FEASIBILITY OF PARTIAL NEUTRALIZATION IN CORRECTING SOIL ACIDITY

by

CLARENCE BURNHAM

A THESIS

submitted to the

OREGON STATE AGRICULTURAL COLLEGE

in partial fulfillment of
the requirements for the
degree of

DOCTOR OF PHILOSOPHY

May 1935

AN ABSTRACT OF THE THESIS OF

Ph.D. - 52 pp.

Clarence Burnham for the Ph.D. in Soils
(Name) (Degree) (Major)

Date Thesis presented May 6, 1935

Title Feasibility of Partial Neutralization in Correcting Soil Acidity

Abstract Approved: [redacted]
(Major Professor)

Investigations were conducted to study the factors of soil acidity affecting the use of lime on marginal lands. Two light acid soils in need of lime were used in this study. Studies were conducted to determine the influence of lime on the yield of red clover and on the nitrifying power of the soils. Tests were made of the effects of lime on reaction, lime requirement, availability of plant nutrients and the exchange reactions of the soil. The use of lime was considered in relation to the fundamental differences present in the two soils. The results of these studies may be summarized as follows:

1. Hydrogen-ion concentration and lime needs of the soils showed no relationship. Lime requirements gave a more accurate indication of lime needs.

2. The Melbourne soil is definitely low in available phoshorus while the Dayton soil is well supplied. Phosphate fixation is high in both soils. Indications were that free iron and aluminum oxides present in the soils were responsible for most of the fixation. Some fixation was due to humus but in a form ultimately available to the plant.

3. Active aluminum was not present in quantities sufficiently large to be toxic to plant growth in the soils studied.

4. Titration curves indicate the soil acids are highly buffered in both soils, thus requiring high lime rates to improve soil reaction.

5. The Melbourne soil has a low base exchange capacity in proportion to the amount of colloid which indicates that the soil is in the process of degeneration.

6. The presence of strong acids as measured by the avidity test indicates that the soil is not completely degenerated.

7. The Dayton soil has a comparatively high base exchange capacity and consequently greater capacity to retain nutrients.

Difference in base exchange capacity of the soils correlates with difference in plant nutrients.

8. The proportion of exchangeable bases to exchangeable hydrogen or base saturation is high in the Dayton soil. The Melbourne soil shows a high degree of unsaturation in respect to bases.

9. Nitrification of the soil's own nitrifiable material was low in both soils. When ammonium sulfate was added, nitrification in the Dayton soil was high. The Melbourne soil has low ability for nitrification even when nitrifiable material is present.

10. When phosphorus and organic matter were supplied the Melbourne soil, nitrification proceeded as vigorously as in the Dayton soil.

11. The most vigorous nitrification resulted with the highest lime treatments. Per unit of lime, the light lime rates were more effective.

12. Nodulation was increased by liming.

13. A close correlation was obtained between nitrification and clover production. The treatments that stimulated plant growth stimulated nitrification.

14. Lime increased clover yields on the Dayton soil. Applications of 250 to 1000 pounds per acre have proved relatively more beneficial than heavier rates. The highest yields, however, were obtained with the heaviest treatments.

15. Total yields remained extremely low on the Melbourne soil even with heavy liming. Manure and phosphorus treatments resulted in large increases in yield. When phosphorus and humus deficiencies were corrected, the beneficial effect of liming the Melbourne soil was apparent. Here again, the small applications proved relatively more effective per unit of lime than the heavier applications.

16. Varying the soil reaction between pH 3.0 and pH 8.0, gave the highest clover yields near neutrality.

17. In the greenhouse studies no apparent benefit was obtained from placing lime close to the seed.

18. The Melbourne soil requires a large expenditure for lime and fertilizers to produce an average yield of red clover. Yields on the Dayton soil are limited by an impervious clay pan. Many crops, including legumes, are less sensitive to soil deficiencies than red clover. For the profitable utilization of marginal lands, crop selection, rather than extensive liming or soil improvement, appears more feasible.

APPROVED:

[redacted]

Professor of Soils

In Charge of Major

[redacted]

Head of Department of Soils

[redacted]

Chairman of School Graduate Committee

[redacted]

Chairman of College Graduate Council.

Acknowledgment and sincere thanks
are due Dr. R. E. Stephenson for
his guidance and kindly criticism.

Table of Contents

	Page
Review of the Literature on Crop Response to Varying Amounts of Lime	2
The Soils Studied	5
Plan of Study	6
Greenhouse Studies with Varying Amounts of Lime	9
Rates and Methods of Placement	11
Nodulation and Inoculation	12
Factors Limiting Response of Clover to Lime Treatments on Melbourne Soil	15
Clover Response to Lime on Soils with Phosphorus and Manure Added	18
Effect of Varying Soil Reaction on the Yield of Red Clover	21
The Effect of Varying Amounts of Lime on Nitrification	25
Nitrifying Power of Soils Treated with Varying Amounts of Lime.	28
Soil Reaction, Lime Requirement and Crop Response	34
Phosphorus Availability and Nature of Phosphate Fixation in Acid Soils	38
Base Exchange Properties and Lime Needs of Acid Soils	46
Nature of Soil Acids	53

Table of Contents (continued)

	Page
Titration Curves	58
Discussion	59
Summary	67
Plate I. Melbourne Soil	71
Plate II. Melbourne Soil	72
Plate III. Dayton Soil	74
Plate IV. Dayton Soil	75
Plate V. Varying Soil Reactions	77
Bibliography	78

FEASIBILITY OF PARTIAL NEUTRALIZATION IN CORRECTING SOIL ACIDITY

The important question of the most economical amount of lime to apply in correcting acid soils has not yet been satisfactorily answered. This in part is because of the heterogeneous nature of the soil and the many factors influencing response to lime. The difficulties in identifying the various influences which determine response to lime are not easily overcome.

Fisher (15), after reviewing experimental work dealing with problems of soil reaction, states, "The very complexity of the soil militates against any single factor being the sole cause of soil acidity." Probably the low production of soils usually attributed to acidity results from the interaction of physical, chemical and bacteriological soil properties. Soils vary in the amount of lime required to bring them to high production. Other things may be needed as much or even more than lime to bring some acid soils to satisfactory yields.

Economic liming becomes particularly significant on soils of initial low productivity when the cost of liming is high. The outlay for lime necessarily must be very limited or there is no profit from improvement. In western Oregon a condition exists where high lime costs on extended areas of marginal cultivated land renders the feasibility of liming questionable. The Melbourne and Dayton series comprise a large portion of this class of soils. The two series represent more than ten per cent of the agricultural land of the Willamette Valley. The extent to which the unproductive and frequently acid lands of this region can be improved with small applications of lime is an important subject for detailed study.

Review of the Literature on Crop Response to Varying Amounts of Lime*

Slipher (41) summarized data from seventeen state experiment stations and found that light rates of liming were more efficient per unit of lime than were the heavy applications. White and Holben (50) compared limestone applied (a) at a rate to fully correct acidity, Veitch method, (b) 1081 pounds, and (c) 540 pounds on three soil types. The smaller two applications produced twice the profits of the heavier application. Crowther and Basu (11) found that over a period of years small frequent lime applications were more economical than the same amount made in a single application as loss from leaching was decreased. Brenchley's (7) results showed a loss where

*Lime and limestone are used interchangeably in this study, and refer to the carbonate form of lime, except where otherwise specified.

heavy lime treatments were used with manure and phosphate, but a profit where light dressings were used. Midgley and Weiser (29) applied lime with and without superphosphate at rates of one-fourth, one-half and full lime requirement by the Jones method. Applications of one-half the lime requirement were as effective as the full requirement. Superphosphate increased the effectiveness of the smaller applications. Hutcheson (21) found the economic rate of liming varied with different crops. Six hundred pound applications of limestone profitably increased yields of soybeans, corn and rye. Larger applications did not pay. Potatoes, oats and wheat were not benefited by lime. Sweet clover, alfalfa and red clover required one ton to prove profitable.

The possibility of reducing the amount of lime necessary to produce crops by localizing the lime near the seed has been suggested by some workers. McCool (27) found on one soil type that applications of 552 pounds of limestone in the row were as satisfactory for alfalfa as three tons broadcast. The results obtained by him on other soil types differed widely. Albrecht and Poirot (3) doubt the necessity of neutralizing completely the acidity of the surface soil. They believe that enough lime to provide localized centers of limed soil accessible to the roots may be all that is needed. Three hundred pounds of 30 mesh lime drilled with the seed was as effective as 5000 pounds of 10 mesh lime broadcast. Both McCool and Albrecht were using lime primarily for its good effect in securing inoculation of legumes. Dawson and Evans (12) found that one ton of limestone applied as a top dressing near the seed was as beneficial as eight and a half tons mixed with the soil. They report that plants require only sufficient lime to help them over the germination period.

That there were some exceptions to the beneficial effect obtained from small applications of lime in the above studies is significant. Fractional neutralization did not prove feasible on all soil types. Turner (48) obtained more promising results with large single applications than with small annual treatments on deteriorated soils. He stressed the need for maintaining a sufficient reserve of calcium carbonate in the soil to maintain the degree of saturation of the exchange complex at approximately 80 per cent. Bauer (5,6) reports that a four ton lime application gives full beneficial effect on crop yields for at least eight years. From field data he shows that it is more economical to apply one heavy application than repeated small applications. Salter (38) obtained little benefit in placing lime close to the seed. He points out that lime is not soluble immediately and the effect of lime would not be evident when the seed germinates.

That the economic liming limit is determined by plant response and may be less than complete neutralization is evident. Field data show that the lime requirement of the plant is as important as the lime requirement of the soil. A profitable rate of liming on one crop may not prove profitable on another crop with different lime needs.

Much experimental evidence shows that the physical, chemical, and biological properties of the soil approach more closely ideal conditions for plant growth where the soil is near neutrality. On acid, thoroughly leached soils, however, other factors than mere neutrality of reaction are important in determining crop yields. Nutrient composition and availability of other nutrients in the soil to which lime is applied affect the crop response.

The Soils Studied

The Dayton and Melbourne soils are mature soil types developed under a rainfall of 38 to 45 inches. The Dayton is a wet valley floor soil developed under imperfect drainage. A clay pan occurs at a depth of 10 to 16 inches of a very compact, impervious, plastic clay horizon 16 to 18 inches thick. The soil is locally known as "white land".

The Melbourne is a red hill soil approaching lateritic characteristics. It is developed under good drainage and is derived from sandstones and shales. It is characterized by brown surface soil and yellow or reddish yellow moderately compact subsoil. The soil is thoroughly leached, low in bases and other nutrients, and low in the capacity to hold bases.

