LIME REQUIREMENT RELATED TO PHYSICAL AND CHEMICAL PROPERTIES OF NINE MICHIGAN SOILS

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LIME REQUIREMENT RELATED TO PHYSICAL AND CHEMICAL PROPERTIES OF NINE MICHIGAN SOILS

by

Gerhard John Ross

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ABSTRACT

LIME REQUIREMENT RELATED TO PHYSICAL AND CHEMICAL PROPERTIES OF NINE MICHIGAN SOILS

by Gerhard John Ross

Nine Michigan soils were used in a greenhouse experiment to study the relationship between lime requirement and several physical and chemical soil properties. The effect of liming on availability and uptake of calcium, magnesium, potassium, and phosphorus was also studied. Three cuttings of alfalfa were harvested and response to liming measured in terms of yield and percentage and uptake of calcium, potassium, and phosphorus. The initial pH of all soils was close to 5.50, and the lime requirement of each soil was taken as the amount of lime needed to raise soil pH from 5.50 to 6.80 by incubating the soils for 13 weeks in the greenhouse. The lime requirement was also measured by the Shoemaker, McLean, and Pratt buffer method. Lime requirement was highly correlated (0.01 level) with cation exchange capacity, organic matter content, a function of organic matter and pH interaction expressed as (pH 6.8 - soil pH) x (%O.M.), and milli-equivalents of exchangeable hydrogen per 100 grams of soil, and was correlated (0.05 level) with clay content.

Within each soil type, an increase in pH due to liming was highly correlated to a corresponding increase in percent base saturation. This relationship was not apparent between soil types. At a given pH level soils containing mostly 2:1 type clay minerals showed a higher percent saturation than did soils containing mostly 1:1 type clay minerals.

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Lime requirement as determined by incubation in the greenhouse was highly correlated with lime requirement as determined by the Shoemaker, McLean, and Pratt buffer method.

The availability of calcium increased consistently with increased rates of lime in all soils. Liming did not appreciably affect availability of magnesium, potassium, and phosphorus.

Liming significantly increased the yield of alfalfa on eight of the nine soils studied. Calcium percentage and uptake of calcium by alfalfa increased with increased rates of lime. Potassium percentage in the alfalfa decreased with additions of lime and was inversely related to calcium percentage. Potassium uptake increased at the higher rates of lime, primarily because of increased yields. Although liming did not appreciably affect phosphorus percentage of alfalfa, phosphorus uptake increased at the higher rates of lime.

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INTRODUCTION

Liming acid soils is an established practice in the humid regions of the world. Numerous studies have been conducted to determine the effect of lime on soil properties and its influence on plant growth. However, relatively few studies have been made concerning the relationship of lime requirement to chemical and physical soil properties, and there is little of this type of information available for Michigan soils.

In the past soil reaction was taken as the only criterion for lime requirement determination. It has been established that because of differences in organic matter content and clay content, soil pH alone is not an adequate criterion for estimating lime needs. Therefore, chemical methods have been developed which take into consideration pH, base saturation, and cation exchange capacity.

Plant response to lime may also vary on different soils with similar pH values. Differences in plant response to lime generally are due to differences in physical and chemical properties of soils.

A greenhouse study, involving nine Michigan soil types, was conducted to investigate the relationship between lime requirement and several physical and chemical soil factors. In addition, values for lime requirement as determined by the McLean, Shoemaker, and Pratt method were compared with values for lime requirement as determined in the greenhouse by incubation of the soils after addition of lime. Alfalfa was grown on nine soils to which different rates of lime were applied to evaluate response of alfalfa to lime on different soil types and to study interaction between lime application and plant nutrient uptake.

LITERATURE REVIEW

Soils in humic regions tend to become acid due to leaching of bases which are replaced by hydrogen ions. Removal of bases in the harvest of crops and use of certain fertilizers, especially nitrogenous fertilizers, intensifies acidifying processes in soils.

Beneficial effects of liming acid soils have long been recognized, but until soils were studied systematically, reasons for beneficial action of lime on acid soils were obscure. Thomas Way (50) discovered the process of base exchange in 1850 and opened the way to a better understanding of changes which occur when a soil is limed. Seventy years later, Hissink (16) introduced the concept of base saturation. Mattson, Wiklander, and others (18, 29, 51, 52) employing theories of the diffuse double layer and Donnan equilibrium have made clear many of the constituents and mechanisms which are involved in ion exchange processes. Their investigations showed that the nature of the colloidal material and the kind and concentration of ions which are present in soil solution and on the exchange complex are the principal factors affecting ion exchange in soil. Experimental evidence shows that these factors, including soil reaction, largely determine the lime requirement of a soil.

Lime requirement of a soil is defined as the amount of lime needed to raise soil pH to a prescribed value. It is generally recommended that a mineral soil be limed to a pH of 6.5 or 6.8, while organic soils seldom need lime unless the pH is below 5.0. A common method for determining lime requirement is by measurement of pH or active soil acidity. Peech and Bradfield (38) considered pH the best single value characteristic for estimating lime requirement of a soil. They recommended using a 1:1 soil:water ratio for routine analyses.

Nevertheless, many investigators recognized that use of pH as a single value characteristic often gives inaccurate and sometimes misleading results in lime requirement determinations. Shimp (44) found that pH alone is insufficient for determining lime requirement of soils which vary in texture and exchange capacity. Others (31, 32, 40) reported that soils having a similar pH value may vary widely in their percent base saturation. For this reason Mehlich (33) prepared a triethanolamine buffer for determination of exchangeable hydrogen and base exchange capacity to indicate lime requirement of soil. Yields of sunflowers showed that lime recommendations based on exchangeable hydrogen and with reference to base exchange capacity were very satisfactory. However, this method was not suited to rapid routine analyses. Therefore, Woodruff (53) developed a buffer, consisting of a solution of p-nitrophenol, calcium acetate, and magnesium oxide with a pH of 7.0, that could be mixed directly with the soil sample. Strength of the buffer and soil to buffer ratio were adjusted so that a pH depression of one-tenth of a unit indicated one milliequivalent of exchangeable hydrogen which would require one thousand pounds of calcium carbonate for neutralization. A major limitation of this method is that large errors in lime recommendations may result from limited accuracy in measuring pH with a pH meter. Woodruff tested this method on numerous Missouri soils having lime requirements which were established by liming practice over a period of years and obtained satisfactory results. However, it was noted by Shoemaker, et al. (45) that the Woodruff method indicated much less lime than the amount actually needed to neutralize certain Ohio soils which contained large amounts of extractable aluminum. Shoemaker, et al. (45) investigated various combinations of a considerable number of buffers. This resulted in preparation of a modified Woodruff buffer which is weaker than Woodruff's buffer. The Shoemaker, McLean, and Pratt (S.M.P.) buffer method has proved very satisfactory for indicating lime requirement of a large number of Ohio soils. The authors suggested that the excellent results may be due to reaction of S.M.P. buffer with the acidity component in soils represented by extractable aluminum since the equilibration pH of the soil-buffer mixture will be low for soils high in active aluminum. Evidently the higher equilibrium pH of the Woodruff buffer with soil preserves the aluminum in the exchange positions of the lattice so that it fails to react normally with this buffer.

Lucas (25) studied the relationship of the lime requirement of soils to their exchange capacity. He found that lime requirement was highly correlated with cation exchange capacity as determined by either copper acetate or ammonium acetate and devised a practical chart for use in recommending limestone based on soil pH and cation exchange capacity.

In sandy soils organic matter content appears to be mainly responsible for cation exchange capacity and consequently for lime requirement. In fine-textured soils the inorganic fraction is more important (21). Tedrow and Gillam (47) showed that sandy soils with contents of organic matter as low as 1.67 percent derived 75 to 80 percent of their cation exchange capacity from organic matter. For loam soils with an average organic matter content of 3.50 percent, 64 to 68 percent of the cation exchange capacity came from organic matter.

Relationships between pH and base saturation have been the subject of many investigations, (31, 32, 40, 44). Morgan (34) pointed out that the relationship between pH and percent base saturation may be fairly constant within a soil type, but that it may vary widely between soil types. Mehlich (31) studied base saturation and pH in relation to soil types of some North Carolina soils and concluded that this relationship is almost solely influenced by the nature of the exchange complex. For montmorillonitic soils base saturation of the exchange complex at pH 7.0 is practically complete; whereas, for kaolinitic soils at the same pH value only 50 to 80 percent of the colloids are base saturated. Marshall (28) studied pure kaolinitic and montmorillonitic clays and found that below 70 percent calcium saturation montmorillonite clays are characterized by a high energy of adsorption for calcium ion. This energy of adsorption is reduced markedly above 70 percent calcium saturation. In the case of kaolinite there is no region where calcium is so strongly adsorbed.

Truog (48) distinguished between lime requirement of the soil and lime requirement of the plant and stated that lime requirement of the plant refers to the actual lime needs of the plant itself, especially in reference to ease and rate at which lime must be secured from the soil by the plant for normal growth.

It is difficult to establish a general pH value which represents an optimum soil reaction for plant growth because optimum pH may vary with different soil types, crops, and crop rotations. Nevertheless, for practical purposes generalizations are necessary and a useful chart has been devised to show graphically the influence of soil reaction on availability of nutrients in soils (49). This chart shows that pH 6.5 is favorable for availability of plant nutrients. Therefore, for general purposes it is usually recommended that acid mineral soils be limed to a pH of 6.5.

Many workers have attempted to isolate the factor which is primarily responsible for failure of plants to grow well in an acid soil (2, 5, 6, 39). Arnon and Johnson (5) have decisively shown that hydrogen, per se, is not toxic to plants except at extreme pH values normally not encountered in soil. Pierre (39) found poor correlation between crop growth and hydrogen ion concentration in different soils and concluded that hydrogen concentration cannot be considered the direct cause of poor plant growth nor the main factor governing response to liming. He noted, however, that on soils producing good growth of sorghum the percent base saturation was higher than on soils with a similar pH value producing poor growth of sorghum.

Several investigators have studied the role of calcium as a plant nutrient (2, 3, 4, 5, 6, 14, 24, 35, 46). Klingebiel and Brown (24) studied calcium from a nutrient standpoint and applied calcium in the row to alfalfa on different soil types. Interaction of treatment and soil showed that plants responded similarly to equivalent treatments on soils having different lime requirements. Moser (35) reported that calcium supplied at low pH values was a more important growth factor than soil pH. Albrecht (2, 3) showed that calcium chloride, calcium acetate, and calcium silicate improved plant growth on acid soils. He (4) stated that "plant injury by soil acidity" is largely a matter of a calcium deficiency and compounds of calcium other than carbonate that do not neutralize soil acidity will serve in place of limestone. Fried and Peech (14) found that plants grown on limed soils absorbed much more calcium and gave much higher yields than those grown on gypsum-treated soils despite higher concentrations of calcium in the soil solution of gypsum-treated soils. They suggested that manganese and aluminum had prevented uptake of calcium since liming, in contrast to gypsum treatment, decreased manganese and aluminum content in the plants. Schmehl, et al. (46), found that symptoms of manganese toxicity appeared on the alfalfa when calcium-manganese ratio in plants was less than 75. Liming decreased the amount of readily soluble aluminum and manganese. Therefore, they concluded that the beneficial effect of liming may be attributed to the decrease in concentration of aluminum and manganese in soil solution.

Truog (49) pointed out that between pH 6.5 and 7.5 conditions are most favorable for phosphate availability. Cook (11) studied several Michigan soils and showed that increasing the degree of base saturation increased available phosphorus in seven soils and decreased it in two others. Dunn (12) reported that liming resulted in a significant increase in phosphorus uptake by alfalfa but that the percent phosphorus in forage went down which indicates that percentage of a particular element in forage does not necessarily indicate availability of that nutrient in the soil. Chai and Caldwell (10) showed that the capacity of a soil to "fix" phosphorus from added KH_2PO_4 increased with departure from a soil pH near neutrality.

Their data indicated that iron phosphates and aluminum phosphates predominate in acid soils, while calcium phosphates predominate in calcareous soils. The authors suggested that iron and aluminum are the main constituents responsible for fixation in acid soils, while in calcareous soils calcium may be the main fixing constituent.

Availability of potassium as affected by liming has been studied by several investigators (15, 26, 27) and many conflicting results have been published. Lysimeter studies of McIntire, *et al*. (27) have shown that lime exerts a repressive influence on the solubility of soil potassium. Others (26, 36) also reported that little, if any, potassium is made available by liming. Yet Jenny and Shade (20) pointed out that without a single exception all their laboratory experiments showed that calcium carbonate liberates adsorbed potassium from soil colloids, and they suggested that depressive effects of lime on availability of potassium may be due to fixation of potassium by soil micro-organisms.

Wiklander (52) has shown from theoretical considerations and experimental evidence that liming affects availability of nutrients in two ways. On one hand calcium replaces more tightly held hydrogen and aluminum. Less firmly adsorbed calcium ions favor adsorption of other nutrients, and consequently the concentration of cations other than calcium in soil solution is decreased. On the other hand, activity and replacing power of the hydrogen ions, which yielded their exchange sites to calcium ions, is increased with the result that adsorbed nutrient cations are more available to plants and more easily lost by leaching. Simultaneous and opposing exchange reactions which occur when a soil is limed, as pointed out by Wiklander (52) show that the effect of lime on ion exchange is rather complex. Nor are ion exchange reactions the only processes that are changed when a soil is limed. There are also other important factors that are influenced by the degree of calcium saturation, such as oxidation-reduction conditions, ion complex formations, fixation of certain nutrients in non-exchangeable form, humification processes, solubility of certain metal oxides, microbial activity, and structure formation which add to the complexity of the influence of lime on availability of nutrients.

