 6 tons CaCO_3



No. 4 - Effect of treatments on sugar beet

- A = check - no lime
- B = 3 tons CaCO_3
- C = 4.35 tons $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$
- D = 2.52 tons MgCO_3
- E = 6 tons CaCO_3

No. 5 - Substitution of $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$ for CaCO_3 on sugar beet

- A = check - no lime
- B = 3 tons CaCO_3
- C = 4.35 tons $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$
- E = 6 tons CaCO_3
- F = 3 tons CaCO_3 + 4.35 tons $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$
- I 9 tons CaCO_3
- J 6 tons CaCO_3 + 4.35 tons $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$

No. 6 - Substitution of MgCO_3 for CaCO_3 on sugar beet

- A = check - no lime
- B = 3 tons CaCO_3
- D = 2.52 tons MgCO_3
- E = 6 tons CaCO_3
- G 3 tons CaCO_3 + 2.52 tons MgCO_3
- I 9 tons CaCO_3
- K 6 tons CaCO_3 + 2.52 tons MgCO_3



No. 7 - Effect of treatments on corn, fertilized with N

A = check - no lime

B = 3 tons CaCO_3

D = 4.35 tons $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$

E = 2.52 tons MgCO_3

F = 6 tons CaCO_3

No. 8 - Effect of treatments on corn, $\frac{1}{2}$ N fertilizer

A = check (+N) - no lime

C = 3 tons CaCO_3 (-N)

G = 6 tons CaCO_3 (-N)

L = 9 tons CaCO_3 (-N)

B = 3 tons CaCO_3 (+N)

No. 9 - Effect of treatments on alfalfa

D = 4.35 tons $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$ (+N)

A = check - no lime (+N)

B = 3 tons CaCO_3 (+N)

C = 3 tons CaCO_3 (-N)

E = 2.52 tons MgCO_3 (+N)

F = 6 tons CaCO_3 (+N)



No. 10 - Response of alfalfa to CaCO_3 + N fertilizer

B = 3 tons CaCO_3 (+N)
 F = 6 tons CaCO_3 (+N)
 K = 9 tons CaCO_3 (+N)
 A = check - no lime (+N)
 C = 3 tons CaCO_3 (-N)
 G = 6 tons CaCO_3 (-N)
 L = 9 tons CaCO_3 (-N)

No. 11 - Effect of lime and N fertilizer on nodulation of alfalfa.

Bottom left: treatment F: - 6 tons CaCO_3 (+N)
 Top left: treatment C: 3 tons CaCO_3 (-N)
 Bottom right: treatment G: 6 tons CaCO_3 (-N)
 Top right: treatment L: 9 tons CaCO_3 (-N)

Note the absence of nodules where N fertilizer was applied.



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