Table 1 shows that the degree of acidity is much the same in the two soils but the Dayton is high in constituents normally present in fertile soils in contrast with the Melbourne which is low in these constituents. Although the Dayton soil is relatively much higher in plant nutrients, a poor physical condition of the subsoil limits crop production. The Melbourne soil is definitely low in fertility which effectually limits crop production. Both soils are acid and the need for lime has been established (44). Will these soils, differing but slightly in reaction but so materially in chemical composition, require the same lime treatments to improve crop yields? Will the soils respond profitably to liming, and if so, at what rates?

Plan of Study

With these problems in mind the following factors influencing the response of the Melbourne and Dayton soils

Table 1. Characteristics of the Soils Used in the Investigation

Average of Several Determinations on the Untreated Soils During Period of Investigation	Melbourne Soil	Dayton Soil
H-ion Concentration, expressed as pH	5.28	5.90
Lime Requirement, tons per acre $CaCO_3$	2.72	1.60
Colloid Content, per cent	19.90	21.50
Organic Matter, per cent	1.46	2.45
Total Nitrogen, per cent	0.059	0.067
Base Exchange Capacity, M.E. per 100 gms. soil	5.74	13.09
Replaceable Calcium, M.E. per 100 gms. soil	1.51	8.22
Replaceable Hydrogen, M.E. per 100 gms. soil	3.50	1.95
Water Soluble Calcium, p.p.m.	12.6	45.5
Nitrate Nitrogen, p.p.m. (Average of all determinations)	3.4	27.0
Available Phosphorus, p.p.m. PO_4 acid soluble[1]	10.6	319.2
Soil Class	Clay loam	Clay

[1] By Truog method (45).

to lime treatments were studied:

1. Plant response to different degrees of acidity

    a. As measured by crop yields

    b. As measured by reaction or pH of the soil

    c. As measured in terms of lime requirement.

2. Bacteriological response to different degrees of acidity

    a. Nitrifying power of the soil with lime and fertilizer treatments.

    b. Nodulation of clover with liming.

3. Availability of nutrients at different reactions

    a. Calcium available with lime treatments

    b. Phosphorus available with lime treatments

    c. Toxins that may be present as a result of soil acidity.

4. Nature of the exchange complex of the soil

    a. Exchange capacity, exchangeable bases, and nature and amount of exchange anions

    b. Degree of saturation of the exchange complex of the soil

    c. Nature and degree of weathering, and composition of soil colloids.

5. Nature of the soil acids

    a. Strength and buffer capacity of the soil acids

    b. Nature of acids and soil degeneration.

Greenhouse Studies with Varying Amounts of Lime

Typical samples of the Melbourne and Dayton soils were secured from cultivated fields. The Dayton soil was collected at the College farm near Corvallis and the Melbourne soil east of Monmouth. The soils were thoroughly mixed and placed in pots in the greenhouse. The treatments included ground limestone at rates varying from 250 to 6000 pounds and gypsum at 500 pounds per 2,000,000 pounds of soil. All treatments were in triplicate: two were planted to red clover and one left fallow for laboratory tests. After germination, the plants were thinned to five in each pot. Three cuttings were obtained. The data show the sum of the three crops with the yields of the duplicate treatments averaged.

The results of these trials are shown in Table 2. The Dayton soil produced increased yields of red clover even with the smallest amounts of lime applied. A lime application of 250 pounds produced an increase of 15 per cent and the yields were steadily increased with larger applications. The smallest increment of lime produced the greatest proportionate increase in yields. Yields of the unlimed Melbourne soil are less than one-fifth that of the Dayton soil. The heavier lime treatments and gypsum proved beneficial but the yields are still far below those obtained on

Table 2. Effect of the Rate of Liming and Method of Application on the Yield and Nodulation of Red Clover

Treatment (Amount and Method of Application)	Dayton Soil: Yield of Red Clover (gms. dry weight)[1]	Dayton Soil: Percentage Increase of Yield Over Inoculated Check	Dayton Soil: Average Number Nodules per Jar	Melbourne Soil: Yield of Red Clover (gms. dry weight)[1]	Melbourne Soil: Percentage Increase of Yield Over Inoculated Check	Melbourne Soil: Average Number Nodules per Jar
Check - not inoculated	186.9		19	29.4		30
Check - inoculated	214.8		56	33.6		37
Mixed with Soil						
Limestone 250 lbs.	248.8	15.83	105	33.7	3.36	98
" 500 "	249.9	16.34	97	36.5	8.63	98
" 1000 "	257.2	19.74	129	32.6	---	72
" 2000 "	250.5	16.62	138	36.8	9.52	115
" 4000 "	262.2	22.07	209	39.0	16.07	106
" 6000 "	268.6	25.05	178	49.1	46.13	103
Near the Seed						
Limestone 250 lbs.	225.8	5.12	131	28.9	---	50
" 500 "	227.2	5.77	124	38.5	14.58	83
" 1000 "	253.7	18.11	173	40.0	19.05	40
On the Seed						
Limestone 500 "	234.4	9.13	107	42.9	27.68	38
Gypsum 500 "	208.0	---	61	60.0	78.57	122

[1] Each jar was 0.785 square foot in area, and contained 4000 gm. soil.

the unlimed Dayton soil. Obviously a three ton lime application, though it causes a significant improvement of the Melbourne soil, is unsatisfactory and lighter treatments cause no increase in yields.

Rates and Methods of Placement

Success with light applications of lime should depend in part upon the placement. Three methods of placement were used: (a) lime mixed with the soil, (b) lime localized one inch below the seed, and (c) lime made to adhere to the seed by mixing with corn syrup. The results are included in the data of Table 2. On the Melbourne soil, since deficiencies other than limestone have limited yields, data on lime placement are not significant. Mixing the lime throughout the soil proved more effective in increasing yields on the Dayton soil than localizing the lime near the seed. Since the plant roots within a very short time have grown beyond the area of liming and the major portion of the roots are not in contact with the lime, the results appear reasonable. Based upon this reasoning lime near the surface of the soil should not prove as beneficial as lime mixed throughout the root zone. This is more apparent with pot studies than under field conditions because of the small quantities of soil in the pots.

During germination, according to some reports (3,12,26), plants are in greatest need of lime. Generalizing such a conclusion would lead to applications of the lime near the seed for best response from small applications. The results above, however, make it questionable whether lime placed near the seed at planting would be effective during germination. Lack of response may be due to the slow solubility of the lime.

The most that the above data show with reasonable certainty is that the Dayton soil produces greater crop yields with lime treatments than without and that the Dayton soil is responsive to small applications of lime. The Melbourne soil yields very little even with high lime treatments.

Nodulation and Inoculation

Legume yields are dependent upon good inoculation and nodulation. A number of experiments have shown that lime increases nodulation and nitrogen fixation by legumes. Lipman and Blair (25) found a greater number of nodules per plant on soybeans grown in limed soil. Albrecht and Davis (2) added calcium carbonate to calcium deficient soil containing nodule organisms and obtained increased nodule production. They believe lime exerts a physiological effect on the plant and bacteria to favor nodulation. Scanlan (39) reported that neutral calcium salts increased nodulation, indicating that acidity has no direct effect but calcium is required for inoculation. His data show that infection occurs in an early stage of the plant's growth and not after maturity. Lime applied near the seed should supply calcium at the critical time for inoculation. Doolas (13) found that nodule organisms remained viable in the soil with the reaction ranging from pH 3.8 to 8.3 but that inoculation does not take place unless calcium is available. McCool (26) states that the beneficial effects of liming legumes is due partly to more favorable conditions for the growth of nodule bacteria. Nitrogen fixing bacteria are sensitive to a deficiency of calcium. When the success of the legume crop depends on the development of nodule bacteria, small amounts of lime near the seed might prove satisfactory. The above condition is not present in the Melbourne soil but may be present in the Dayton as the data of these studies indicate.

After the third cutting of clover the roots were removed from the soil by careful washing over a screen. The nodules of macroscopic size were counted. The average number of nodules with the different lime treatments is given in Table 2. Inoculation of the seed resulted in an increased number of nodules on the roots. Inoculation with liming produced the largest number of nodules. The smallest amounts of lime applied were almost as effective in increasing nodulation as the heavy lime treatments. Yields apparently were not determined entirely by nodulation. The roots, corresponding with the increased top yields, are more numerous with lime treatments. This accounts in part for the greater nodulation; however, the larger yields are no doubt partly due to better inoculation.

From these results it appears that small applications of lime were relatively more effective than large applications in increasing nodulation of clover. Since the small amounts of lime used did not alter the soil reaction appreciably, the nodule bacteria apparently were not as sensitive to an acid reaction as to the calcium deficiency of the soils.

Artificial inoculation increased the yield of red clover 14 per cent on both the Melbourne and Dayton soils. Yields should be materially increased by inoculating limed soil if lime is beneficial to the organisms causing inoculation. Maximum response from lime is dependent upon infection of the clover with a vigorous strain of nodule bacteria, therefore on the lime treatments reported all seedings were inoculated.

Factors Limiting Response of Clover to Lime Treatments on Melbourne Soil

As the greenhouse trials show a definite improvement in the crop producing power of the Dayton soil with lime treatments and no appreciable returns from the lime with Melbourne soil, experiments were started to determine the cause of the low yields on the Melbourne soil. An effort to find the treatment that would give satisfactory yields included various combinations of fertilizers and lime applied to the soil first in pots and then in the field. The results from the pots are shown in Table 3. All treatments gave some increase above the untreated soil, but the outstanding response was obtained with manure, phosphate and lime. Phosphorus proved more beneficial than any other fertilizer added. This indicates that phosphorus is the primary deficient element limiting growth of crops on this soil. Phosphorus must be supplied before significant response is obtained from lime. The results indicate also that the soil is lacking in organic matter.