EXPERIMENTAL PROCEDURE

Greenhouse Studies

A greenhouse study was initiated in September, 1960, using nine soil types which varied in texture from loamy sand to clay. Locations of each of the nine soil types are given in Table 1.

Samples from the surface layer (zero to seven inches) and the subsoil (seven to fourteen inches) of each soil type were collected from sites given in Table 1. The soils were air-dried and screened through a one-fourth inch screen. Calcic limestone was thoroughly mixed with each soil at rates given in Table 2. The limed soils were placed in glazed three-gallon pots and distilled water added to bring the moisture content to field capacity of each soil.

After an incubation period of thirteen weeks, each treatment was divided into three replicates. Tall containers were constructed by placing a bottomless number ten tin can on top of a similar can with bottom and taping the two together. The lower half of each container was filled with 3200 grams of subsoil and the upper half was filled with 3200 grams of surface soil. Each of the three replicates was placed on a long table in a randomized block design.

Phosphorus and potassium levels of the soils were adjusted to the equivalent of 340 pounds P_2O_5 and 340 pounds of K_2O per acre by adding superphosphate and muriate of potash at planting time. The quantity to be added was obtained by subtracting the soil test value from 340 pounds per acre.

Vernal alfalfa was planted in March, 1961, and thinned to ten plants per container when the plants had reached a height of one inch. The alfalfa was harvested when the first blossoms appeared

Table 1. Soil type, location, mechanical composition, organic matter content and cation exchange capacity of the nine soils studied.

Soil Type	Location	Sand (%)	Silt (%)	Clay (%)	Organic Matter (%)	Cation Exchange Capacity (me./100g)
Ontonagon clay	Sec. 21, T48N, R40W, Waracheck Farm, Ontonagon Co.	9	31	60	6.07	32.50
Iron River silt loam	Sec. 14, T42N, R35W, Petroff Farm, Iron River Co.	16	70	14	4.55	20.25
Warsaw loam	Sec. 19, T4S, R11W, Rhoda Farm, Kalamazoo Co.	48	34	18	2.80	16.62
Munising sandy loam	Sec. 31, T54N, R33W, Larsen Farm, Houghton Co.	72	19	9	3.16	14.25
Kalamazoo loam	Sec. 30, T2S, R6W, Lutz Farm, Calhoun Co.	42	45	13	3.72	12.25
Pence sandy loam	Sec. 13, T43N, R33W, Groof Farm, Iron Co.	67	26	7	2.19	11.25
Montcalm sandy loam	Sec. 27, T9N, R7W, State Game Hunting Area, Montcalm Co.	72	21	7	1.87	8.83
Nester sandy loam	Sec. 30, T9N, R6W, Thomas Farm, Montcalm Co.	62	28	10	1.61	7.85
Plainfield loamy sand	NW$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 27, T5N, R1W, Clinton Co.	84	10	6	0.89	6.08

Table 2. The effect of rate of application of lime on soil reaction.

Soil Type		Lime Applied (Pounds per acre) 0	500	1000	1500	2000	2500	3000	4000	5000	6000	7000
Ontonagon clay	pH at planting time*	5.50	--	5.41	5.48	5.50	5.53	5.74	5.87	5.94	6.09	6.22
	pH after 3 cuttings	5.44**	--	5.47	5.50	5.53	5.62	5.67	5.76	5.83	5.88	5.97
Iron River silt loam	pH at planting time	5.50	5.29	5.32	5.40	5.50	5.58	5.65	6.00	--	--	--
	pH after 3 cuttings	5.49	5.60	5.61	5.65	5.70	5.78	5.87	6.00	--	--	--
Warsaw loam	pH at planting time	5.50	--	5.45	5.60	5.68	5.75	5.85	6.25	6.42	6.52	--
	pH after 3 cuttings	5.45	--	5.39	5.55	5.55	5.68	5.71	5.85	5.98	6.13	--
Munising sandy loam	pH at planting time	5.50	5.45	5.64	5.67	5.71	5.80	5.98	6.21	--	--	--
	pH after 3 cuttings	5.55	5.58	5.64	5.73	5.82	5.85	5.83	6.00	--	--	--
Kalamazoo loam	pH at planting time	5.35	5.15	5.32	5.45	5.71	5.77	6.10	6.34	--	--	--
	pH after 3 cuttings	5.26	5.30	5.41	5.58	5.55	5.71	5.74	6.03	--	--	--
Pence sandy loam	pH at planting time	5.50	5.45	5.70	5.80	5.91	6.09	6.17	6.41	6.65	--	--
	pH after 3 cuttings	5.48	5.58	5.58	5.80	5.88	5.92	6.11	6.28	6.54	--	--
Montcalm sandy loam	pH at planting time	5.40	5.55	5.67	6.30	6.37	6.42	6.55	6.78	--	--	--
	pH after 3 cuttings	5.60	5.58	5.59	5.75	5.93	6.12	6.23	6.58	--	--	--
Nester sandy loam	pH at planting time	5.15	5.21	5.53	5.85	6.18	6.40	6.58	6.73	7.00	--	--
	pH after 3 cuttings	5.24	5.50	5.55	5.67	5.91	6.09	6.28	6.47	6.83	--	--
Plainfield loamy sand	pH at planting time	5.60	5.76	6.08	6.39	6.89	7.01	7.11	7.01	--	--	--
	pH after 3 cuttings	5.56	5.74	5.75	5.87	5.99	6.32	6.48	6.40	--	--	--

*Measured after 13 weeks incubation.
**Each value reported is an average of three replications.

and cut at a height of one and one-half inches from soil. The plant material was dried at 60° C., weighed, ground in a Wiley mill, and the material from the first two cuttings saved for analysis.

Three cuttings were obtained over a six-month period ending September 4, 1961. After the last harvest, samples were taken from subsoil and topsoil for chemical analysis.

METHODS OF ANALYSIS

Soils

Soil samples were taken before potting the soils, at planting time, and after the last harvest. All samples were crushed and sieved through a two millimeter screen prior to analysis.

Mechanical analysis of the nine soils studied was determined by the pipette method (23).

The organic matter content was determined by the dry-combustion method as described by Piper (41).

Soil pH was measured with a Beckman (Model G) potentiometer using a 1:1 soil to water ratio.

Cation exchange capacity and exchangeable calcium, magnesium, and potassium were determined by centrifuge methods as described by Richards. (43)

Lime requirement of each soil was evaluated by the buffer method as described by Shoemaker, *et al*. (45) and compared with lime requirement indicated by incubating the soils with lime for thirteen weeks in the greenhouse.

Available phosphorus was determined by the method of Bray (9). The extracting solution consisted of 0.03 N NH_4F and 0.025 N HCl. A soil extracting solution ratio of 1:8 was used.

Qualitative identification of the clay minerals in each soil was made by x-ray diffraction. Forty to fifty milligrams of clay was deposited from suspension onto a porous plate and washed with three increments of a 0.1 *N* $MgCl_2$ solution which contained three percent glycerol by volume. The deposit was first air dried and then dried in a desiccator for two days. The sample was then mounted on a Norelco x-ray spectrometer using nickel filtered copper radiation. After the first x-ray exposure the magnesium-saturated, glycerol-solvated, oriented particles were potassium saturated by using 0.1 N KCl solution, and the excess of KCl washed out with distilled water. The sample was then heated to 110° C. and x-ray analysis repeated. Finally the sample was heated to 550° C. for twelve hours and x-ray analysis again repeated.

Plants

Samples of the plant material were wet digested with nitric and perchloric acid as described by Piper (41). The residue was dissolved in 0.05 N HCl and calcium and potassium determined using a Coleman Model 21 flame photometer. The phosphorus content was determined by the ammonium molybdate-colorimetric procedure as outlined by Fiske and Subbarrow (13).

Lime

Bellevue limestone (calcic) was sieved through an 80-mesh screen, and its neutralizing value determined by standard A.O.A.C. methods (7). A calcium carbonate equivalent of 75 percent was obtained.

RESULTS AND DISCUSSION

Soil Reaction and Lime Requirement

Data for soil reaction are given in Table 2. Soil pH was measured prior to liming, after the limed soils had been incubated for thirteen weeks in the greenhouse, and after harvest of the third cutting of alfalfa. Soil pH values of the nine soils prior to liming varied from 5.15 to 5.60 with an average pH of 5.44. The data in Table 2 show that at rates of 2,000 pounds of lime per acre and higher, pH decreased during growth of three cuttings of alfalfa. This decrease in pH was less apparent at rates below 2,000 pounds of lime per acre. This result would be expected because yield of alfalfa and uptake and removal of bases by alfalfa were higher at high rates of liming than at low rates. The check soils were not incubated prior to planting. A comparison of pH of unincubated checks with pH of treatments with the first increment of lime of incubated soils at planting time shows that for most soils pH of the checks was higher than pH after addition of the first increment of lime. This depression in pH did not occur in the poorly buffered Plainfield, Montcalm, and Nester soils. After growth of three cuttings of alfalfa the depression in pH was not apparent and the checks showed a lower pH than treatments with the first increment of lime on all soils except Warsaw loam. Alban and Lin (1) reported similar observations on Oregon soils. These observations may be explained by the fact that the number and activity of micro-organisms increase in limed and incubated soils which gives rise to an accumulation of organic acids and a decrease in soil pH.

Percent base saturation of each soil at different pH values is given in Table 3. A close linear relationship exists within each soil type between increase in pH and increase in percent base saturation at successive increments of lime. Inspection of the data in Table 3 fails to show the same relationship between soil types. The lack of correlation of pH to percent base saturation between different soil types may be explained by differences in strength of adsorption of exchangeable cations. Differences in strength of adsorption may be due to variations in type and proportion of clay minerals present in different soil types. Also, variations in organic matter content may affect the strength with which bases are adsorbed on the colloidal complex. The effect of different types of clay minerals on percent base saturation is shown in Table 4. This table includes data for percent base saturation and estimated amounts of different types of clay minerals. The x-ray diffraction patterns are shown in Figures 1, 2 and 3 of the appendix. The data in Table 4 show that in general lower base saturation percentages are associated with soils having a relatively greater proportion of kaolinite, a 1:1 type clay mineral. Higher base saturation percentages tend to be associated with soils containing a relatively greater proportion of 2:1 type clay minerals. For example, at a pH of 6.00 the base saturation of the colloidal complex in Munising sandy loam is 36.9 percent. At the same pH, the base saturation of the colloidal complex in Ontonagon clay is 77.0 percent. The data in Table 4 show that the greater proportion of clay minerals in Munising sandy loam is kaolinite, a 1:1 type clay mineral, whereas, the clay minerals in Ontonagon clay consist mainly of montmorillonite and vermiculite which are 2:1 type clay minerals.

Table 3. The effect of rate of application of lime on soil reaction and percent base saturation of nine Michigan soils.

Soil Type	C.E.C. me/100g		Lime Applied (Pounds per Acre) 0	500	1000	1500	2000	2500	3000	4000	5000	6000	7000	Correlation Coefficient[1]
Ontonagon clay	32.50	pH	5.50	--	5.41	5.48	5.50	5.53	5.74	5.87	5.94	6.09	6.22	
		Base Sat.(%)	60.6	--	65.4	68.4	69.9	71.7	75.5	74.8	76.5	77.4	79.2	0.881**
Iron River silt loam	20.25	pH	5.50	5.29	5.32	5.40	5.50	5.58	5.65	6.00	--	--	--	
		Base Sat.(%)	30.2	33.7	33.6	35.6	37.0	40.0	41.5	46.0	--	--	--	0.849**
Warsaw loam	16.62	pH	5.50	--	5.45	5.60	5.68	5.75	5.85	6.25	6.42	6.52	--	
		Base Sat.(%)	38.7	--	39.2	44.1	46.2	55.9	51.9	56.3	61.4	62.9	--	0.932**
Munising sandy loam	14.25	pH	5.50	5.49	5.64	5.67	5.71	5.80	5.98	6.21	--	--	--	
		Base Sat.(%)	20.7	23.9	30.1	33.1	32.6	35.2	36.9	39.9	--	--	--	0.896**
Kalamazoo loam	12.25	pH	5.35	5.15	5.32	5.45	5.71	5.77	6.10	6.34	--	--	--	
		Base Sat.(%)	35.3	41.8	43.3	46.0	47.7	57.2	44.7	62.9	--	--	--	0.742*
Pence sandy loam	11.25	pH	5.50	5.45	5.70	5.80	5.91	6.09	6.17	6.41	6.65	--	--	
		Base Sat.(%)	26.2	32.0	32.7	34.5	41.7	44.3	50.0	51.7	59.6	--	--	0.973**
Montcalm sandy loam	8.83	pH	5.40	5.55	5.67	6.30	6.37	6.42	6.55	6.78	--	--	--	
		Base Sat.(%)	29.3	34.4	38.0	39.7	43.4	50.2	52.8	65.1	--	--	--	0.904**
Nester sandy loam	7.85	pH	5.15	5.21	5.53	5.85	6.18	6.40	6.58	6.73	7.00	--	--	
		Base Sat.(%)	38.3	42.7	48.2	51.2	52.8	59.5	65.0	74.1	82.3	--	--	0.959**
Plainfield loamy sand	6.08	pH	5.60	5.76	6.08	6.39	6.89	7.01	7.11	7.01	--	--	--	
		Base Sat.(%)	26.3	39.3	42.8	47.8	55.0	52.3	62.3	62.0	--	--	--	0.953**

[1]Correlation coefficients for the relationship between soil reaction and percent base saturation.
*Significant at the 1 percent level.
**Significant at the 5 percent level.