A fertility trial with the Melbourne soil in the field (Table 4) shows corroborative results. The average yield of red clover on good soils in this region is two tons per acre. The best lime and fertilizer treatment in

Table 3. The Influence of Lime and Fertilizer Treatments of Melbourne Soil on the Yield of Red Clover - Greenhouse Studies

Treatment	Rate of Application Lbs. per Acre	Red Clover Yield in Gms. Dry Weight	Per Cent Increase Over Check
Check	No treatment	31.3	
Limestone	2000	35.0	11.8
Limestone	4000	36.3	15.9
Limestone	6000	36.7	17.3
Limestone Treble phosphate	4000 100	38.7	23.7
Limestone Treble phosphate Manure	4000 100 10 tons	42.3	35.1
Sodium nitrate Treble phosphate Potassium chloride	200 100 100	38.2	22.0
Sodium nitrate Treble phosphate	200 100	40.2	28.4
Treble phosphate	100	39.2	25.2
Superphosphate	300	38.2	22.0
Gypsum	250	35.9	14.7
Limestone Sulfur	200 50	35.7	14.0
Limestone	200	31.3	0

Table 4. Response of Red Clover to Lime and Fertilizer Treatments on Melbourne Soil Under Field Conditions

Treatment	Yield of Clover Tons per Acre	Type of Crop
Check	0.78	Mostly weeds, little clover
Limestone, 500 lbs.	0.90	" "
Limestone, 1000 lbs.	0.85	" "
Limestone, 2000 lbs.	0.97	" "
Limestone, 4000 lbs.	0.93	" "
Limestone, 6000 lbs.	1.17	" "
Limestone, 4000 lbs. Manure, 12 tons	0.93	Mostly weeds, more clover
Limestone, 4000 lbs. Manure, 12 tons Superphosphate, 300 lbs.	1.49	Clover
Manure, 12 tons	0.53	Mostly weeds, more clover
Limestone, 4000 lbs. Complete Fertilizer, 350 lbs.	1.62	" "
Limestone, 4000 lbs. Sodium Nitrate, 100 lbs. Potassium Chloride, 50 lbs.	0.82	Mostly weeds
Lime, 4000 lbs. Sodium Nitrate, 100 lbs.	1.37	Mostly weeds, more clover
Limestone, 4000 lbs. Superphosphate, 200 lbs. Potassium Chloride, 50 lbs.	1.71	Clover, some weeds

this study brings the yield from the Melbourne soil to 1.71 tons. The data indicate that while this soil may be improved any material improvement in yields is brought about only by expenditures for fertilizers amounting to more than the crop increase is worth.

Clover Response to Lime on Soils with Phosphorus and Manure Added

Since need for lime in addition to phosphorus and organic matter is evident on the Melbourne soil there arises the question of the most beneficial amount of lime to apply with the other treatments. To answer this question both soils were treated with treble superphosphate and manure in large amounts to insure a sufficiency of phosphorus and organic matter that these might not prove limiting factors in the presence of lime. Limestone was applied at rates ranging from 250 to 8000 pounds per 2,000,000 pounds of soil. Yields of red clover from the duplicate pots for each treatment are shown in Table 5. Comparative yields of one of the four crops harvested are shown in Plates I, II, III and IV.

The Melbourne soil fails to produce red clover without treatment and does not show benefit from lime until other deficiencies are corrected. The phosphorus

Table 5. Effect of Lime Treatments in the Presence of Phosphorus and Manure as Measured by Crop Response

Treatment in Pounds per Acre	Dayton Soil		Melbourne Soil	
	Yield[1] of Red Clover Grams Per Jar	Per Cent Increase Over Fertilized Check	Yield of Red Clover Grams Per Jar	Per Cent Increase Over Fertilized Check
No treatment	75.9		8.2	
Phosphorus[2] and manure[3]	96.8		54.3	
Lime 250 lbs., phosphorus and manure	126.7	29	67.3	24
Lime 500 lbs., " " "	128.7	32	82.6	52
Lime 1000 lbs., " " "	111.9	16	81.7	50
Lime 2000 lbs., " " "	125.1	29	92.1	69
Lime 4000 lbs., " " "	131.6	36	104.9	93
Lime 8000 lbs., " " "	113.8	18	103.7	91
Gypsum 500 lbs., " " "	101.5	5	66.4	22

[1] Average of two plantings, treatments in duplicate

[2] Phosphorus as treble phosphate 2000 lbs. per 2,000,000 lbs. soil

[3] Manure 40 tons dry basis per 2,000,000 lbs. of soil

and organic matter deficiencies mask the need for lime on the Melbourne soil. Yield increases after adding phosphorus and organic matter were obtained with even the small applications of 250 and 500 pounds of lime, increasing applications showing corresponding increase in yields. The smaller amounts of lime are very effective in correcting the calcium deficiency of the soil when other essential nutrients are provided. The Melbourne soil can be brought to a fair state of productiveness but only by liberal and complete fertilization (Table 3). The most effective greenhouse treatments result in yields that compare well with the untreated Dayton soil.

The Dayton soil is benefited by the phosphorus and manure. Lime also improves the yields. The higher rates with liming, however, did not prove any more beneficial than the low rates. Calcium deficiency appears supplied by the 250 pound application and increasing amounts are not needed.

Both the soils in this study with the same treatments as noted above were planted to Austrian field peas, a quick growing annual legume. No significant difference was obtained with any of the treatments and therefore the yield data are not reported. The peas grew equally well on both soils and lime, phosphorus and manure added had no apparent beneficial effect upon their growth. At harvest a fairly heavy yield of peas was produced. The pea is a gross feeder as compared with red clover and obtained sufficient nutrients even from the impoverished Melbourne soil to produce a good growth. The results from the crop are related to show that in economic liming the kind of crop must be considered as well as the soil character. From the standpoint of economy selection of the right crop to be grown on a given soil appears more important than any lime or fertilizer treatment.

Effect of Varying Soil Reaction on the Yield of Red Clover

Unfavorable soil reaction and lack of sufficient calcium are corrected by liming. Calcium deficiency in acid soils is generally associated with a high concentration of hydrogen ions. Hydrogen replaces calcium in the exchange complex and the calcium released is lost by leaching.

An attempt was made to study the effect of varying soil reaction while the soluble calcium was maintained at a high level. Portions of the Melbourne soil were treated with a normal sulfuric acid or calcium oxide in amounts to give reactions varying from pH 3.5 to pH 8.0. The soil had to be treated several times before a reaction was obtained that remained somewhat constant. The soil was placed in pots and planted to red clover. Phosphorus as treble phosphate was added at the rate of 100 pounds per 2,000,000 pounds of soil. Reactions were checked at frequent intervals throughout the test with the quinhydrone electrode. Table 6 shows that over a six months period the reaction remained within a range sufficiently narrow to give an indication of effect of reaction on the plant.

No leaching of the calcium from the pots could occur. Determinations showed that soluble calcium remained sufficiently abundant to eliminate the possibility of deficiency. The acid treatments of the soil liberated calcium. Thus an acid reaction is obtained with calcium present in a soluble form.

The best growth and highest yields were at a pH 7.0. Yields within a range of pH 6.0 to pH 8.0 were only slightly lower. Below pH 6.0 the yields were definitely poor. Plate V illustrates the growth of the clover at varying soil reactions. Apparently the beneficial effect of liming in this case comes from correcting the acidity of the soil and not because of the calcium supplied.

Crop yield data reported by Salter from the Ohio Station (38) show that the best crop yields were obtained

Table 6. Effect of Soil Reaction on the Yield and Calcium Content of Red Clover Grown on Melbourne Soil

Limits of H-ion Concentration pH	Treatment to Attain Desired Reaction	Dry Weight Red Clover[1] Grams	Calcium in Plant[1] Per Cent	Water Soluble Calcium in Soil[1] p.p.m.
5.67 to 5.75	Check	10.0	1.68	35
2.97 to 3.72	N/1 H_2SO_4	No growth	---	230
3.98 to 4.25	" "	5.8	1.86	233
4.32 to 5.33	" "	10.4	1.71	134
6.09 to 6.35	Calcium oxide	16.0	2.68	39
6.26 to 6.52	" "	15.6	2.01	51
6.84 to 7.03	" "	20.0	2.22	72
7.70 to 8.00	" "	17.8	1.90	75

[1]Tests in duplicate

from field soils when maintained at about neutrality.

Table 7. Yields for One Crop Rotation at Different Soil Reactions. (After Salter)

Reaction pH	Corn[1] Bu.	Wheat[1] Bu.	Red Clover[1] lbs.
4.5	15.3	26.5	645
5.0	31.6	29.4	951
6.0	34.3	35.4	1748
7.0	40.6	38.9	2997
8.0	31.7	37.8	2724

[1]The yields are averaged for four corn crops, two wheat crops, and five red clover crops.

Data of the literature generally show that the best yields, the greatest bacteriological activity and the highest concentration of available nutrients occur at a soil reaction near neutrality.

In order to explain the very poor plant growth below pH 6.0 and the good growth obtained between pH 6.0 and pH 8.0 it may be stated that acidity values increase logorithmically as follows:

pH Value	No. of Times Acidity Exceeds That of Neutrality
3	10,000
4	1,000
5	100
6	10
7	1

A soil acidity of pH 6.0 or pH 8.0 does not vary enough from neutrality to affect plant growth appreciably. Only the large applications of lime have increased the pH of the Melbourne soil to pH 6.0 and above. The largest crop increases and the most vigorous nitrification have resulted with the heaviest lime treatments applied.

The Effect of Varying Amounts of Lime on Nitrification

There is close correlation between nitrification and crop production. Increased nitrification of the soil's own organic matter from the addition of lime usually cannot be observed, probably because the greatly increased number of organisms in the soil following the use of lime results in the consumption of most of the nitrates by the organisms. The ba cteria build the nitrates into protoplasmic tissue.

The Melbourne and Dayton soils were investigated to determine the probable relation of nitrification to the crop yields just reported.

The rate at which calcium goes into solution and thus becomes available to growing plants is probably dependent for the most part upon biological processes in the soil which produce active solvents. Nitric acid is perhaps the most vigorous and abundant solvent normal to good soils. Nitrates and soluble calcium were determined in both the fallow soils at intervals of one, two, four and six months after liming. The data are reported in Table 8. The Dayton soil which shows much stronger nitrification shows also a much larger amount of water soluble calcium.

The limestone is slowly soluble and continues to become more soluble with time. Other solvents than nitric acid are no doubt acting upon the lime. The limestone (page 36) was fairly coarse in texture with some 50 per cent of the particles coarser than 32 mesh. These naturally require time to go into solution. Gypsum treatment has resulted in an immediate increase in water soluble calcium which remains quite constant during the six months period.

Nitrates produced in acid soils without the addition of nitrifiable material are limited even under

Table 8. Soluble Calcium and Nitrate Nitrogen in a 1:5 Water Extract of the Soil[1]

Melbourne Soil	First Month After Treatment Ca p.p.m.	First Month After Treatment N p.p.m.	Second Month After Treatment Ca p.p.m.	Second Month After Treatment N p.p.m.	Fourth Month After Treatment Ca p.p.m.	Fourth Month After Treatment N p.p.m.	Six Month After Treatment Ca p.p.m.	Six Month After Treatment N p.p.m.
Check	5	3	12	3	12	4	25	4
Limestone 250 lbs.	6	4	21	3	14	3	25	6
" " 500 "	7	4	8	3	16	2	25	6
" " 1000 "	8	4	12	3	16	4	30	8
" " 2000 "	8	4	12	4	18	3	35	8
" " 4000 "	9	2	12	5	24	4	40	6
" " 6000 "	10	5	21	6	28	5	45	10
Gypsum 500 "	25	2	57	3	56	2	45	7
Dayton Soil								
Check	30	24	50	30	36	27	70	28
Limestone 250 lbs.	40	20	72	48	56	25	70	28
" " 500 "	20	22	53	47	40	28	120	28
" " 1000 "	40	26	68	20	60	18	80	32
" " 2000 "	40	26	80	37	56	35	90	32
" " 4000 "	40	23	76	22	56	35	110	50
" " 6000 "	40	29	76	26	60	28	100	40
Gypsum 500 "	60	20	137	19	82	28	105	28

[1]Nitrates by the phenoldisulfonic acid method.
Calcium was precipitated as oxalate and titrated with permanganate.

favorable greenhouse conditions. Table 8 shows that the nitrates remain practically constant during the six months period and in the Melbourne soil they remain at a low level. The Dayton soil shows approximately five times as much nitrate as the Melbourne. This ratio is about the same as the crop producing power of the two soils.

There is a definite relation between water soluble calcium and nitrate nitrogen in the soil solution. Pohlman (36) obtained a correlation between calcium and nitrate nitrogen of 0.858. Albrecht (1) obtained a correlation between water soluble calcium and nitrates of about 80 per cent. This relationship is likewise shown in Table 8. The nitric acid formed from nitrates must be a major solvent in bringing limestone into solution. Thus the lime status of the soil and the nitrification process are closely related.

Nitrifying Power of Soils Treated with Varying Amounts of Lime. When fresh nitrifiable material is added to the soil in suitable amounts the stimulating effect of lime in increasing nitrification becomes easily measurable. The lime is essential to neutralize acids produced by the nitrification process. These acids must be neutralized if nitrification is to proceed unchecked.

To study the nitrifying power of the soils, ammonium sulfate was added in amounts equivalent to 300 p.p.m. N in the soil. For this study, soil was taken from the greenhouse pots previously treated with varying amounts of lime. Portions of soil were weighed into beakers, treated with ammonium sulfate and incubated under laboratory conditions. Moisture was maintained at about two-thirds sa turation. Nitrates were determined before nitrification began and after incubation periods of four, six and eight weeks. Water soluble calcium was determined before nitrification and again after eight weeks to obtain the effect of nitrification upon the solution of lime. Tables 9 and 10 present the data.

Additions of limestone appreciably increase the nitrifcation of ammonium sulfate. The rate of nitrification is almost directly proportional to the amount of calcium carbonate applied. The Dayton soil shows a greater nitrifying efficiency than the Melbourne which indicates that the nitrifying power of the two soils and their productiveness are closely related. The nitrification process is very effective in dissolving lime. Water soluble calcium is increased 400 per cent for the Melbourne and 800 per cent for the Dayton soil. The higher nitrifying power of the Dayton soil results in a proportionately greater amount of water soluble calcium.

Table 9. Nitrification of Ammonium Sulfate by the Melbourne Soil as Affected by Lime Treatments[1]

Treatment in Pounds per Acre	Before Nitrification: Nitrate N p.p.m.	Before Nitrification: Water Soluble Ca p.p.m.	After Four Weeks Nitrate N p.p.m.	After Six Weeks Nitrate N p.p.m.	After Eight Weeks: Nitrate N p.p.m.	After Eight Weeks: Water Soluble Ca p.p.m.
Check	3.5	12	16	23	30	47
250 lbs. Limestone	3.0	15	22	23	28	57
500 lbs. "	2.7	15	34	20	36	45
1000 lbs. "	3.5	18	24	30	38	68
2000 lbs. "	3.0	18	20	28	52	78
4000 lbs. "	3.5	24	42	34	56	98
6000 lbs. "	5.5	24	30	36	56	108
500 lbs. Gypsum	2.5	28	18	26	36	122

[1] Ammonium sulfate added equivalent to 300 p.p.m. of N to the soil.

Table 10. The Nitrification of Ammonium Sulfate by the Dayton Soil as Affected by Lime Treatments[1]

Treatment in Pounds per Acre	Before Nitrification: Nitrate N p.p.m.	Before Nitrification: Water Soluble Ca p.p.m.	After Four Weeks Nitrate N p.p.m.	After Six Weeks Nitrate N p.p.m.	After Eight Weeks Nitrate N p.p.m.	After Eight Weeks Water Soluble Ca p.p.m.
Check	27	36	56	80	80	308
250 lbs. Limestone	25	46	62	85	90	314
500 " "	24	38	70	60	100	304
1000 " "	19	54	72	140	110	362
2000 " "	35	56	136	200	120	422
4000 " "	35	56	108	130	130	490
6000 " "	30	60	144	150	150	484
500 lbs. Gypsum	30	52	60	80	100	328

[1] Ammonium sulfate added equivalent to 300 p.p.m. of N to the soil.

Nitric acid present in the form of its salt is one of the strongest soil acids known and is therefore important in rendering nutrients and especially the bases in the soil, more available to crops.

Applications of phosphorus, manure and lime raise the crop producing power of the Melbourne to nearly the level of the Dayton soil. Studies were planned to determine if nitrification in the Melbourne soil were increased to a similar extent as crop producing power. Soil samples were drawn from the fallow soils in the greenhouse and prepared for nitrification as previously outlined. Each treatment was in duplicate and nitrates were determined at the same intervals as in the previous study. Results are given in Table 11.

Phosphorus and manure definitely increased nitrification in the Melbourne soil. Lack of phosphorus and organic matter for the nitrifying organisms had undoubtedly impeded the nitrifying process in the untreated soils. Crop production and nitrification were increased to approximately the same extent. Significantly, nitrification in the Melbourne soil is raised to near the same level as nitrification in the Dayton soil by these treatments. The relationship of nitrification and crop production is therefore close. That treatment which

Table 11. Effect upon Nitrification of Phosphorus and Manure with Lime Treatments[1]

Treatment	Melbourne Soil p.p.m. N				Dayton Soil p.p.m. N			
	Before Nitrification	Four Weeks After	Six Weeks After	Eight Weeks After	Before Nitrification	Four Weeks After	Six Weeks After	Eight Weeks After
No treatment	4	9	11	15	7	19	36	33
P[2] and M[3]	10	25	44	60	7	25	72	75
" " ", Lime 250 lbs.	10	30	71	55	8	32	78	49
" " ", " 500 "	10	35	54	51	8	28	78	50
" " ", " 1000 "	10	27	59	36	9	28	81	48
" " ", " 2000 "	10	25	64	70	9	31	90	91
" " ", " 4000 "	10	100	121	165	10	85	165	155
" " ", " 8000 "	10	125	240	290	9	150	250	250
" " ", Gypsum 500 lbs.	9	13	32	30	9	31	65	44

[1]Ammonium sulfate added equivalent to 300 p.p.m. of N to the soil.
[2]P = phosphorus as treble phosphate 2000 pounds per 2,000,000 pounds of soil.
[3]M = manure 40 tons dry basis per 2,000,000 pounds of soil.

builds nitrifying power of the soil builds crop producing power. This test shows also that greater nitrification follows increasing lime applications.

Soil Reaction, Lime Requirement and Crop Response

The pH and lime requirement are commonly used to diagnose acid soils. The former measures the active acidity in the soil solution and the latter measures the titratable or total acidity. To determine the effect of lime applications on soil acidity when the soils were treated with different amounts of lime in the greenhouse, the soils were sampled after one month and again after six months incubation. At each sampling the reaction and lime requirement were determined. The results secured at the two samplings are presented in Table 12.

The pH after one month's incubation shows that lime applications decreased the hydrogen ion concentration with increasing amounts of lime applied. In no case did the soils become neutral in reaction although the acidity was reduced to a point generally considered satisfactory for crop production (pH 6.4) with a limestone application of one ton on the Dayton soil and two tons on the Melbourne soil. The pH determinations after six months'

Table 12. The Change in Reaction and Lime Requirement of Soils Treated with Varying Quantities of Lime

Lime Applied	Dayton Soil				Melbourne Soil			
	One Month		Six Months		One Month		Six Months	
	Lime Requirement[1]	pH[2]	Lime Requirement	pH	Lime Requirement	pH	Lime Requirement	pH
None	1.40	5.75	1.84	6.00	2.73	5.22	2.80	5.55
250 lbs. Limestone	1.40	6.05	1.88	6.18	2.16	5.28	2.57	5.58
500 " "	1.33	5.92	1.68	6.18	1.96	5.43	2.48	5.70
1000 " "	1.32	6.32	1.52	6.35	1.96	5.67	2.08	5.75
2000 " "	1.18	6.48	0.64	6.40	1.68	6.30	2.00	5.75
4000 " "	1.04	6.54	0.72	6.52	1.36	6.37	1.12	6.01
6000 " "	0.78	6.58	0.96	6.69	1.19	6.40	0.97	6.09
500 " Gypsum	1.52	5.31	1.84	6.00	2.08	5.30	2.40	5.57

[1] Jones Lime Requirement method. Tons of $CaCO_3$ required per 2,000,000 pounds soil.

[2] pH by quinhydrone electrode.

incubation show only slight variations from the results secured after one month.

The lime requirement is apparently a more sensitive measurement of the effect of added lime than pH (Table 12). A lime requirement is found however, by the test even when lime is applied to the soil in excess of its indicated requirement. Apparently the limestone does not react completely with the soil or the methods are faulty in indicating lime requirement. The mechanical analysis of the limestone was as follows:

Larger than 17 mesh	24.7 per cent
Between 17 and 32 mesh	24.8 " "
Between 32 and 120 mesh	18.3 " "
Smaller than 120 mesh	32.3 " "

The limestone was 89.9 per cent pure calcium carbonate. The slow solubility of the coarser particles and the impurity of the limestone requires a larger application than indicated by lime requirement methods to effect a neutral soil reaction. Also, incomplete mixing with soil probably prevents intimate contact of the lime with the soil acids. Other investigators (43,49) noted failure to obtain a neutral reaction when lime was applied to the soils in amounts indicated by lime requirement methods.

Many investigators (1,10,16) have noted no close relation between soil reaction and plant growth. These data indicate the futility of depending entirely upon pH or lime requirement to determine the most beneficial amount of lime to use. The Melbourne soil was supplied with lime in considerable excess of the indicated lime requirement, yet the yields of red clover were not increased appreciably. Deficiencies of available phosphorus and organic matter are frequently associated with acid soils, neither of which are indicated by acidity tests. These deficiencies limit crop growth as effectively as shortage of lime, as the data of Table 5 indicate.