Table 4. The effect of type of clay mineral on percent base saturation.

Soil Type	Clay (%)	Organic Matter (%)	Cation Exch. Cap. (me./100g)	pH	Base Sat. (%)	Kaolinite (%*)	Illite (%*)	Montmorillonite (%*)	Vermiculite (%*)	Chlorite (%*)
Ontonagon clay	60	6.07	32.50	6.00	77.0	x	xx	xxx	xx	x
Iron River silt loam	14	4.55	20.25	6.00	46.0	xxxx	x	0	xx	x
Warsaw loam	18	2.80	16.62	6.00	56.0	xxx	xxx	0	xx	x
Munising sandy loam	9	3.16	14.25	6.00	36.9	xxxx	xx	0	x	x
Kalamazoo loam	13	3.72	12.25	6.00	61.0	xxx	x	0	xxxx	0
Pence sandy loam	7	2.19	11.25	6.00	44.0	xxx	x	0	xx	x
Montcalm sandy loam	7	1.87	8.83	6.00	40.3	xxxx	x	0	xx	x
Nester sandy loam	10	1.61	7.85	6.00	51.9	xxx	xx	0	xx	x
Plainfield loamy sand	6	0.89	6.08	6.00	42.0	xxxx	x	0	xx	xx

*Legend
x = 0-10 percent of total clay content
xx = 10-30 percent of total clay content
xxx = 30-50 percent of total clay content
xxxx = 50-70 percent of total clay content

These results confirm findings of Marshall (28) and Mehlich (32). They showed that bases, especially calcium, were adsorbed more strongly on 2:1 type clay minerals than on 1:1 type clay minerals. Consequently, percent base saturation at a given pH was considerably higher in montmorillonitic soils than in kaolinitic soils. The practical implication of these results is that at a given pH, calcium is more easily available to plants in kaolinitic soils than in montmorillonitic soils. Thus, montmorillonitic soils require more lime at a given pH, cation exchange capacity, and percent base saturation than kaolinitic soils to effect a sufficient release of calcium to plants. From the results discussed previously it may be concluded that soil pH alone and base saturation alone are inadequate criteria for predicting lime requirement of soils. However, a close relationship was found between exchangeable hydrogen, obtained by the difference between cation exchange capacity, and total base content of the soils, and lime requirement[1] as shown in Figure 1. Shimp (44) reported a similar relationship for 15 Michigan soils. These results indicate that exchangeable hydrogen is a good criterion for evaluating lime requirement of soils.

Soil Texture and Lime Requirement

It is commonly accepted that soil texture affects lime requirement of soils. In this experiment percent silt in soil and lime requirement were not correlated as shown in Figure 2. This result indicates that silt contributes relatively little to buffer capacity and lime requirement of soils. Percent clay in the soil was significantly

[1]Lime requirement used in correlation studies is the amount of lime needed to raise soil pH from an average pH of 5.5 to 6.8 as determined by incubating the nine soils for 13 weeks in the greenhouse.

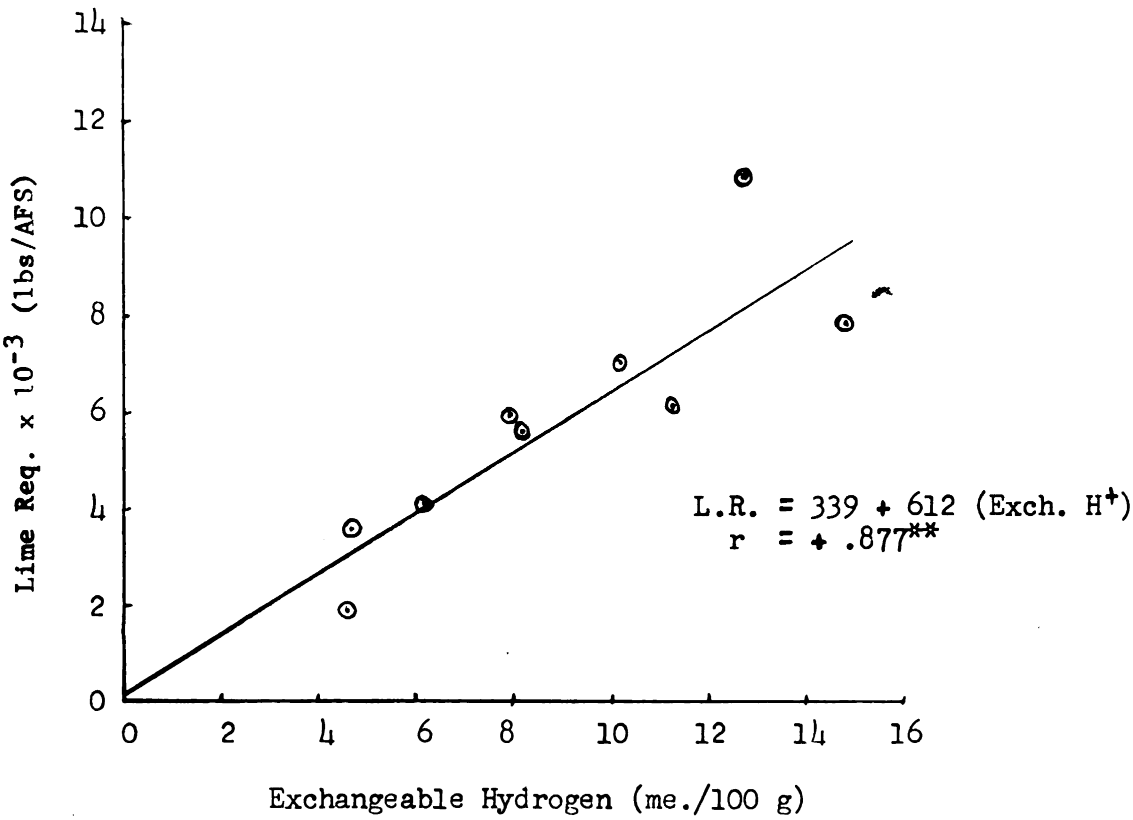


Figure 1. **Linear correlation between exchangeable hydrogen and lime requirement for nine Michigan soils.**

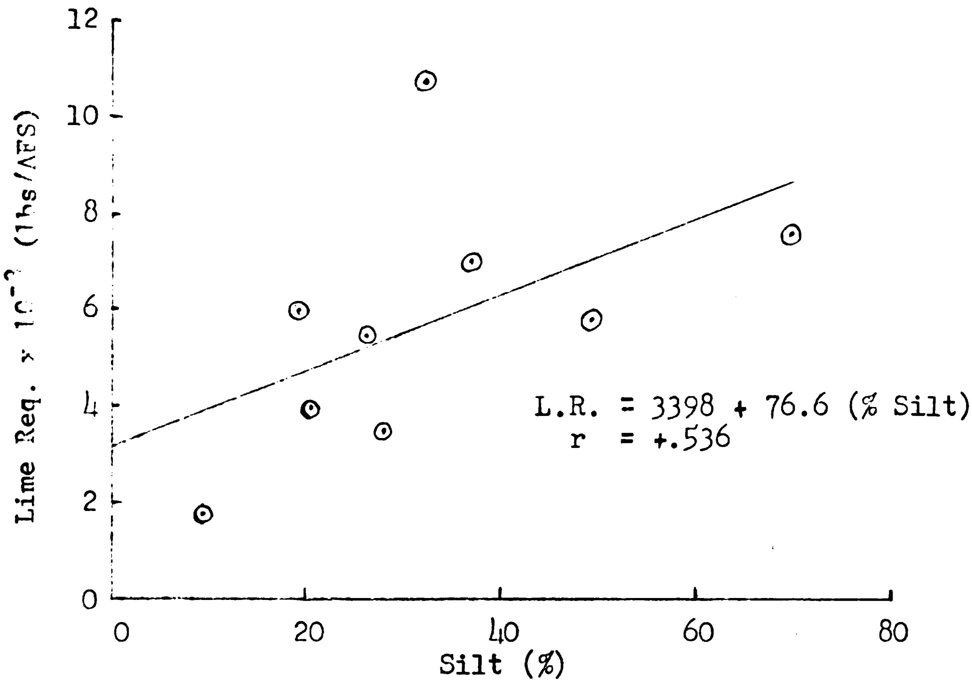


Figure 2. Linear correlation between percent silt and lime requirement of nine Michigan soils.

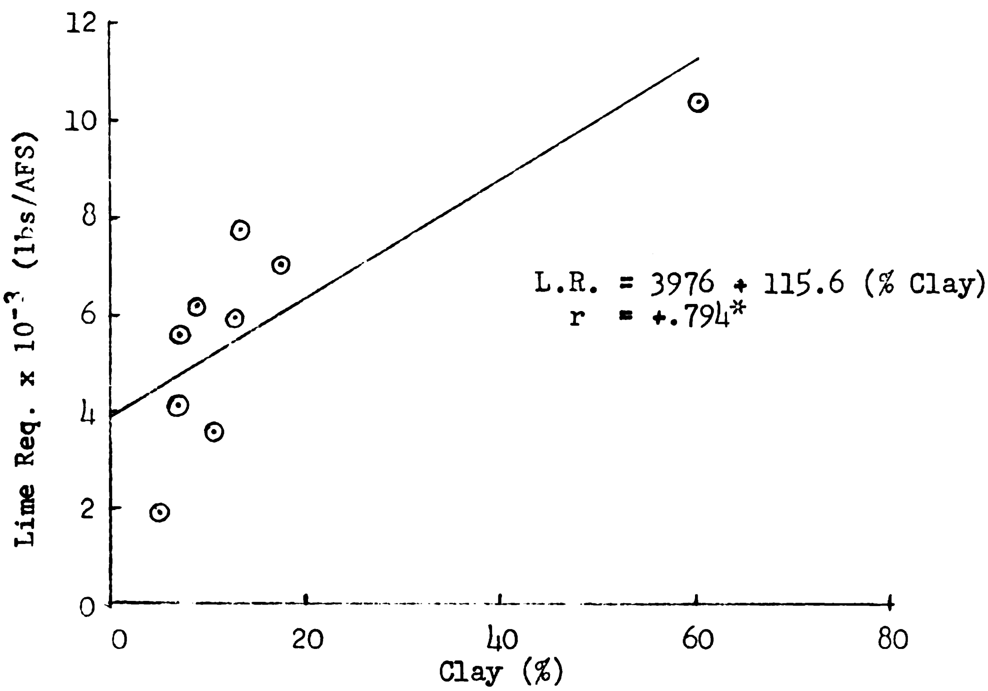


Figure 3. Linear correlation between percent clay and lime requirement of nine Michigan soils.

related to lime requirement as shown in Figure 3. Shimp (44), on 15 Michigan soils and Keeney, et al. (22), on 23 Wisconsin soils noted that clay content did not appear to be an important factor in lime requirement determination. However, it is easier to explain a good correlation between these two factors than to account for poor correlation because clay, as an important colloidal constituent in most soils, should contribute a significant share to the buffer capacity and lime requirement of acid soils.

Organic Matter and Lime Requirement

The important effect of organic matter on lime requirement is indicated in Figure 4. This result agrees with findings of other investigators (21, 22, 32, 34). Keeney, et al. (22) found that organic matter was significantly related to lime requirement and that a function of pH and organic matter interaction, (pH 6.5 - soil pH) x (% O.M.), was highly correlated with lime requirement. As is shown in Figure 5, this function is also highly correlated with the lime requirement of the Michigan soils studied in this investigation. The clay content of eight of the nine soils on which this equation was tested was below eighteen percent. In these soils, variations in buffer capacity are closely related to differences in organic matter content. This may account for the high correlation of the function of pH and organic matter interaction with lime requirement of these soils. It is questionable, however, whether this equation would hold true for soils having a relatively low organic matter content and high clay content. The equation may also give anomolous results in calculating lime requirement for very acid soils containing relatively large amounts

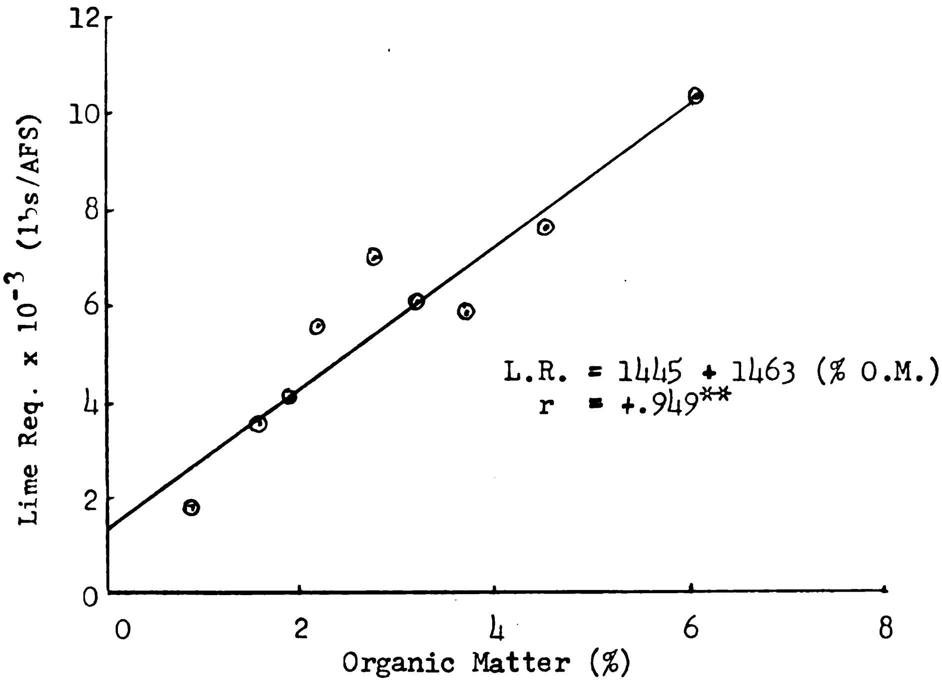


Figure 4. Linear correlation between percent organic matter and lime requirement for nine Michigan soils.

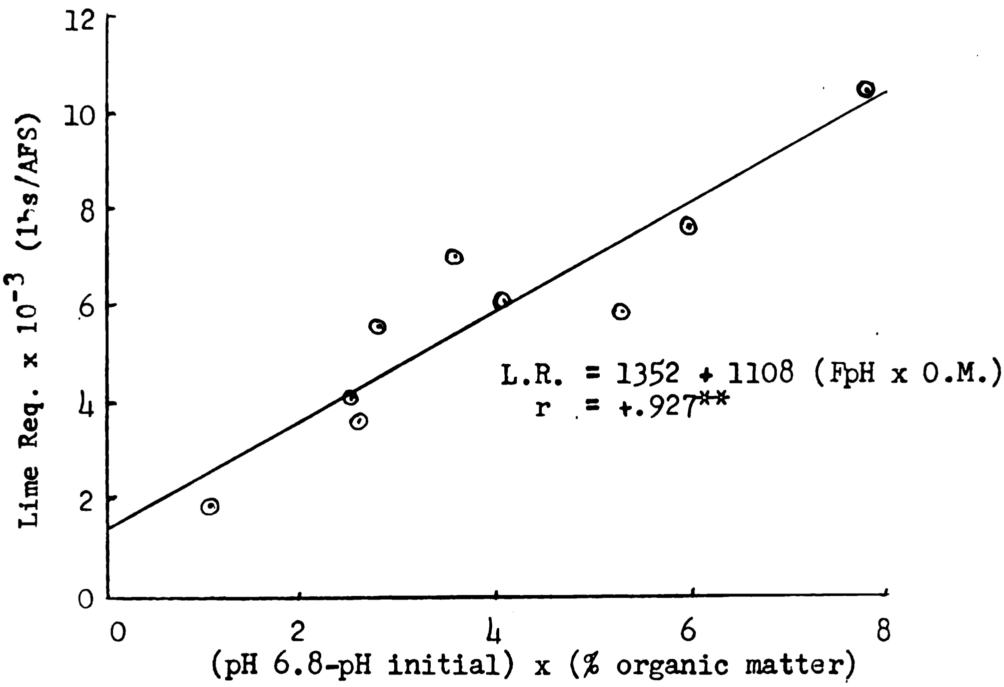


Figure 5. Linear correlation between a function of pH--organic matter interaction and lime requirement for nine Michigan soils.

of exchangeable aluminum.

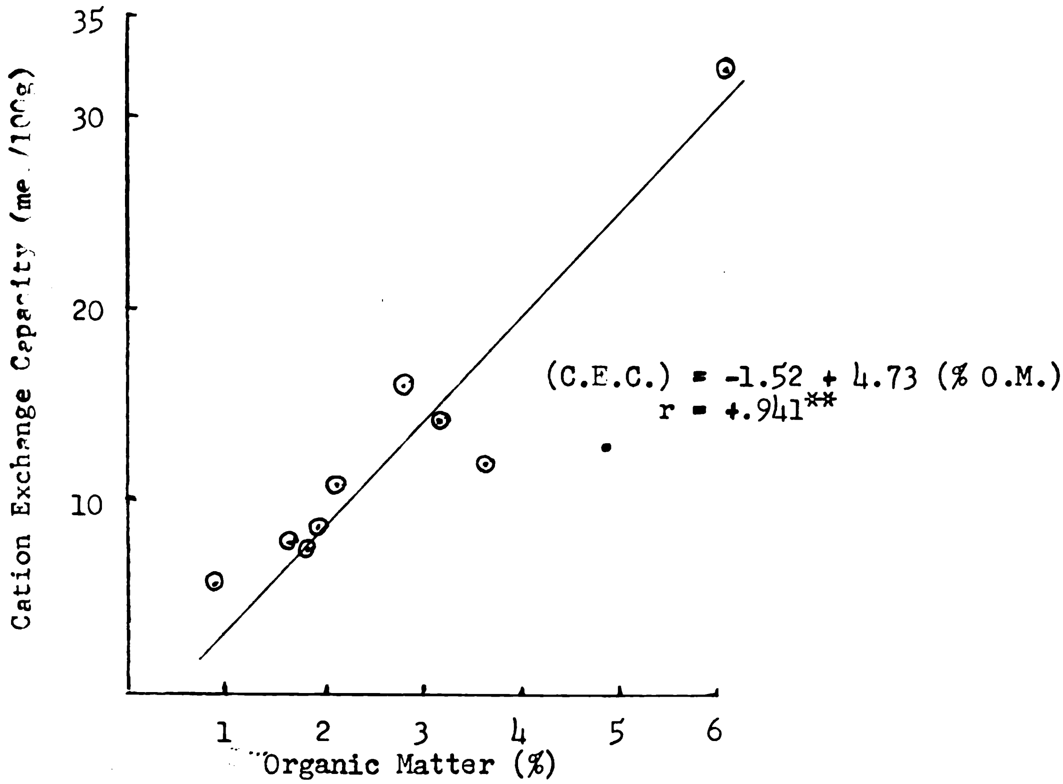
Organic Matter and Cation Exchange Capacity

The important effect of organic matter content on cation exchange capacity is illustrated in Figure 6. Similar results have been reported in the literature (21, 34, 48). Tedrow and Gillam (47) showed that in coarse- and medium-textured soils cation exchange capacity is mainly derived from organic matter, while in fine-textured soils the major proportion of cation exchange capacity is derived from clay. Clay content of eight of the nine soils studied in this investigation was below eighteen percent. Thus, the effect of organic matter on cation exchange capacity should be relatively large. This is confirmed in Figures 6 and 7, in which is shown that cation exchange capacity is less affected by variations in clay content than by variations in organic matter content.

Cation Exchange Capacity and Lime Requirement

Lime requirement was highly correlated with cation exchange capacity as illustrated in Figure 8. This is to be expected from the pronounced relationships between lime requirement and clay content, lime requirement and organic matter content, cation exchange capacity and organic matter content, and cation exchange capacity and clay content, which have previously been discussed. Except for variations in percent base saturation due to differences in types of clay, the reserve acidity of an acid soil is proportional to the cation exchange capacity. Since the major portion of lime reacts with the reserve acidity of a soil, lime requirement at a given pH increases with increasing reserve acidity

Figure 6. Linear correlation between organic matter content and cation exchange capacity for nine Michigan soils.



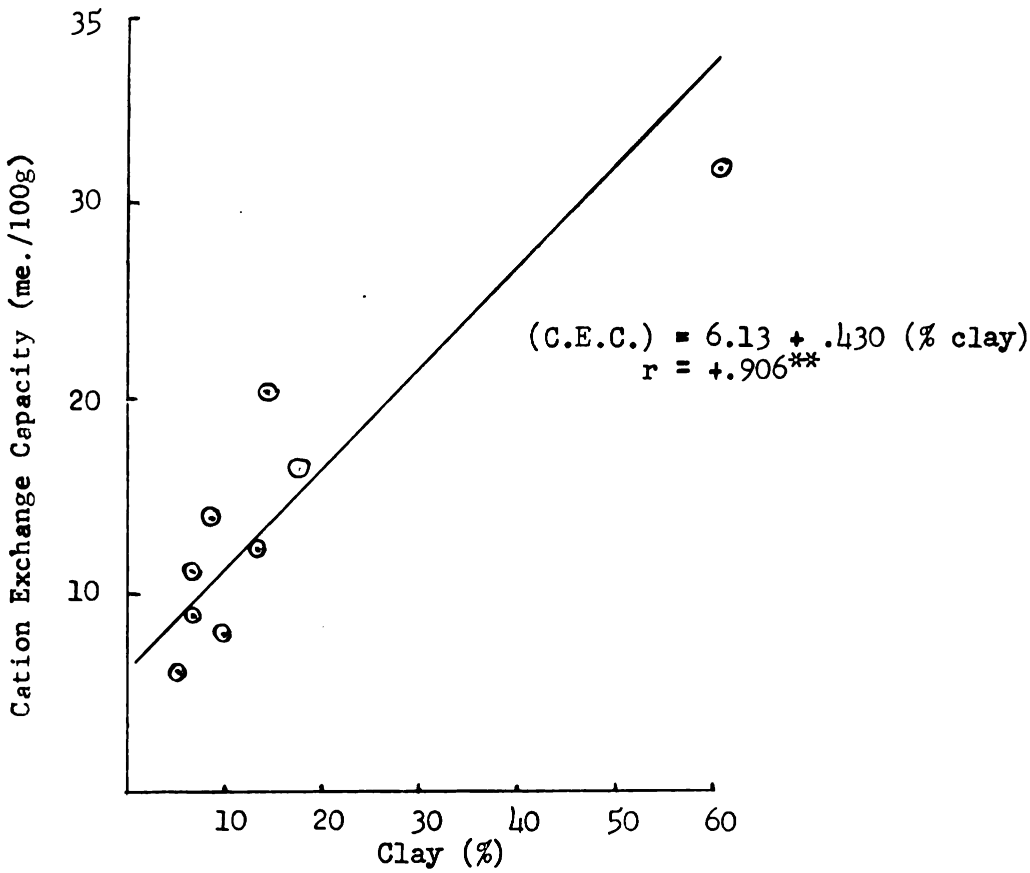


Figure 7. Linear correlation between clay content and cation exchange capacity for nine Michigan soils.

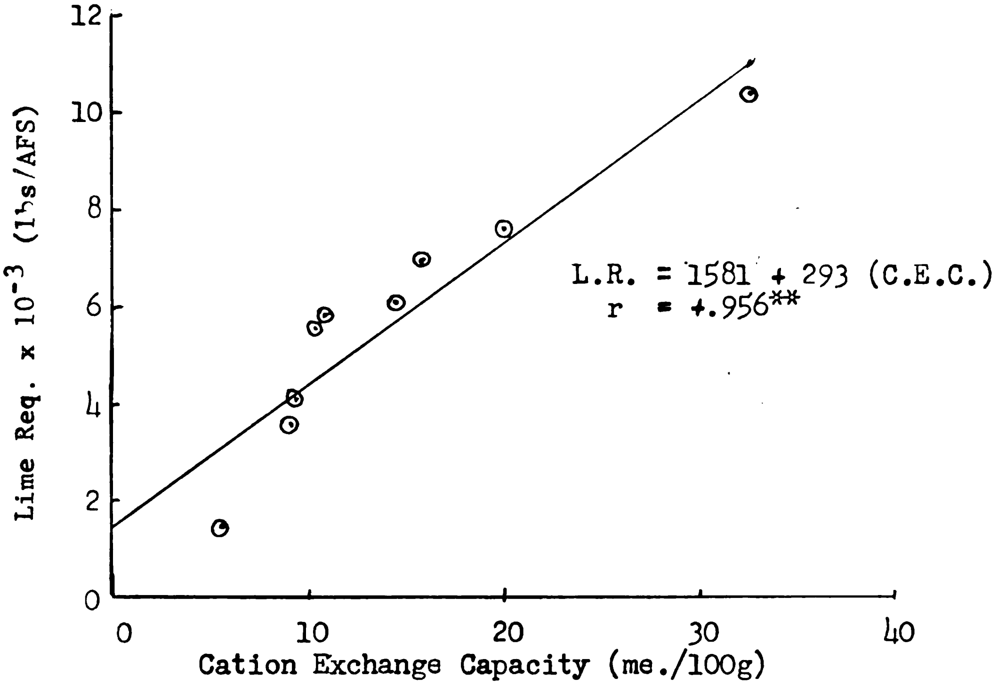


Figure 8. Linear correlation between cation exchange capacity and lime requirement for nine Michigan soils.