Lack of available calcium sometimes limits legume growth on acid soils. Gypsum supplies calcium and sulfur but has little effect upon the soil reaction or lime requirement. Erdmann (14) observed that gypsum had no effect on hydrogen ion concentration. Skinner and Beattie (40) reported an increase in lime requirement after an annual application of 500 pounds of gypsum for five years. Pierre (33) noted that gypsum was not beneficial in overcoming the injurious effect of acidity. He explained that calcium sulfate adds calcium to the soil solution and through the base exchange reaction, liberates hydrogen from the soil complex into the soil solution, thus forming sulfuric acid. In this study, gypsum caused a marked increase in clover yields without affecting the soil reaction appreciably.

Phosphorus Availability and Nature of Phosphate Fixation in Acid Soils

Data by the Truog method (45), Table 13, definitely show a deficiency of available phosphorus in the Melbourne soil. Only 10 p.p.m. of available phosphate is found in the Melbourne as compared with 319 p.p.m. in the Dayton soil. According to Truog 125 p.p.m. of phosphate as PO_4 is the division between soils requiring phosphorus and those with sufficient for good plant growth. On this basis the Melbourne soil is very deficient and the Dayton high in available phosphorus. The yields obtained on the two soils in the greenhouse (Table 2) correlate well with the phosphate availability shown in the above data.

The effect of manure and phosphorus with varying lime applications is shown in Table 13. The manure and treble phosphate increased the available phosphorus materially. Lime had no significant influence on the solubility of the phosphorus.

Snider (42) reports that eight tons of lime resulted in no appreciable difference in available phosphorus. Ford (17) determined the amount of calcium hydroxide required to prevent fixation of phosphorus by certain acid soils. He added increasing amounts of a saturated solution of $Ca(OH)_2$ until complete recovery of the applied

Table 13. Effect of Phosphorus and Manure with Lime Treatments on Available Phosphorus

Treatment in Pounds per Acre	Dayton Soil		Melbourne Soil	
	p.p.m. PO_4	pH	p.p.m. PO_4	pH
No treatment	319	5.00	10	4.80
Phosphorus[1] and manure[2]	383	5.14	102	4.46
Lime 250 lbs., phosphorus and manure	410	4.90	105	4.97
Lime 500 lbs., " " "	329	4.84	102	4.88
Lime 1000 lbs., " " "	400	5.09	107	5.14
Lime 2000 lbs., " " "	320	5.60	108	5.09
Lime 4000 lbs., " " "	490	6.80	102	6.74
Lime 8000 lbs., " " "	545	7.71	102	8.10
Gypsum 500 lbs., " " "	500		122	

[1] Phosphorus as treble phosphate 2000 lbs. per 2,000,000 lbs. soil

[2] Manure 40 tons dry basis per 2,000,000 lbs. soil

phosphorus was obtained. His results were as follows:

Amount of Lime Required to Prevent Phosphorus Fixation - Adapted from Ford (17)

Soil	Fixation[1] by Un-limed Soil, Per Cent	Saturated Lime Water Required per Gram of Soil to Stop Fixation	Calculated to Tonx $CaCO_3$ per Acre Necessary to Prevent Fixation
Dekalb Silt Loam	50	15 cc.	32
Decatur " "	35	7	13
Tilsit " "	55	20	43
Memphis " "	50	12	25

[1] 50 p.p.m. of P added to one-gram samples of soil.

The amount of lime to prevent fixation of phosphorus entirely is shown to be much higher than any field application. Probably the amount of lime commonly applied to soils has no immediate influence upon phosphorus fixation.

Available phosphorus remained almost constant through the range pH 4.46 to pH 8.10. The data show that if allowance is made for some variations in phosphorus determinations, changing the soil reaction by liming had no effect upon the available phosphorus in either soil.

The increase in available phosphorus from a 2000 pound treatment of treble phosphate appears extremely low. The Dayton soil particularly shows very little increase in available phosphorus over the untreated soil. Failure of phosphorus fertilizers to increase available phosphorus in the Dayton soil cannot be explained from this study.

The phosphate fixing power of limed and unlimed greenhouse soils and of soils recently obtained from the field was determined by the Heck method (18). As shown in Table 14, the fixation was high and almost the same in the two soils. The capacity for fixation by the soils was sufficient to change all of the 2000 pounds of the treble phosphate to an unavailable form. The following data are conclusive proof of the high fixing power of these soils. Four hundred p.p.m. phosphorus (or 1225 p.p.m. PO_4) was added to the soils. The Dayton soil fixed 85 per cent of this amount which is equivalent to 4338 pounds of treble phosphate per acre. The Melbourne soil fixed 82 per cent which is equivalent to 4186 pounds of treble phosphate per acre.

The limited amount of available phosphorus in the Melbourne and the high amount in the Dayton soil cannot be explained on the basis of fixing power as determined by this method. Possibly excessive leaching has removed the available phosphate from the Melbourne soil. The Dayton

Table 14. Phosphate Fixing Power of Field Soil, and Limed and Unlimed Greenhouse Soils

	Dayton Soil			Melbourne Soil		
	Field Soil p.p.m.P	Greenhouse Soil p.p.m.P	Greenhouse Soil and Two Tons Lime p.p.m. P	Field Soil p.p.m.P	Greenhouse Soil p.p.m.P	Greenhouse Soil and Two Tons Lime p.p.m. P
Phosphorus added	400.0	400.0	400.0	400.0	400.0	400.0
Total phosphorus extracted	220.0	160.0	193.0	93.0	77.0	97.0
Phosphorus in soil before treatment	110.0	100.0	113.0	6.3	6.7	22.3
Applied phosphorus recovered	110.0	60.0	80.0	86.7	70.3	74.7
Percentage fixation	75	85	80	78	82	81

has been less leached. The data would indicate a probable marked response by the Melbourne and little by the Dayton when phosphate fertilizers are used.

Fixation of phosphate by the soil has been attributed to the insolubility of compounds formed with iron and aluminum. Investigations have shown that precipitated phosphates of these trivalent bases are sources of available phosphate for plants. There may be several forms of phosphate, especially of iron, some of which are of low availability. Ford (17) studied phosphate fixation of pure minerals. He found that while ferric and aluminum phosphates were quite soluble, phosphate fixed by Goethite was very insoluble. McGeorge and Breazeale (28) report that mineral phosphates of iron and aluminum are insoluble both in CO_2 free and CO_2 saturated water and unavailable to plants.

Humus has been reported (34) responsible for fixation of phosphorus in the form of organic phosphates unavailable to plants. Ford (17) considers fixation by humus as negligible. McGeorge and Breazeale (28) find that while organic compounds of phosphorus are usually quite insoluble in water, they are readily decomposed by microorganisms. Consequently, organic phosphates are excellent forms for plant use. They are held in a form to prevent leaching and yet are available to plants by bacterial activity.

Phosphate fixation was determined in both soils with the free oxides of iron and aluminum removed. Fixation was determined also after removal of humus. The method employed by Truog and Chucka (47) was used to remove the free oxides. The soil was treated alternately with two per cent sodium carbonate solution and N/10 HCl. The humus was removed from separate samples by oxidation with hydrogen peroxide, then thoroughly leached with water and the phosphate fixing power determined. The results given in Table 15 show only 14.3 per cent fixation in the Melbourne and 19.5 per cent fixation in the Dayton soil with iron and aluminum oxides removed, or one-fourth to one-fifth as great as in the untreated soil. With the humus removed fixation was 68 per cent in the Melbourne and 70 per cent in the Dayton soil, just slightly lower than the fixation in the untreated soils. In these soils phosphorus appears to be fixed largely by iron and aluminum oxides, but not entirely. Humus causes some phosphate fixation even in these soils low in organic matter. The Dayton soil has 2.45 per cent organic matter and the Melbourne 1.46 per cent. Soils higher in organic matter would probably show a relatively greater fixation by humus. To what extent lime may reduce phosphate fix-

Table 15. Phosphate Fixation in Soils with Free Oxides of Aluminum and Iron Removed and with Humus Removed

	Dayton Soil		Melbourne Soil	
	Free Fe and Al Oxides Removed p.p.m. P	With Humus Removed p.p.m. P	Free Oxides of Fe and Al Removed. p.p.m. P	With Humus Removed p.p.m. P
Phosphorus added	400	400	400	400
Total phosphorus extracted	360	660	373	175
Phosphorus in soil before treatment	39	540	30	47
Applied phosphorus recovered	321	120	343	128
Percentage fixation	19.7	70.0	14.3	68.0

ation over a period of years cannot be answered from these studies.

Poor crop yields are sometimes attributed to toxic amounts of active aluminum in the soil (33). The possibility of aluminum toxicity in the low producing Melbourne soil was checked in this study. The data show that neither soil contains sufficient active aluminum to be toxic to plant growth. The method of Burgess (8) for determining active aluminum soluble in 0.5 N acetic acid was used. The amount of active aluminum present in the soils can account for considerable phosphate fixation, however. The Melbourne soil containing 403 p.p.m. Al_2O_3 would be able, theoretically, to fix 732 p.p.m. phosphorus by the formation of aluminum phosphate. The Dayton soil containing 308 p.p.m. Al_2O_3 would fix 573 p.p.m. phosphorus. No doubt the iron and aluminum of these soils are together largely responsible for the precipitation of phosphorus fertilizers added and perhaps also for the low availability of the natural phosphates of the Melbourne soil.

Base Exchange Properties and Lime Needs of Acid Soils

Soil reaction is determined by the nature and relative amounts of cations associated with the exchange complex. Soils are acid because of the presence of exchangeable hydrogen. Soils of like pH and colloidal content may differ in response to lime due to fundamental differences in the colloid complex. In this investigation base exchange capacity, exchangeable bases and colloidal content were studied in relation to plant growth.

Base exchange capacity was determined as follows: 5 grams of 20 mesh soil were leached with 500 c.c. of N/20 HCl in a Gooch crucible to replace all of the exchangeable bases. The soil was then leached with neutral N/2 barium chloride. After completely saturating the complex with barium ions the excess barium chloride was washed with warm water. The leachings were tested for chlorides to determine complete removal. The soils were next leached with 500 c.c. of N/2 neutral ammonium chloride to replace the barium with ammonia. The leachate was collected. Barium was determined gravimetrically and the exchange capacity calculated.

Exchange hydrogen was determined by a modification of Parker's method (31). Calcium acetate was used instead of barium acetate for leaching. The end-point was determined by titrating with N/20 sodium hydroxide.

The exchangeable hydrogen was subtracted from the exchange capacity to obtain total exchangeable bases. Exchange calcium and exchange magnesium were determined by leaching the soil with N/10 barium chloride and using the soap titration method of Burgess and Breazeale (9). The results are expressed as milligram equivalents per 100 grams of soil.