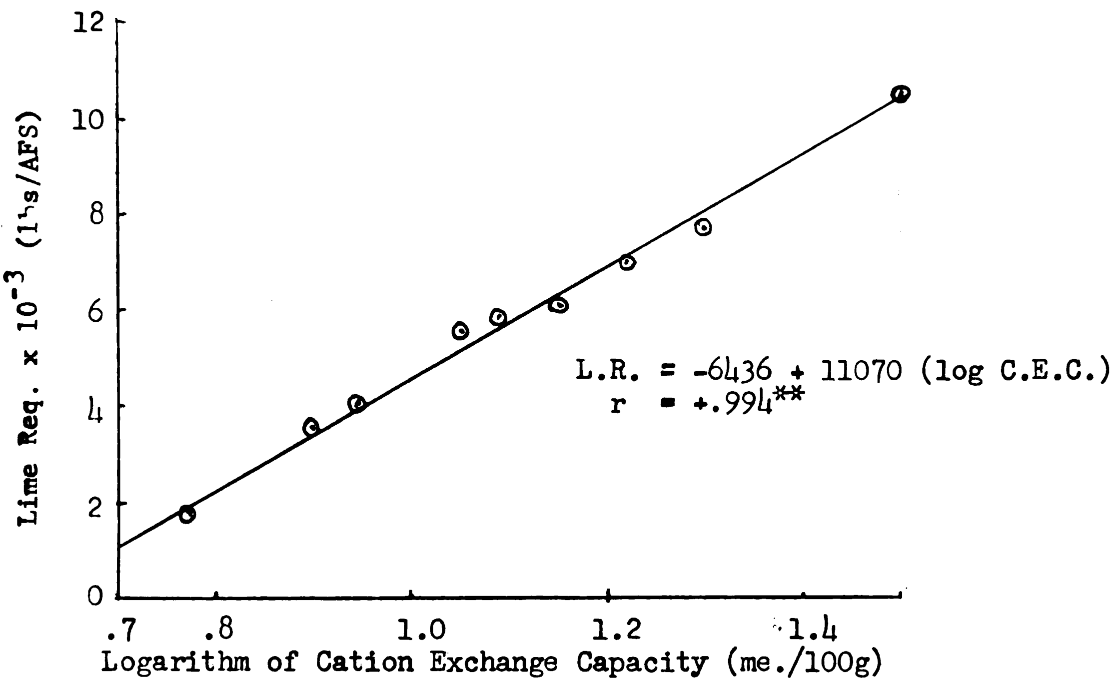


Figure 9. Linear correlation between the logarithm of cation exchange capacity and lime requirement for nine Michigan soils.

and cation exchange capacity. The plotting of lime requirement against cation exchange capacity suggested a correlation between lime requirement and the logarithm of cation exchange capacity. Plotting the data for these two factors resulted in a nearly perfect linear relationship, as shown in Figure 9. The graph indicates that increase in lime requirement is lowered with increasing cation exchange capacity. No reference to such a relationship is made in the literature, and it is difficult to explain. Additional experiments with a larger number of soils are necessary to discover whether or not such a relationship is valid.

Lime Requirement Determination by the Shoemaker, McLean, and Pratt Method

Lime requirement of the nine soils studied was also determined in the laboratory by using the Shoemaker, McLean, and Pratt (S.M.P.) buffer method. As shown in Figure 10, lime requirement determined in the greenhouse and lime requirement indicated by the S.M.P. buffer method were closely correlated. Shoemaker, *et al*. (45) and Keeney, *et al*. (22) obtained the same relationship in similar studies. Figure 10 also illustrates that less lime was required by incubating the soils in the greenhouse than was indicated by the S.M.P. method. The reason for this may be that S.M.P. lime recommendations are based on the use of coarser limestone than was used in this experiment. Furthermore, S.M.P. lime recommendations are suited to field conditions. Because reactions in soils in the greenhouse are generally more intensive than in the field, it is to be expected that S.M.P. lime recommendations are high for soils in the greenhouse.

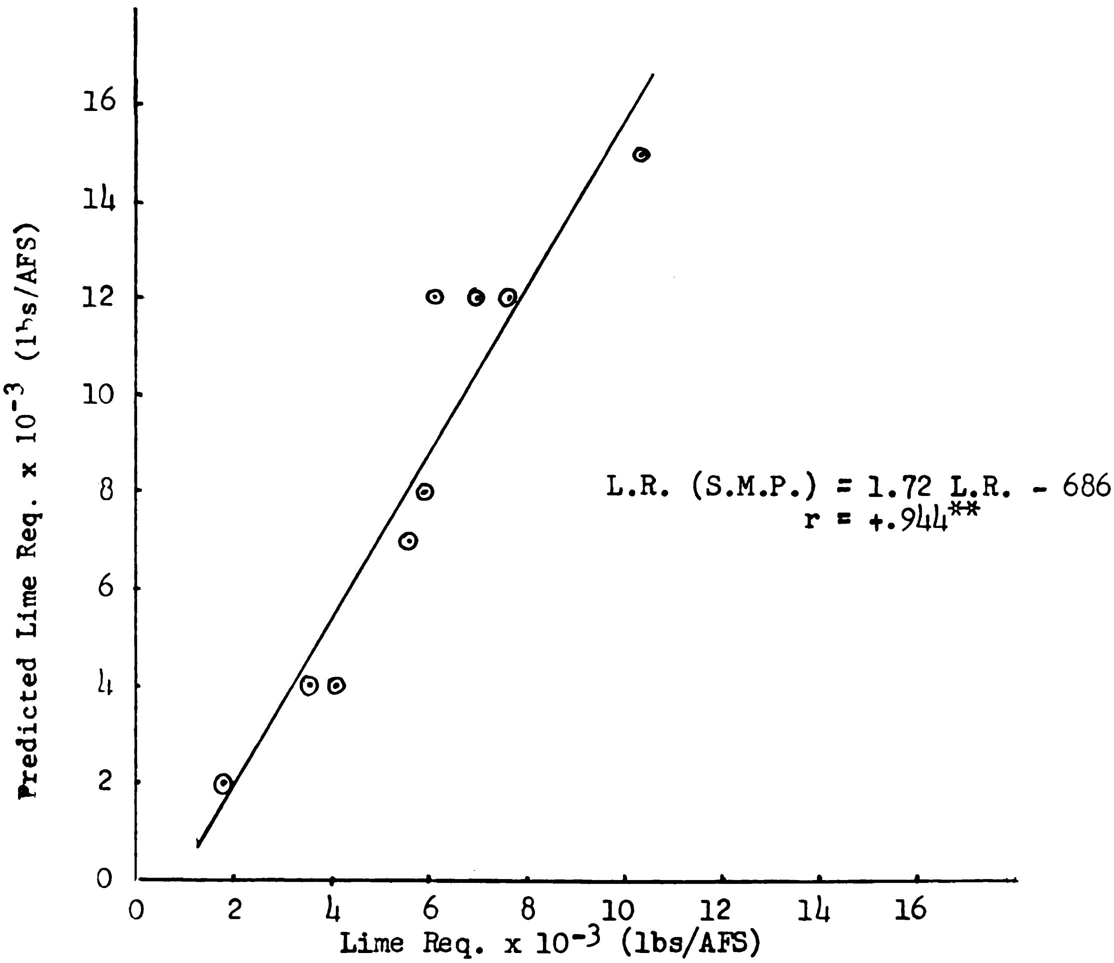


Figure 10. **Linear correlation between lime requirement and predicted lime requirement for nine Michigan soils.**

Effect of Liming on Plant Nutrients and Yield of Alfalfa

Table 5 contains the data for acid-fluoride extractable phosphorus, exchangeable calcium, magnesium and potassium as measured by soil test at given rates of lime. Exchangeable calcium in the soils increased consistently with increased rates of lime application. Exchangeable magnesium did not show this trend and remained relatively constant.

The data for the yield of alfalfa and its calcium, potassium, and phosphorus content and uptake are given in Tables 1 to 9 in the appendix. The data were statistically analyzed and grouped according to Duncan's multiple range method. Bar graphs representing the totals of each of the plant factors for three cuttings of alfalfa are included as Figures 11 to 18 in the discussion.

Calcium

The effect of lime additions on yield of alfalfa and its calcium uptake and content is shown in Figures 11, 12 and 13, respectively. Liming increased yield of alfalfa on eight of the nine soils studied. On the Ontonagon soil the check gave a higher yield than did the treatments of 1,000 and 2,000 pounds of lime per acre. The first increment of 1,000 pounds of lime per acre gave a large increase in yield on the Plainfield and Warsaw soils. Suzuki[1] found that the unlimed Plainfield and Warsaw soils at pH 5.60 and 5.50, respectively, were high in aluminum phosphate. These results suggest that the large increase in

[1]Suzuki, A., Lawton, K., and Doll, E. C. Phosphorus uptake and soil tests as related to forms of phosphorus in some Michigan soils. (Submitted to Soil Sci. Soc. Amer. Proc.)

Table 5. The effect of rate of application of lime on available phosphorus, exchangeable calcium, exchangeable magnesium, and exchangeable potassium of nine Michigan soils.

		Lime Applied (Pounds per Acre)				
Soil Type	Rate	0	500	1000	1500	2000
Ontonagon clay	pH	5.50	--	5.41	5.48	5.50
	Avail. P_2O_5	24	--	16	24	24
	Exch. Ca.	5550	--	5925	6075	6325
	Exch. Mg.	1200	--	1350	1500	1450
	Exch. K_2O	690	--	698	695	735
Iron River silt loam	pH	5.50	5.29	5.32	5.40	5.50
	Avail. P_2O_5	56	58	56	56	58
	Exch. Ca.	2050	2375	2450	2575	2725
	Exch. Mg.	75	175	130	150	130
	Exch. K_2O	123	123	118	113	123
Warsaw loam	pH	5.50	--	5.45	5.60	5.68
	Avail. P_2O_5	312	--	304	320	320
	Exch. Ca.	2050	--	2150	2366	2533
	Exch. Mg.	170	--	117	183	167
	Exch. K_2O	475	--	508	515	512
Munising sandy loam	pH	5.50	5.49	5.64	5.67	5.71
	Avail. P_2O_5	136	160	152	160	144
	Exch. Ca.	1017	1150	1467	1617	1617
	Exch. Mg.	33	50	80	83	67
	Exch. K_2O	243	246	227	262	250
Kalamazoo loam	pH	5.35	5.15	5.35	5.45	5.71
	Avail. P_2O_5	24	26	27	26	22
	Exch. Ca.	1467	1667	1766	1950	2016
	Exch. Mg.	33	50	80	83	67
	Exch. K_2O	243	246	227	262	250
Pence sandy loam	pH	5.50	5.45	5.70	5.80	5.91
	Avail. P_2O_5	88	96	104	112	104
	Exch. Ca.	1000	1250	1267	1400	1700
	Exch. Mg.	67	83	100	67	83
	Exch. K_2O	120	98	80	83	78
Montcalm sandy loam	pH	5.40	5.55	5.67	6.30	6.37
	Avail. P_2O_5	168	168	176	168	168
	Exch. Ca.	867	883	1117	1183	1317
	Exch. Mg.	80	133	87	83	83
	Exch. K_2O	150	163	162	157	153

Table 5. Continued.

Lime Applied (Pounds per Acre) 2500	3000	4000	5000	6000	7000	Correlation Coefficient[1]
5.53	5.74	5.87	5.94	6.09	6.22	
24	32	24	24	24	32	0.189
6600	6975	7050	7275	7525	7925	
1425	1500	1400	1400	1325	1225	
730	735	728	720	698	693	+0.079
5/59	5.65	6.00	--	--	--	
56	56	58	--	--	--	+0.244
2975	3100	3375	--	--	--	
125	125	175	--	--	--	
123	108	123	--	--	--	+0.060
5.75	5.85	6.25	6.42	6.52	--	
328	302	296	280	296	--	-0.718*
2750	2883	3200	3516	3616	--	
180	183	167	183	180	--	
523	525	528	527	523	--	+0.661
5.80	5.98	6.21	--	--	--	
144	152	144	--	--	--	-0.171
1766	1850	2016	--	--	--	
67	83	83	--	--	--	
238	228	246	--	--	--	+0.094
5.77	6.10	6.34	--	--	--	
24	24	26	--	--	--	-0.210
2433	1866	2733	--	--	--	
67	83	83	--	--	--	
238	228	246	--	--	--	-0.246
6.09	6.17	6.41	6.65	--	--	
112	104	96	88	--	--	-0.119
1866	2033	2166	2550	--	--	
50	100	67	50	--	--	
83	95	92	85	--	--	-0.406
6.42	6.55	6.78	--	--	--	
168	184	168	--	--	--	-0.142
1550	1650	2083	--	--	--	
83	83	80	--	--	--	
160	147	157	--	--	--	+0.371

[1]Correlation coefficients for the relationship between soil reaction and available phosphorus and between soil reaction and exchangeable potassium. Weights in pounds per acre.
*Significant at the 5 percent level.

Table 5. Continued

Soil Type	Rate	Lime Applied (Pounds per Acre) 0	500	1000	1500	2000
Nester sandy loam	pH	5.15	5.21	5.53	5.85	6.18
	Avail. P_2O_5	56	72	64	72	72
	Exch. Ca.	867	983	1150	1300	1350
	Exch. Mg.	133	133	133	100	100
	Exch. K_2O	178	177	173	173	165
Plainfield loamy sand	pH	5.60	5.76	6.08	6.39	6.89
	Avail. P_2O_5	128	117	114	120	122
	Exch. Ca.	467	767	851	1000	1183
	Exch. Mg.	83	83	83	67	67
	Exch. K_2O	70	100	98	102	90

Table 5. Continued.

Lime Applied (Pounds per Acre)						Correlation
2500	3000	4000	5000	6000	7000	Coefficient
6.40	6.58	6.73	7.00	--	--	
64	72	72	72	--	--	+0.524
1533	1700	2033	2300	--	--	
117	113	80	67	--	--	
153	160	163	163	--	--	-0.835**
7.01	7.11	7.01	--	--	--	
123	123	122	--	--	--	+0.130
1167	1333	1333	--	--	--	
33	80	83	--	--	--	
93	97	82	--	--	--	+0.200

**Significant at the 1 percent level.

Figures 11 and 12
Legend

1 Check
2 1000 pounds per acre of limestone
3 2000 pounds per acre of limestone
4 4000 pounds per acre of limestone

A Plainfield loamy sand
B Kalamazoo loam
C Pence sandy loam
D Montcalm sandy loam
E Munising sandy loam
F Nester sandy loam
G Warsaw loam
H Ontonagon clay
L Iron River silt loam

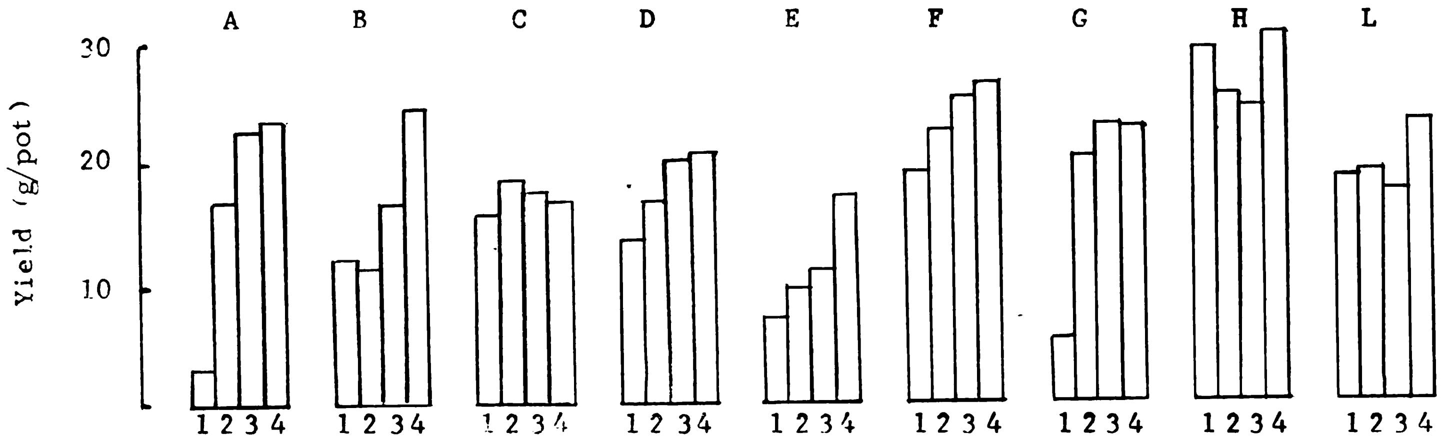


Figure 11. The effect of rate of application of lime on the total yield of three cuttings of alfalfa grown on nine Michigan soils.

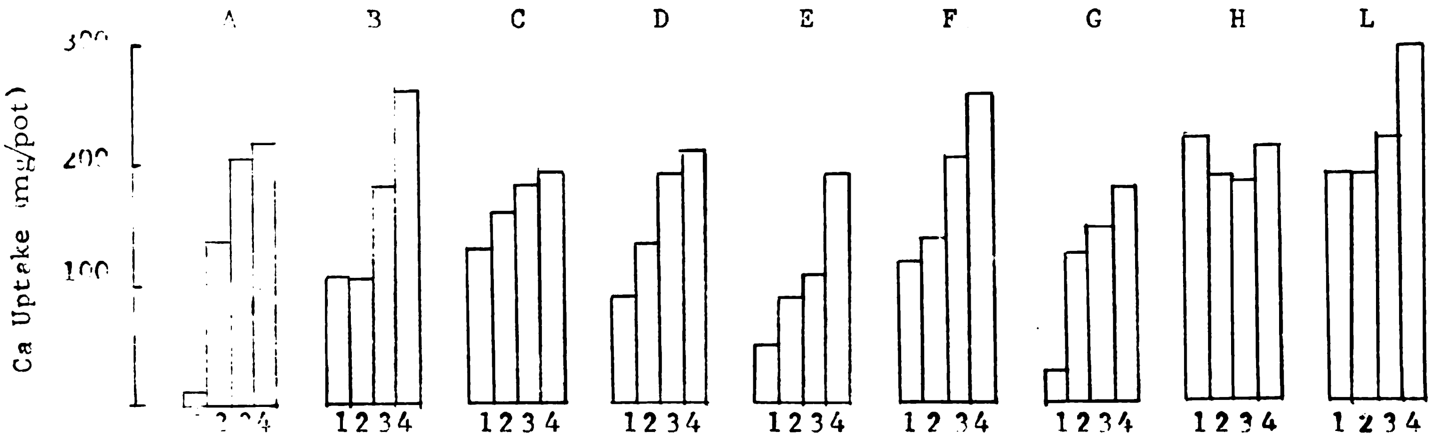


Figure 12. The effect of rate of application of lime on the total calcium uptake by two cuttings of alfalfa grown on nine Michigan soils.

Figures 13 and 14
Legend

1 Check
2 1000 pounds per acre of limestone
3 2000 pounds per acre of limestone
4 4000 pounds per acre of limestone

A Plainfield loamy sand
B Kalamazoo loam
C Pence sandy loam
D Montcalm sandy loam
E Munising sandy loam
F Nester sandy loam
G Warsaw loam
H Ontonagon clay
L Iron River silt loam

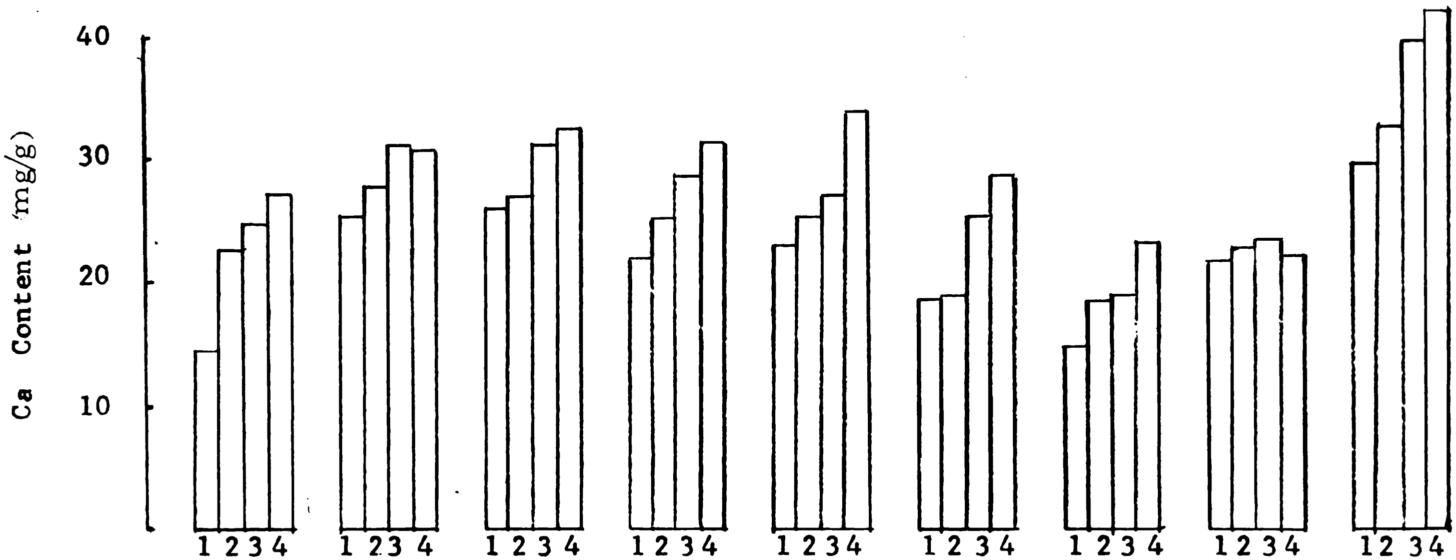


Figure 13. The effect of rate of application of lime on the calcium content of two cuttings of alfalfa grown on nine Michigan soils.

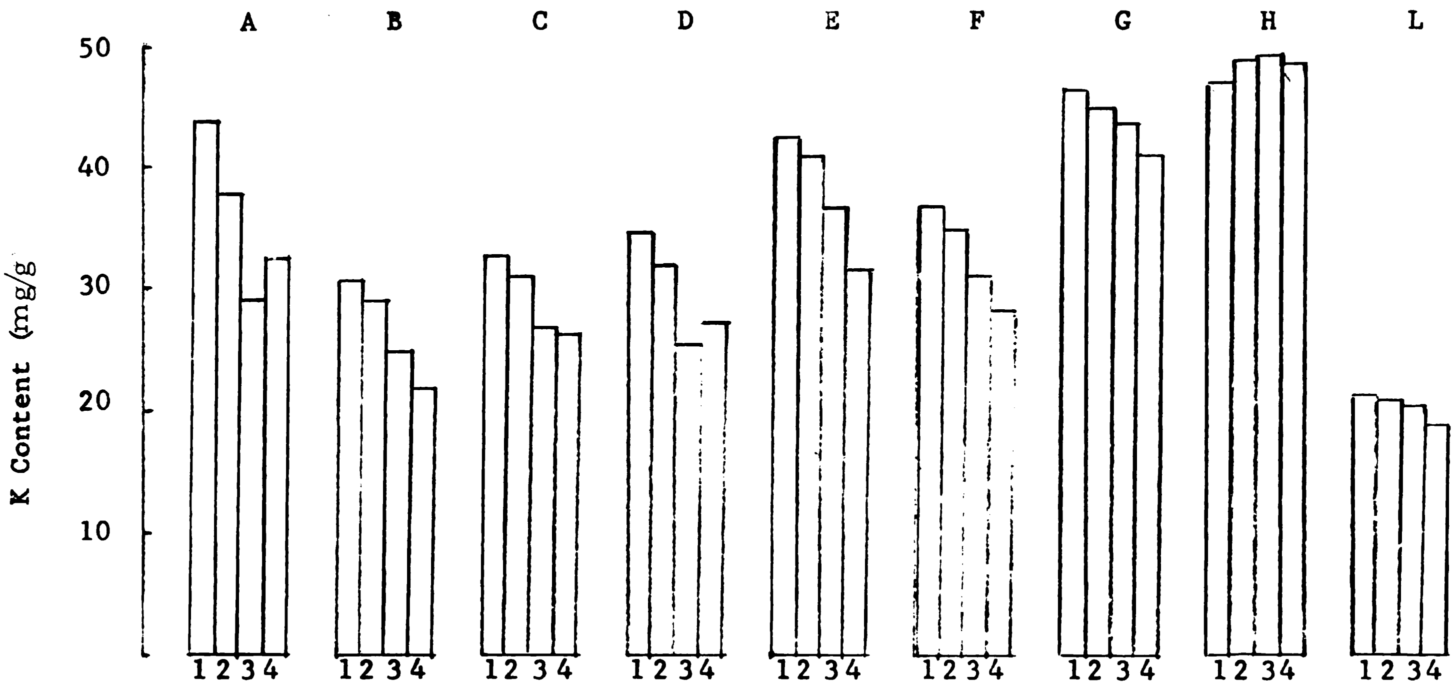


Figure 14. The effect of rate of application of lime on the potassium content of two cuttings of alfalfa grown on nine Michigan soils.

yield at a low rate of lime may be due to immobilization of toxic amounts of aluminum. The yields on the remaining soils show a more gradual increase with successive increments of lime. Figure 11 also points out that pH alone is a poor indicator of yield response of alfalfa to lime. For example, the checks of Ontonagon, Nester, and Iron River soils with pH 5.50, 5.15, and 5.50, respectively, produced more than four times the yield than did the checks of Plainfield and Warsaw soils with pH 5.60 and 5.50, respectively. However, lime applied at a rate of 1,000 pounds per acre increased the yield on the Plainfield and Warsaw soils eight and four times, respectively; at 1,000 pounds of lime per acre little or no increase in yield was apparent on the Ontonagon, Nester, and Iron River soils.

The effect of liming on calcium uptake and calcium content of alfalfa is given in Figures 12 and 13, respectively. A comparison of Figures 11, 12 and 13 indicates that within each soil type, increased lime applications generally coincided with increased yield, calcium content, and calcium uptake. On the Ontonagon soil, the yield, calcium content and uptake of calcium by alfalfa was not appreciably increased with increased rates of lime. This soil contained 60 percent clay and had a base saturation of 60 percent. Therefore, the Ontonagon soil initially contained a relatively large amount of calcium. This may account for the lack of response of yield, calcium content, and calcium uptake to additions of lime on the Ontonagon soil.

Potassium

The data in Table 5 show that exchangeable potassium in the soil decreased significantly with addition of lime to Nester sandy loam. Addition of lime did not produce a significant change in exchangeable potassium in the other eight soils studied. According to Wiklander (52) decreased availability of potassium may be due to a strong adsorption of potassium on the colloidal complex of a limed soil. In such a soil calcium ions replace aluminum and hydrogen ions to a greater or lesser extent. Adsorption of potassium is favored by this replacement since calcium ions are less strongly adsorbed than hydrogen and aluminum ions. On the other hand, potassium ions may become more available due to increased activity and replacing power of hydrogen ions which yielded their exchange sites to calcium ions. The rate of each of these two opposing reactions determines whether availability of potassium will be increased, decreased, or unaffected in a limed soil. This hypothesis explains the insignificant effect of liming on eight of the nine soils and the decrease in availability of potassium on the Nester soil. However, the decrease in amount of exchangeable potassium in the Nester soil is relatively small (approximately eight percent) and may be within limits of experimental error.