The colloids in the two soils were determined by Olmstead's dispersion method (30) and checked with the vapor absorption method (37).

In acid soils calcium, magnesium, potassium and hydrogen constitute the major portion of the cations present on the exchange complex. The sum of these ions should equal the base exchange capacity. To determine the accuracy of the methods used, the sum of the exchangeable calcium, magnesium and hydrogen is compared with the exchange capacity in Table 16.

Table 16. Exchangeable Calcium, Magnesium and Hydrogen and Base Exchange Capacity

Exchangeable Cations	Melbourne Soil, M.E.	Dayton Soil, M.E.
Ca	1.50	7.45
Mg	0.47	2.63
H	3.95	1.95
Sum of cations	5.92	12.03
Base Exchange Capacity by $BaCl_2$ method	5.74	13.09

Though different reagents were used for exchangeable bases and total exchange capacity, the sum of the cations check the base exchange capacity rather closely. Omission of exchangeable potassium does not significantly affect the exchange capacity of the soils.

Nature of the Exchange Complex. Soils vary considerably in their capacity to retain bases. The total exchange capacity is the sum of exchange capacities of the humus and of the mineral complex. Humus has several times greater base absorption power than the mineral colloids. Hissink (20) reports the equivalent weight of humus at 176 and a clay at 1225.

The calculated equivalent weight of the Melbourne colloid is 3467 and the Dayton colloid is 1642. The figures were obtained by dividing the colloidal content of the soils by the exchange capacity expressed as M.E. The greater equivalent weight of the Melbourne colloid indicates a lower combining power than the Dayton colloid. A high percentage of the colloidal material in this soil is inert, and imparts to the soil a low base exchange capacity. Large amounts of lime applied to the Melbourne soil cannot be retained against leaching.

Different colloids contain widely different amounts of replaceable base. Pate (32) reporting on a number of soils obtained ratios of colloid to replaceable bases varying from 2.05 to 5.97. The ratio for the Dayton and Melbourne soil is shown in Table 17.

Table 17. Ratio Colloid to Replaceable Bases

Soil	Colloid Content Per Cent	Replaceable Bases M.E.	Ratio
Dayton	21.5	11.04	1.94
Melbourne	19.9	2.24	8.88

The Dayton soil shows 4.6 times as much replaceable bases in the exchange compound as the Melbourne. This ratio is about the same a s the crop producing power of the two soils.

The greater amount of organic matter accounts in part for the greater absorptive capacity of the Dayton soil. The lateritic degeneration of the older Melbourne soil results in a greater proportion of inactive colloidal material. Lateritic weathering is characterized by an accumulation of free iron and aluminum oxides. The breaking down of the active complex into the free sesquioxides materially reduces the absorptive capacity of the soil.

Base Saturation and Response to Liming. The harmful effect of soil acidity depends in part upon the proportion of exchangeable bases to exchangeable hydrogen. Pierre and Scarseth (35) conclude that hydrogen ion concentration cannot be considered a direct factor in causing poor plant growth. They believe that the ratio of exchange calcium to exchange hydrogen is the best indication of the need for lime. They found that sorghum grown in soils with uniform pH values of 4.8 showed no correlation between reaction and yields, but a good correlation with base saturation and yields. The base saturation in the Dayton and Melbourne soils is shown in Table 18.

Table 18. Percentage Base Saturation in the Dayton and Melbourne Soils

Soils	Base Exchange Capacity M.E.	Exchangeable Bases M.E.	Base Saturation Per Cent
Melbourne	5.74	2.24	39.0
Dayton	13.09	11.04	84.3

The Dayton soil is 84.3 per cent saturated and the Melbourne soil 39 per cent saturated. Turner (48) obtained a degree of base saturation of 72 to 88 per cent on good calcareous soils and base saturation of 40 per cent and below on poor soils in need of lime. According to Turner's data the Dayton can be classed as a "good" soil and the Melbourne as a "poor" soil in respect to degree of saturation. It is generally believed that when a soil contains sufficient replaceable bases to satisfy about 80 per cent of the base exchange capacity of the soil, lime is not likely to be needed for crop production. However, lime may be needed in excess of the saturation capacity to improve soil structure. Hissink (19) states flocculation is improved when soil is 95 per cent saturated. The beneficial effect of liming the Dayton soil even though it is over 80 per cent saturated may be attributed in part to improvement of soil structure.

Relationship of Exchangeable Bases with Lime Treatments and Crop Yields. Exchange calcium found six months after liming closely correlates with the amount of lime applied and the crop yields. With a lime treatment of three tons exchange calcium increased from 7.45 M.E. to 9.14 M.E. on the Dayton soil and from 1.98 M.E. to 3.73 M.E. on the Melbourne soil.

The untreated Melbourne soil showed a 39.0 per cent saturation with bases. One ton of lime per acre increased this value to 47.7 per cent. With an addition of three tons of lime per acre there was an increase to 65.2

per cent. Thus with three tons of lime per acre, the degree of saturation was increased more than 25 per cent, but the exchange complex was not completely saturated with bases.

The Dayton soil showed a much greater saturation with bases than the Melbourne soil. The degree of saturation of this soil was only slightly increased by applications of lime; an increase of five per cent resulted with a three ton lime application.

The total acidity is only partially neutralized by the lime applications. Both soils exhibit a high buffer capacity requiring large applications of lime to effect a change in total acidity.

Nature of Soil Acids

Soil acids, though generally weak, may differ considerably in strength. The strength of acids results in part from the degree of weathering that has occurred in the soil. Weathering and leaching cause decomposition of the complex alumino-silicic acids. The deeply weathered soils generally have the weakest acids. Strong acids naturally break down or are leached out first but there is a stage in the leaching process in which the stronger acids have been liberated but not yet broken down. At this stage the

Table 19. The Relation of Exchangeable Bases to Liming and Plant Growth

Treatment in Lbs. Per Acre	Yield of Clover Grams	Exchangeable Calcium M.E.	Exchangeable Hydrogen M.E.	Per Cent of Total Acidity Neutralized	Per Cent Base Saturation
Melbourne Soil					
Check	33	1.98	3.50	---	39.0
Limestone 500 lbs.	39	2.16	3.20	8.6	44.2
" 2000 "	37	2.76	3.00	14.3	47.7
" 6000 "	49	3.73	2.00	42.9	65.2
Dayton Soil					
Check	200	7.45	1.95	---	85.1
Limestone 500 lbs.	230	8.05	1.95	none	84.7
" 2000 "	250	8.53	1.50	23.1	88.5
" 6000 "	270	9.14	1.30	33.3	90.1

parallelism between high lime requirement and high hydrogen-ion concentration is often observed. The strength of soil acids has been measured by the Truog avidity method (46). Jenny (23) measures the strength of soil acids and expresses the results as "Symmetry values". His method differs only in that the strong acid hydrochloric in the form of its salt, is used instead of Truog's acetic for comparison. Since both methods show the same thing only the Truog method was employed. The degree of dissociation $\left[\alpha = \frac{(H^+)}{(\text{Total Acidity})}\right]$ of the soil acids was calculated. Table 20 gives a summary of data obtained.

The avidity method provides that the potassium added to the soil is just equivalent to the exchangeable hydrogen. Only 9.7 per cent of the hydrogen is replaced from the Dayton soil by the potassium while 24.7 per cent is released from the Melbourne soil. That the Melbourne soil possesses the stronger acid is shown also by the greater degree of dissociation. The acids are in that stage which precedes more or less complete degeneration. The acids of the Melbourne soil do not show characteristics associated with acids of extremely degenerated soils. The titration curves of the Melbourne soil (Figure I) show that the acids are well buffered. Acids of completely degenerated soils are poorly buffered.

Table 20. Strength of the Soil Acids

	Melbourne Soil	Dayton Soil
Avidity (as per cent of K absorbed by the soil acids)	24.7 %	9.7 %
Hydrogen-ion Concentration pH	4.97 pH	5.90 pH
Total Acidity	3.50 M.E.	1.95 M.E.
Degree of Dissociation (from H-ion concentration)	0.0306 %	0.0065 %

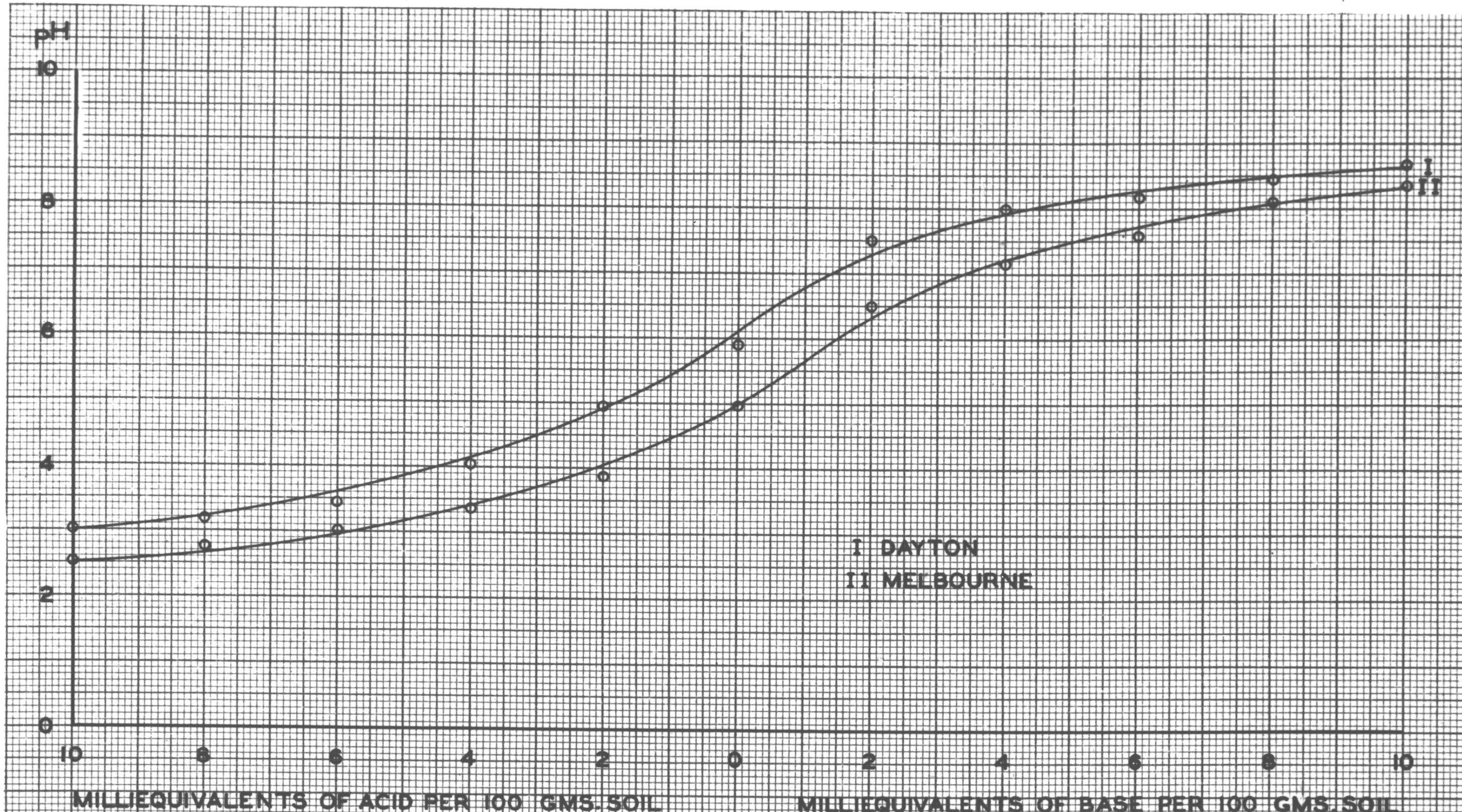
Titration Curves. Soil suspensions were titrated electrometrically on the hydrogen electrode with N/10 HCl and N/50 $Ca(OH)_2$. The suspensions were allowed to stand eighteen hours to attain equilibrium. One c.c. of N/10 acid or base to ten grams of soil is equivalent to one milliequivalent of hydrogen per 100 grams of soil.

The titration curves of these soil acids are graphically shown in Figure I. These curves show clearly the high buffer capacity of the soils. To attain neutrality requires 3.15 M.E. of base for the Melbourne soil which is equivalent to 6300 pounds of calcium carbonate per 2,000,000 pounds of soil. The amount of base required to bring the Dayton soil to neutrality is 1.3 M.E. which is equivalent to 2600 pounds of calcium carbonate per 2,000,000 pounds of soil. The Jones lime requirement method indicated a similar lime requirement.

The titration curves afford another check on the base exchange methods. In Table 21 the number of M.E. of base required to give a neutral reaction is shown to be equal to the exchangeable hydrogen determined by Parker's method (31). The exchangeable bases at neutrality from the titration curve is exactly equal to the exchange capacity of the Melbourne soil and just slightly less for the Dayton soil.

Table 21. Degree of Saturation from Titration Curves

$Ca(OH)_2$ Added to Soil	Melbourne Soil		Dayton Soil	
	Exchangeable: Bases M.E.	pH	Exchangeable: Bases M.E.	pH
0.5	2.74	5.3	11.65	6.5
1.0	3.24	5.7	12.15	6.8
1.5	3.74	6.1	12.65	7.1
2.0	4.24	6.4		
2.5	4.74	6.7		
3.0	5.24	6.9		
3.5	5.74	7.1		



TITRATION CURVES

DAYTON AND MELBOURNE SOILS

Soil degeneration is fundamentally a loss in base exchange capacity. The Melbourne soil has a very low base exchange capacity in proportion to the amount of colloid. In comparison with the Dayton soil over one-half of the base exchange capacity of the soil has been lost. The nature of the soil acids shows the Melbourne soil to be in an incipient stage of degeneration. The relatively strong acids still remain an active part of the exchange complex. With time and weathering the soil will likely exhibit all characteristics of degenerated soils. Maintaining the calcium equilibrium of the soil by liming effectively arrests degeneration.

Discussion

In Table 22 the comparative clover yields of both the Dayton and Melbourne soils are shown. The data are averages of all of the treatments. The Dayton soil has over six times as much clover producing power as the Melbourne when the soils are untreated. The same ratio holds when lime is used without fertilizers. When phosphorus and manure are applied, the ratio is reduced to 1 : 1.7. The yields of the Dayton always exceed the yields on the Melbourne soil. Lime treatments in addition to phosphorus and manure brings the yields of the two soils somewhat nearer together.

Table 22. Comparative Yields and Nitrifying Power of Dayton and Melbourne Soils

Soil Treatment	YIELD OF RED CLOVER Gms. Dry Wt.			NITRIFYING POWER p.p.m. N after Six Weeks Nitrification		
	Melbourne	Dayton	Ratio	Melbourne	Dayton	Ratio
Untreated	10.5	67.0	1 : 6.4	23	80	1 : 3.5
Limestone	12.4	83.1	1 : 6.7	28	128	1 : 4.5
Manure and Phosphorus	54.3	96.8	1 : 1.7	44	72	1 : 1.6
Manure, Phosphorus and Lime	88.7	123.0	1 : 1.4	102	124	1 : 1.2

The comparative nitrifying power of the Dayton and Melbourne soils is shown in Table 22. The results as a whole indicate very definitely the close relationship between clover producing power and the nitrifying power of the soils. When the soils are untreated or only limed the ratio of the nitrifying power is wide. When phosphorus and manure are used the ratio is narrowed. The use of lime with the phosphorus and manure brings the nitrifying power, as it did the yields, close together. These results show that the nitrification in the Melbourne soil is very poor without phosphorus and manure, but is increased to almost that of the Dayton soil with the fertilizers. The ratios of nitrification and of clover yields are almost identical.

The laboratory studies show that the Melbourne is a partially degenerated soil with little capacity to hold nutrients, especially the bases. The Dayton has the capacity to retain nutrients. The nutrient supply of the soil is high. The comparative soil characteristics are shown in Table 23. The colloid content of the soils is about the same, yet the colloid in the Melbourne has less than one-half the base exchange capacity and holds only about one-fifth as much bases as is held by the Dayton. The Melbourne thus shows marked degeneration as well as a high degree of unsaturation in respect to bases. A large

Table 23. Comparative Properties of the Dayton and Melbourne Soils

Soil Properties	Melbourne	Dayton	Ratio
Colloid Content, per cent	19.9	21.5	1 : 1.1
Base Exchange Capacity, M.E.	5.74	13.09	1 : 2.3
Exchangeable Bases, M.E.	2.24	11.04	1 : 5.0
Exchangeable Calcium, M.E.	1.51	8.22	1 : 5.4
Water-soluble Calcium, p.p.m.	12.6	45.5	1 : 3.6
Nitrates, p.p.m. N	3.4	27.0	1 : 7.9
Available Phosphorus, p.p.m. PO_4	10.6	319.2	1 : 30.1

portion of the colloid is inert and does not function in base retention. Exchangeable bases are important to the nutrient supplying power of the soil. The ratio of the exchangeable bases in the soils studied closely approximates the ratio of clover production. The ratios of nitrate nitrogen, water soluble calcium and available phosphorus show the same marked difference in the nutrient supplying power of the two soils. The wide ratio of 1 : 30 of available phosphorus conforms with the large increases obtained from phosphorus fertilizers on the Melbourne soil and only the slight benefit from phosphorus on the Dayton soil.

Degenerated soils are characterized by loss of base exchange capacity, and lack of buffer capacity though high in colloids. The Melbourne is not yet a dead soil, but the data indicate that it is well on the way. I.S. Allison (4) states some of these soils in California are so far gone as to be entirely withdrawn from cultivation. These southern soils, if not older, are more thoroughly leached. The data indicate how seriously the Melbourne soil of this study has been leached.

The titration curves indicate the acids in both soils are highly buffered. Avidity tests show the acids in the Melbourne soil are relatively strong. The Melbourne soil appears to have reached that stage of leaching where free acids of considerable strength remain. The next step presumably will be the breaking down of these acids with further loss of base retaining capacity. These are the logical steps in ageing and degeneration.

Varying the reaction of the Melbourne soil between wide limits has demonstrated that the highest yields and the most vigorous nitrification occur at neutrality. A neutral reaction can be obtained only by the addition of large amounts of lime. This, in addition to the heavy fertilization required to bring the soil to high production, requires a rather large expenditure for the crop increases obtained. The practical question arises whether improving the soils, with the large expenditures, is advisable. Improvement is always possible, but unless there is reasonable assurance of some profit, few will care to undertake a soil improvement program.

These studies show that the Dayton soil is materially improved as measured by crop response with small amounts of lime. These results must be interpreted, however, with due consideration for the condition of the soil in the field. The Dayton, because of its subsoil is much less productive in the field than in the greenhouse. Samples of Dayton surface soil when removed from the handicap of the subsoil are quite productive. To that extent greenhouse data are discredited in drawing conclusions applicable to the field. On the Melbourne soil excellent increases are obtained from limestone after phosphorus and organic matter are added but the total clover yields are never more than moderate.

When Austrian field peas were used as an indicator crop in pot studies, fair yields resulted on both soils. The peas grew equally well on the Dayton and Melbourne soils. Lime, phosphorus and manure apparently did not cause much improvement in growth. These results suggest that for best utilization of these marginal lands, crops sensitive to fertilizer and lime deficiencies should be avoided.

Crowther and Basu (11) found that after fifty years of field tests at Rothamstead, yields were maintained without the use of lime on acid soils by choosing crops of low lime requirement. Hyslop (22) states that Highland bent grass for seed can be grown profitably on the Melbourne soil, and with very little expenditure for fertilizers. He suggests that only phosphorus fertilization is needed for bent grass. This crop proves not only remunerative, but prevents erosion and builds organic matter.

Probably for extensive acreages of marginal land it is advisable to utilize crops that will grow successfully, if such crops can be found, rather than to fertilize and lime heavily for growing general farm crops with high fertility requirements. A farm unit containing small acreages of Dayton or Melbourne soils as a part of the farm offers a somewhat different problem. Under such conditions, large expenditures to make the poor spots produce may be justified even though there is little or no profit from the poor land. Improvement of small areas in otherwise good land prevents the poor land from seriously depreciating the value of the whole farm.

Lime is not a major limiting factor in the productive capacity of either of the above soils under field conditions. Until other deficiencies are corrected, little or no response is obtained from lime, particularly on the Melbourne soil. With other deficiencies corrected, small applications may help the inoculation of legumes, but greater responses are obtained from the heavier applications. The placement of the lime, on or near the seed, had little effect upon the crop response with either soil under greenhouse conditions. If marginal lands are profitably utilized, crop selection, rather than extensive liming or soil improvement, appears more feasible.

Summary

1. The soils in these studies are marginal in respect to profitable utilization. The data show the Melbourne series to be highly weathered soils near complete degeneration. An impervious clay pan limits crop production on the Dayton series.

2. The Dayton and Melbourne soils, though having approximately the same active acidity, differ widely in total acidity. The Melbourne soil is high in total acidity indicating a high lime requirement. The Dayton soil, in comparison, is low in total acidity and consequently shows a low lime requirement.