Although liming did not appreciably affect the amount of exchangeable potassium in the soil, potassium content in the plants decreased with additions of lime on nearly all soils as shown in Figure 14. A comparison of Figures 13 and 14 shows that calcium content varied inversely with potassium content. It may be seen from Figure 16 that the sum of calcium and potassium contents in the plants is relatively constant for all soils and lime treatments. These results agree with those of several investigators (8, 14, 18, 19), who

Figures 15 and 16
Legend

1 Check
2 1000 pounds per acre of limestone
3 2000 pounds per acre of limestone
4 4000 pounds per acre of limestone

A Plainfield loamy sand
B Kalamazoo loam
C Pence sandy loam
D Montcalm sandy loam
E Munising sandy loam
F Nester sandy loam
G Warsaw loam
H Ontonagon clay
L Iron River silt loam

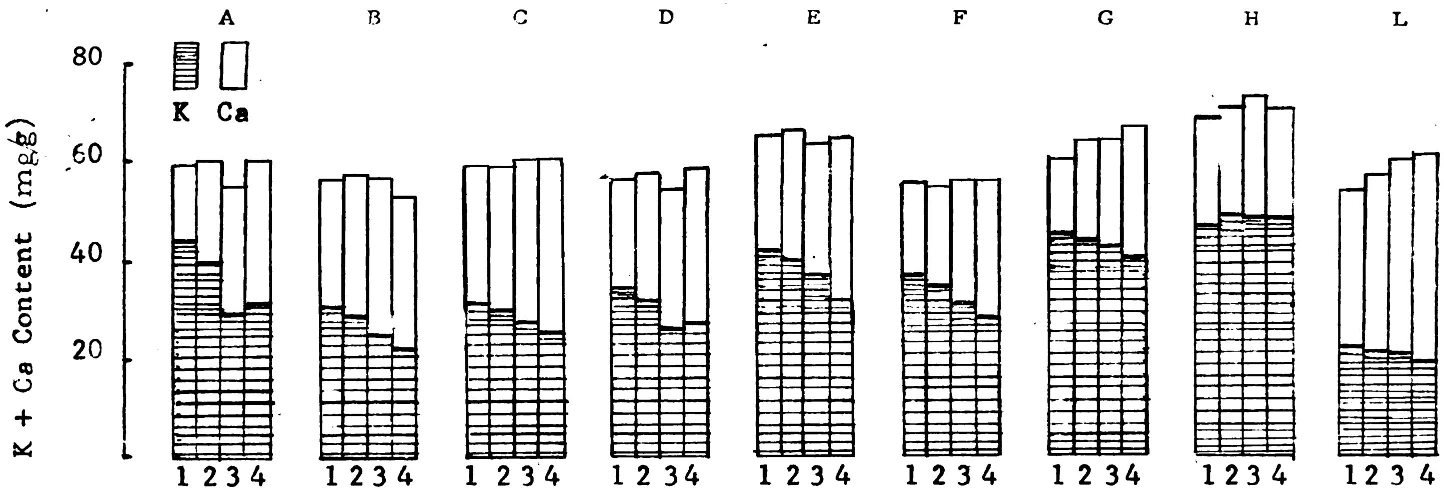


Figure 16. The effect of rate of application of lime on the potassium and calcium content of two cuttings of alfalfa grown on nine Michigan soils.

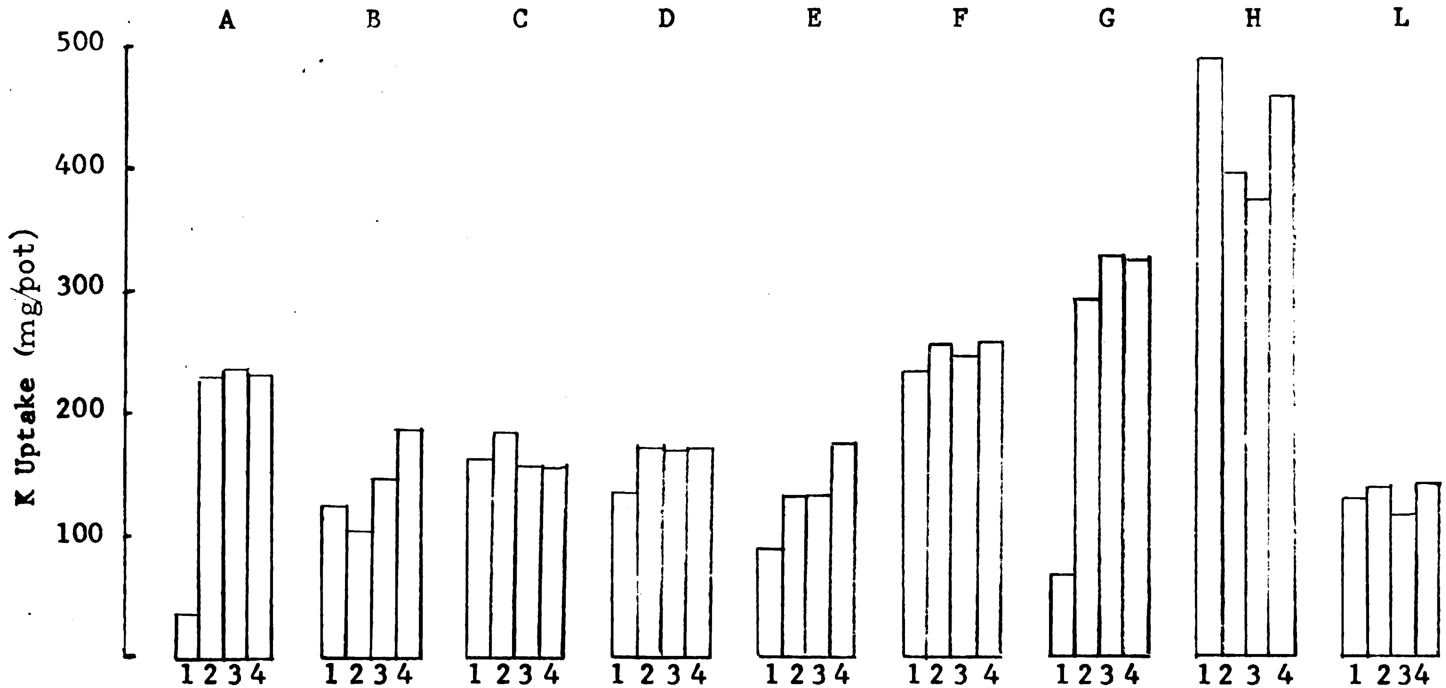


Figure 15. The effect of rate of application of lime on the total potassium uptake by two cuttings of alfalfa grown on nine Michigan soils.

found that when the concentration of calcium relative to that of potassium is low the calcium actually favors potassium absorption by the plants. When the calcium is materially increased the potassium absorption is depressed. Jacobson, et al. (18) studied hydrogen-calcium interaction in relation to potassium absorption by excised barley roots in solution. They explained the stimulating effect of calcium on potassium absorption at a low pH by postulating that the presence of calcium in solution creates a barrier probably at the cell surface which prevents hydrogen ions from interfering with potassium absorption. Cation constancy in plants and the inverse relationship between potassium and calcium uptake have been explained as being due to the controlling role of potassium in effecting electrical neutrality in the plants[1].

The uptake of potassium is shown in Figure 15. In nearly all cases liming increased the amount of potassium taken up by the plants, primarily because of increase in yield of alfalfa.

Phosphorus

As shown in Table 5, liming significantly affected phosphorus availability in the Warsaw soil only. Suzuki[2] found that this soil was high in aluminum phosphate as determined by extraction with 0.5 N NH_4F. He found high positive correlations between amount of aluminum phosphate present in the soil and amount of phosphorus extracted by Bray's acid-fluoride extracting solution. Because the Warsaw soil used in Suzuki's

---

[1] Hendricks, Sterling B. U.S.D.A., Beltsville, Maryland. Personal communication.

[2] Suzuki, A., Lawton, K., and Doll, E. C. Phosphorus uptake and soil tests as related to forms of phosphorus in some Michigan soils. (Submitted to Soil Sci. Soc. Amer. Proc.)

and in this experiment came from the same location, his results may explain the decrease in Bray's acid-fluoride extractable phosphorus at increased pH levels in this experiment since Bray's phosphorus test appears to measure a considerable proportion of aluminum phosphates and aluminum compounds become more immobile at increased pH values.

The decrease of available Bray's phosphorus in Warsaw loam upon addition of lime was reflected in a corresponding decrease in phosphorus content of alfalfa grown on this soil. Liming also decreased phosphorus content of alfalfa on the Munising and Ontonagon soils as shown in Figure 17. Liming increased the uptake of phosphorus in eight of the nine soils studied, primarily because of increased yields of alfalfa as shown in Figure 18. These results agree with those reported by Dunn (12). He grew alfalfa on Washington soils in the greenhouse and found that on some soils phosphorus content of alfalfa was decreased by liming. However, uptake of phosphorus by alfalfa was increased by liming on all soils used in his study.

Figures 17 and 18
Legend

1 Check
2 1000 pounds per acre of limestone
3 2000 pounds per acre of limestone
4 4000 pounds per acre of limestone

A Plainfield loamy sand
B Kalamazoo loam
C Pence sandy loam
D Montcalm sandy loam
E Munising sandy loam
F Nester sandy loam
G Warsaw loam
H Ontonagon clay
L Iron River silt loam

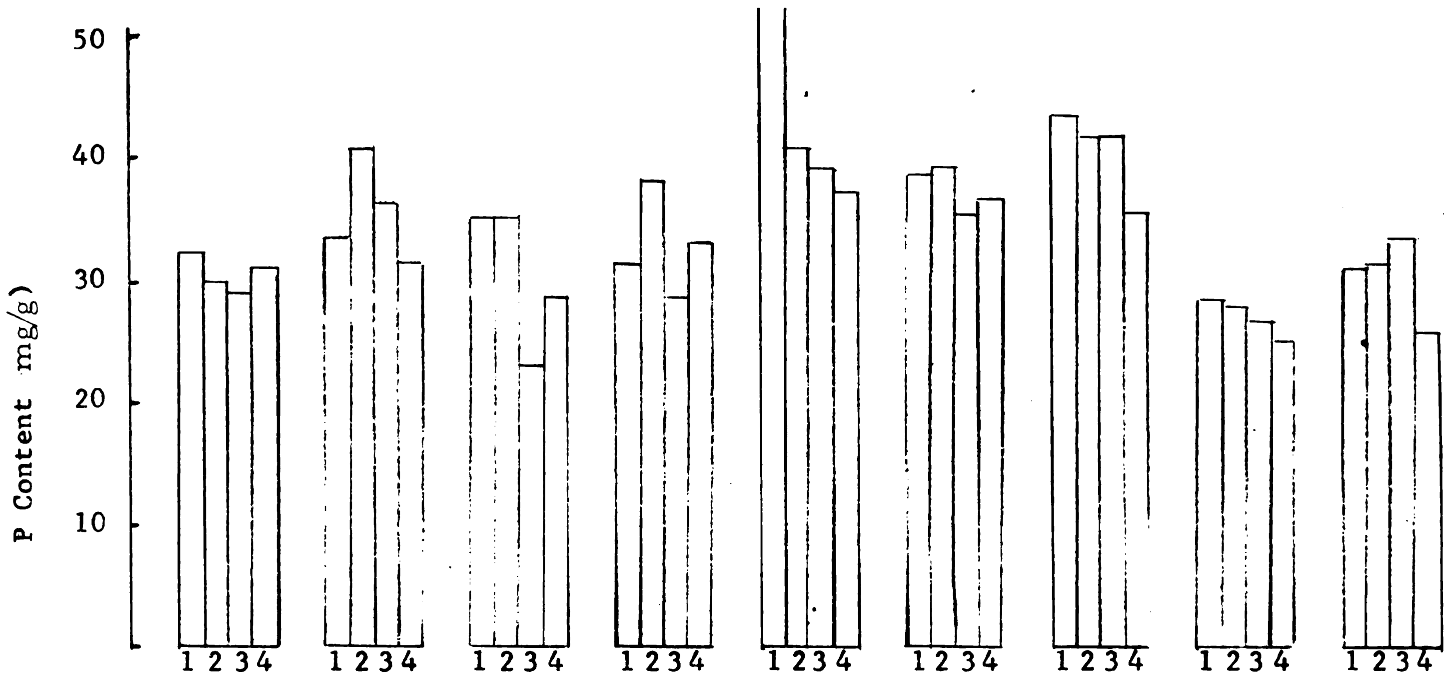


Figure 17. The effect of rate of application of lime on the phosphorus content of two cuttings of alfalfa grown on nine Michigan soils.

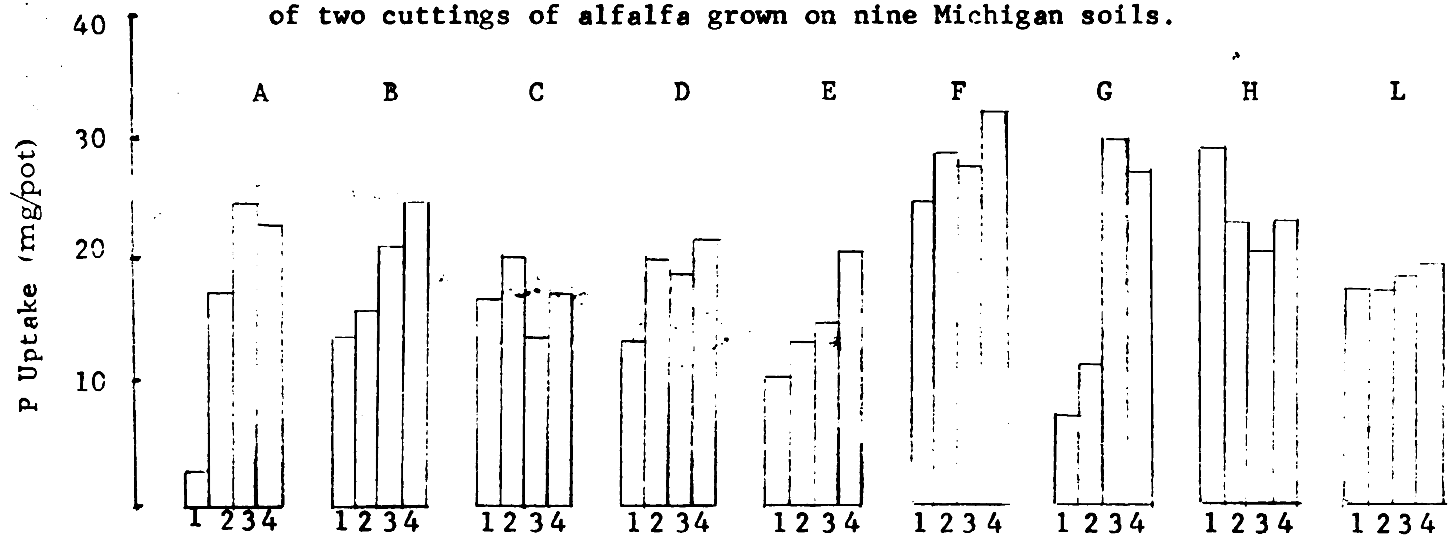


Figure 18. The effect of rate of application of lime on the total phosphorus uptake by two cuttings of alfalfa grown on nine Michigan soils.