3. The Melbourne soil is definitely lacking in available phosphorus while the Dayton soil is well supplied. Phosphorus must be supplied before lime can be fully effective in increasing clover yields.

4. Phosphate fixation is high in both soils. Indications were that free iron and aluminum oxides present in the soils were responsible for most of the fixation. Some fixation was due to humus but in a form ultimately available to the plant. Liming at the rates used in this study did not lessen phosphate fixation.

5. Active aluminum was not present in quantities sufficiently large to be toxic to plant growth in the soils

studied. Aluminum toxicity is not a factor, therefore, in liming these soils.

6. Nitrification in the Dayton soil was high when nitrifiable material was added. The most vigorous nitrification resulted with the highest lime treatments. Per unit of lime, the light lime rates were more effective.

7. The Melbourne soil had low ability for nitrification even when nitrifiable material was present. Lime did not stimulate nitrification. When phosphorus and organic matter were supplied, nitrification proceeded as vigorously as in the Dayton soil. With these deficiencies supplied liming stimulated nitrification in proportion to the amount added.

8. A close correlation was obtained between nitrification and clover production. The treatments that stimulated nitrification stimulated plant growth.

9. Lime increased clover yields on the Dayton soil. Applications of 250 to 1000 pounds per acre have proved relatively more beneficial than heavier rates. The highest yields, however, were obtained with the heaviest treatments.

10. Total yields remained extremely low on the Melbourne soil even with heavy liming. Manure and phosphorus treatments resulted in large increases in yield. When phosphorus and humus deficiencies were corrected, the bene-

ficial effect of liming the Melbourne soil was apparent.

11. On varying the soil reaction between pH 3.0 and pH 8.0, the highest clover yields were obtained near neutrality. Titration curves indicate the soil acids are highly buffered in both soils, thus requiring high lime rates to improve soil reaction. The feasibility of liming to the neutral point is therefore questionable.

12. In the greenhouse studies no apparent benefit was obtained from placing small amounts of lime close to the seed. Lime placement does not appear to be a factor in the economic liming of marginal soils.

13. Many crops, including some legumes, are less sensitive to soil deficiencies than red clover. For the profitable utilization of marginal lands, crop selection rather than extensive liming or soil improvement appears more feasible.

Plates I and II

Melbourne soil. Effect of varying quantities of limestone with treble phosphate and manure on the growth of red clover.

Plate I. Melbourne Soil

Plate II. Melbourne Soil

Plates III and IV

Dayton soil. Effect of varying quantities of limestone with treble phosphate and manure on the growth of red clover.

Plate III. Dayton Soil

Plate IV. Dayton Soil

Plate V

Effect of varying the reaction of the Melbourne soil on the growth of red clover. Untreated check = pH 5.3. Treated soils = pH 3.0, pH 4.0, pH 5.0, pH 6.0, pH 6.5, pH 7.0, and pH 8.0.

Plate V. Varying Soil Reactions

Bibliography

(1) Albrecht, W. A. Calcium and hydrogen-ion concentration in the growth and inoculation of legumes. Jour. Amer. Soc. Agron. 24:793-806. 1932.

(2) Albrecht, W. A. and Davis, F. L. Physiological importance of calcium in legume inoculation. Bot. Gaz. 88:310-321. 1929.

(3) Albrecht, W. A. and Poirot, E. M. Fractional Neutralization of soil acidity for the establishment of clover. Jour. Amer. Soc. Agron. 22:649-657. 1930.

(4) Allison, I. S. Private communication. April, 1935.

(5) Bauer, F.C., Snider, H. I, and Lamb, John Jr. Merits of light vs. heavy liming are determined. Ill. Sta., Rpt. 40, pp. 24-28. 1927.

(6) Bauer, F. C. Response of Illinois soils to limestone. Ill. Expt. Sta. Bul. 405. 1934.

(7) Brenchley, W. E. The effect of light and heavy dressing of lime on grassland. Jour. Min. Agr. 32:504-512. 1925.

(8) Burgess, P. S. A method for the determination of "active" aluminum in acid soils. Soil Sci. 15:131-136. 1923.

(9) Burgess, P. S. and Breazeale, J. F. Methods for determining the replaceable bases of soils, either in the presence or absence of alkali salts. Ariz. Tech. Bul. 9:198-200. 1926.

(10) Cooper, H. P. Relation of hydrogen-ion concentration of soils to the growth of certain pasture plants. Pl. Physiology 7:527-532. 1932.

(11) Crowther, E. M. and Basu, J. K. The influence of fertilizers and lime on the exchangeable bases and soil reactions of a light acid soil after 50 years of continuous barley and wheat. Second Internat. Cong. of Soil Sci., Vol. II, Comm II, pp. 146-151. 1933.

(12) Dawson, R. B. and Evans, T. W. The establishment of grasses on very acid moorland. Jour. Min. Agr. 37:1181-1191. 1931.

(13) Doolas, G. Z. Soil acidity and soybean inoculation. Soil Sci. 30:273-288. 1930.

(14) Erdman, L. W. The effect of gypsum on soil reaction. Soil Sci. 12:433-448. 1921.

(15) Fisher, E. A. Studies on soil reaction. Jour. Agr. Science 11:19-65. 1920.

(16) Fleetwood, J. R. Easily soluble calcium of soils as an indicator of their response to liming. Soil Sci. 19:441-458. 1925.

(17) Ford, M. C. The nature of phosphate fixation in soils. Jour. Amer. Soc. Agron. 25:134-144. 1932.

(18) Heck, A. F. A method for determining the capacity of a soil to fix phosphorus in difficultly available form. Soil Sci. 37:477-482. 1933.

(19) Hissink, D. J. Method for estimating adsorbed bases in soils and the importance of these bases in soil economy. Soil Sci. 15:269-276. 1923.

(20) Hissink, D. J. The relation between the values pH, V and S (humus). The equivalent weight of the humus substance. Intern. Soc. Soil Sci. Trans. Second Comm. A:198-204 and A:174-192.

(21) Hutcheson, T. B. Rate of liming. Va. Sta., Rpt. for 1919-1927, pp. 123-124. 1927.

(22) Hyslop, G. R. Private communication. March, 1935.

(23) Jenny, H. Studies on the mechanism of ionic exchange in colloidal aluminum silicates. Jour. Phys. Chem. 36:2217-2258. 1932.

(24) Jones, C. H. Method for determining the lime requirement of soils. Jour. Assoc. Off. Agr. Chem., 1:43-44. 1915.

(25) Lipman, J. G., and Blair, A. W. The yield and nitrogen content of soybeans as influenced by lime. Soil Sci. 4:71-77. 1917.

(26) McCool, M. M. Methods of applying lime. Jour. Amer. Soc. Agron., 19:198-199. 1927.

(27) McCool, M. M. The use of small amounts of lime in the row. Jour. Amer. Soc. Agron., 22:530-536. 1930.

(28) McGeorge, W. T. and Breazeale, J. F. Studies on iron, aluminum, and organic phosphates and phosphate fixation in calcareous soils. Ariz. Tech. Bul. 40:59-111. 1932.

(29) Midgley, A. R. and Weiser, V. L. Need and use of lime on Vermont soils. Vermont Sta. Bul. 371. 1934.

(30) Olmstead, L. B., Alexander, L. T., and Middleton, H. E. A pipette method of mechanical analysis of soils based on improved dispersion procedure. U.S.D.A. Tech. Bul. 170: 1-22. 1930.

(31) Parker, F. W. Methods for the determination of the amount and avidity of exchangeable hydrogen in soils. Proc. First Intern. Soc. Soil Sci. 2:164-174. 1926.

(32) Pate, W. W. The influence of the amount and nature of the replaceable base upon the heat of wetting of soils and soil colloids. Soil Sci. 20:329-335. 1925.

(33) Pierre, W. H. Hydrogen-ion concentration, aluminum concentration in the soil solution and percentage base saturation as factors affecting plant growth on acid soils. Soil Sci. 31:183-207. 1930.

(34) Pierre, W. H. and Parker, F. W. The concentration of organic and inorganic phosphorus in the soil solution and the availability of organic phosphorus to plants. Soil Sci. 24:119-128. 1927.

(35) Pierre, W. H. and Scarseth, G. D. Determination of the percentage base saturation of soils and its value in different soils at definite pH values. Soil Sci. 31:99-114. 1930.

(36) Pohlman, G. G. The relationship of nitrification and sulfur oxidation to the aluminum and hydrogen-ion concentration of some very acid soils. Soil Sci. 36:47-55. 1933.

(37) Robinson, W. O. The absorption of water by soil colloids. Jour. Phys. Chem. 26:647-653. 1922.

(38) Salter, R. M. Profitable cropping depends on correct soil reaction. Ohio Sta. Bul. 532. Fifty second Ann. Rpt., pp. 17-18. 1934.

(39) Scanlan, R. W. Calcium as a factor in soybean inoculation. Soil Sci. 25:313-326. 1928.

(40) Skinner, J. J. and Beattie, J. H. Influence of fertilizers and soil amendments on soil acidity. Jour. Amer. Soc. Agron. 9: 25-35. 1916.

(41) Slipher, J. A. The problem of the rate of soil liming. Jour. Ind. and Eng. Chem. 19:561-564. 1927.

(42) Snider, H. J. A chemical study of a soil under long-continued field experiments. Jour. Amer. Soc. Agron. 26:946-953. 1934.

(43) Stephenson, R. E. Nitrification in acid soils. Iowa Res. Bul. 58. 1920.

(44) Stephenson, R. E. and Powers, W. L. Liming western Oregon soil. Ore. Sta. Bul. 325. 1934.

(45) Truog, E. The determination of the readily available phosphorus of soils. Jour. Amer. Soc. Agron. 22:874-882. 1930.

(46) Truog, E. A new apparatus for the determination of soil carbonates and new methods for the determination of soil acidity. Jour. Indus. and Eng. Chem. 8: pp. 341. 1916.

(47) Truog, E. and Chucka, J. A. The origin, nature and isolation of the inorganic base exchange compounds of soils. Jour. Amer. Soc. Agron. 22:553-557. 1930.

(48) Turner, P. E. The state of unsaturation of the soil in relation to its field behavior and lime requirement. Soil Sci. 30:349-381. 1930.

(49) Walker, R. H., Brown, P. E. and Young, A. W. Some chemical and bacteriological effects of various kinds and amounts of lime on certain Southern Iowa soils. Iowa Res. Bul. 148. 1932.

(50) White, J. W. and Holben, F. J. Economic values of different forms and amounts of agricultural lime. Pa. Sta. Bul. 211. 1927.