SUMMARY AND CONCLUSIONS

Liming studies were conducted in the greenhouse on nine Michigan soils. The initial pH of all soils was close to 5.50. Different rates of lime were added to the soils which were then incubated for 13 weeks in the greenhouse. At the end of the incubation period alfalfa was planted and three cuttings harvested. Results of mechanical and chemical soil analyses were studied and correlations calculated to determine the effect of different soil factors on lime requirement. The effect of liming on availability of plant nutrients in the soils and on response of alfalfa was also studied. Yield, calcium, potassium, and phosphorus content and uptake were measured and statistically analyzed.

The results of this experiment are summarized as follows:

1. Neither soil reaction nor percent base saturation alone indicated lime requirement of the soils or response of alfalfa to liming.
2. Variation in soil pH was related to variation in percent base saturation within each soil type. This relationship was not found between different soil types.
3. Exchangeable hydrogen, clay content, organic matter content, and a function of pH-organic matter interaction, (pH 6.8 - soil pH) x (% O.M.) were closely correlated with lime requirement. Silt content was not related to lime requirement.
4. Organic matter content and clay content were significantly related to cation exchange capacity. The

effect of organic matter content on cation exchange capacity was more pronounced than the effect of clay content on cation exchange capacity.

5. Cation exchange capacity was very closely related to lime requirement. Cation exchange capacity, which is a function of the colloidal properties of clay and organic matter, was more highly correlated with lime requirement than were either clay content or organic matter content. A nearly perfect correlation was obtained between the logarithm of cation exchange capacity and lime requirement.
6. Lime requirement indicated by the Shoemaker, McLean and Pratt method and lime requirement determined by incubating the soils for 13 weeks in the greenhouse were closely correlated.
7. Liming increased the yield of alfalfa significantly on nearly all soils. On Plainfield sandy loam and Warsaw loam a rate of 1000 pounds of lime per acre was sufficient to increase yield of alfalfa from a negligible quantity on the checks to approximately 70 percent of the maximum yield obtained from each soil.
8. Increase in calcium uptake and calcium content of alfalfa was directly proportional to increase in yield and lime applied.
9. Potassium content of alfalfa decreased with increased calcium content at successive increments of lime. Uptake of potassium increased with additions of lime

primarily because of increased yields of alfalfa.

10. Liming enhanced total phosphorus uptake by alfalfa. However, phosphorus content of alfalfa decreased on three soils with addition of lime, and was not significantly changed on the remaining six soils.

From the results of this study it may be concluded that soil reaction alone and percent base saturation alone are inadequate criteria for evaluating lime requirement of soils. Response of yield of alfalfa to liming may vary with different soil types at the same pH and cannot be predicted from soil pH only.

The results of this study point out that the soil factors, other than pH, which are most important in indicating lime requirement are cation exchange capacity, organic matter content, exchangeable hydrogen, and clay content, arranged in order of decreasing importance. Soil reaction in conjunction with these soil factors should give an accurate indication of lime requirement. Because most of these factors are related to soil type, lime requirement determinations based on soil reaction and soil type should lead to more accurate lime recommendations.

Results of this study also indicate that soil factors besides pH play a role in governing response of alfalfa to liming. The scope of this study does not permit making any definite conclusions but indications are that at a low pH amounts of exchangeable calcium and aluminum in the soil are important in determining whether or not alfalfa will respond to liming. More study is needed to determine the importance of these factors on different soil types.

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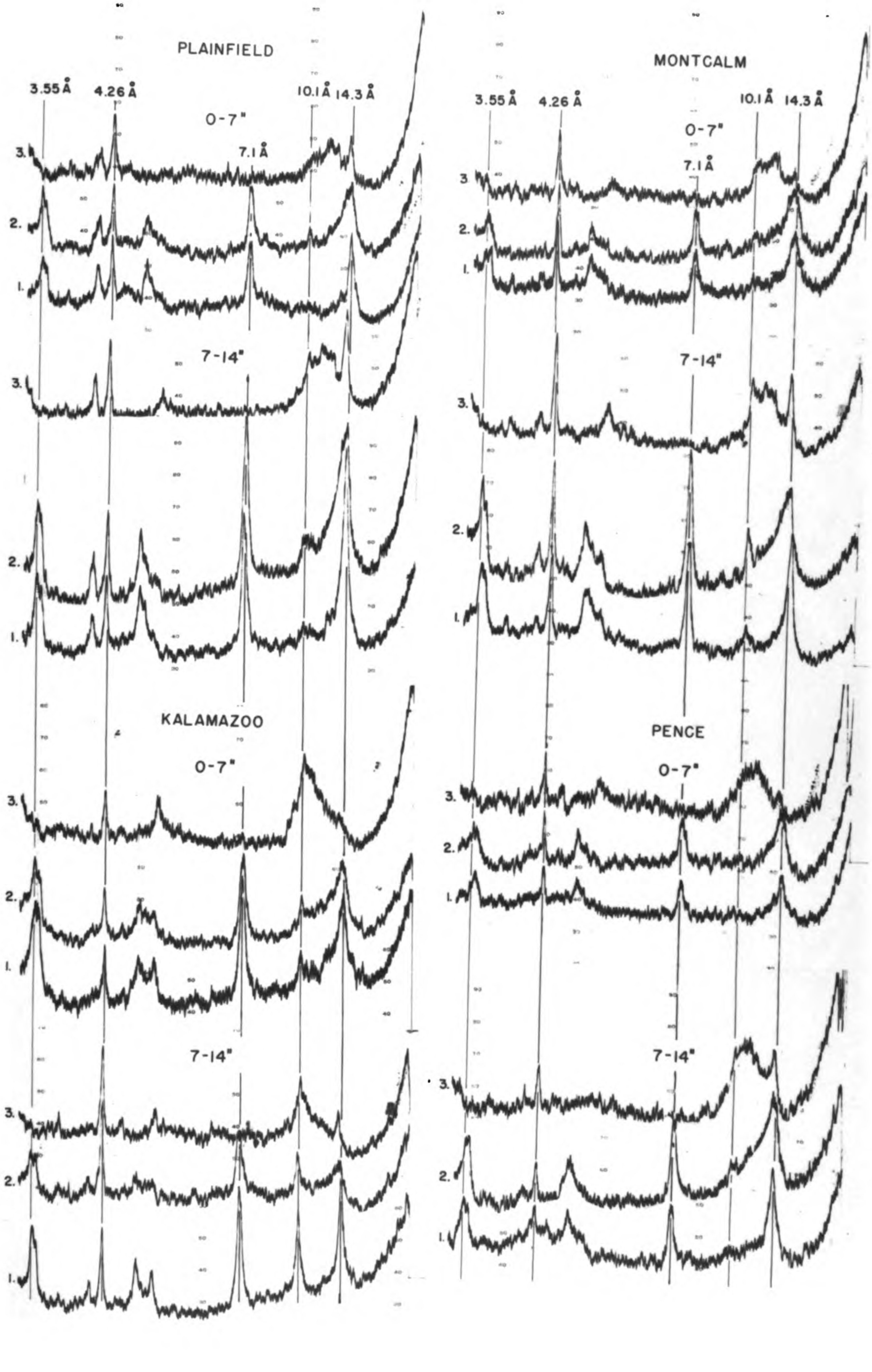
Figure 1. X-ray diffraction patterns of the $<2\mu$ fractions of surface and subsoil samples of Plainfield loamy sand, Kalamazoo loam, Montcalm sandy loam, and Pence sandy loam.

Patterns No. 1 Correspond to Mg^{++} and glycerol saturated samples.

Patterns No. 2 Correspond to samples which were K^{+} saturated and heated to 110° C.

Patterns No. 3 Correspond to samples which were K^{+} saturated and heated to 550° C.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PENCE

Figure 2. X-ray diffraction patterns of the $<2\mu$ fractions of surface and subsoil samples of Munising sandy loam, Ontonagon clay, Nester sandy loam, and Warsaw loam.

Patterns No. 1 Correspond to Mg^{++} and glycerol saturated samples.

Patterns No. 2 Correspond to samples which were K^{+} saturated and heated to 110° C.

Patterns No. 3 Correspond to samples which were K^{+} saturated and heated to 550° C.

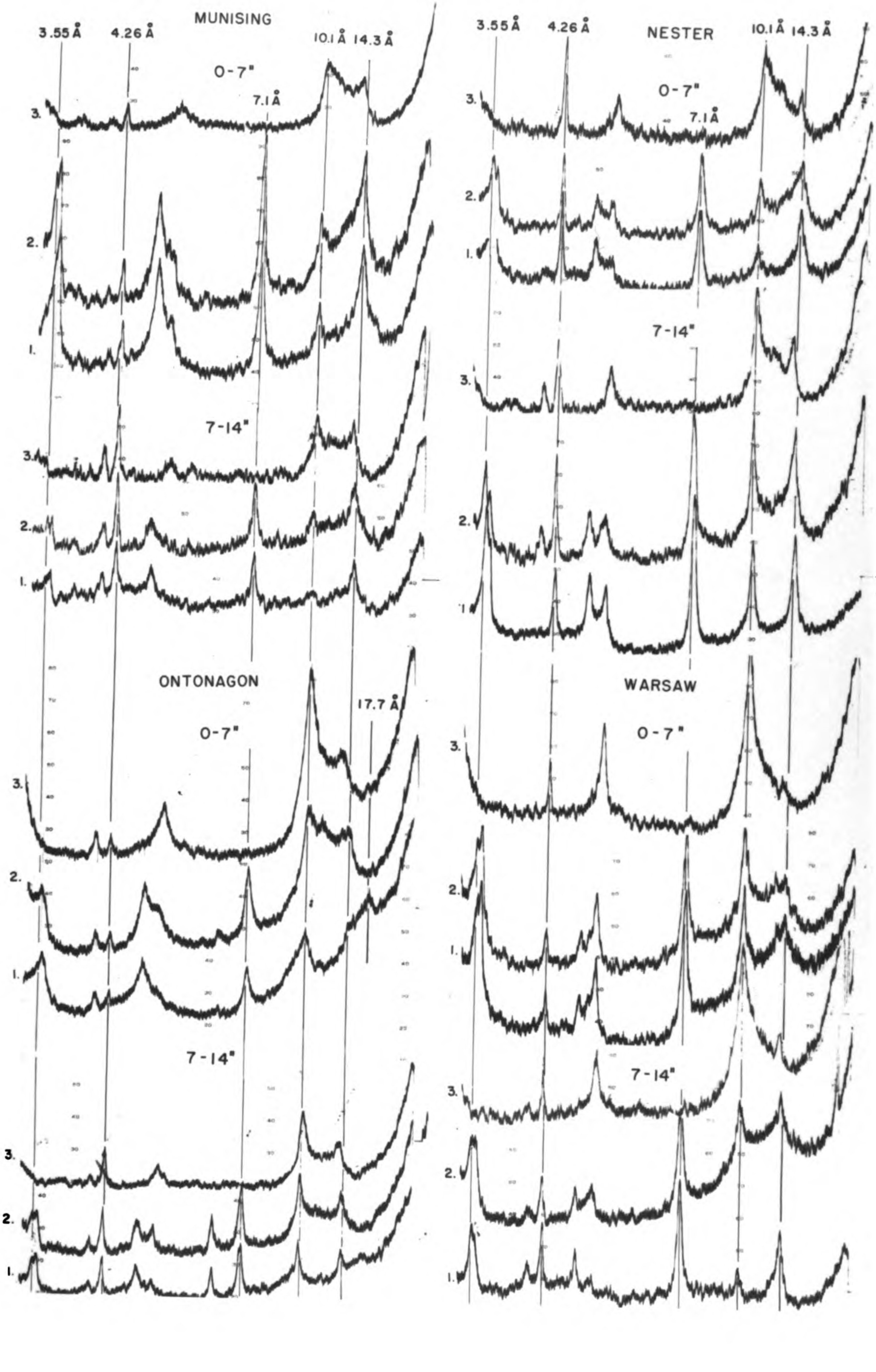
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Figure 3. X-ray diffraction patterns of the $<2\mu$ fractions of surface and subsoil samples of Iron River silt loam.

Patterns No. 1 Correspond to Mg^{++} and glycerol saturated samples.

Patterns No. 2 Correspond to samples which were K^{+} saturated and heated to 110° C.

Patterns No. 3 Correspond to samples which were K^{+} saturated and heated to 550° C.

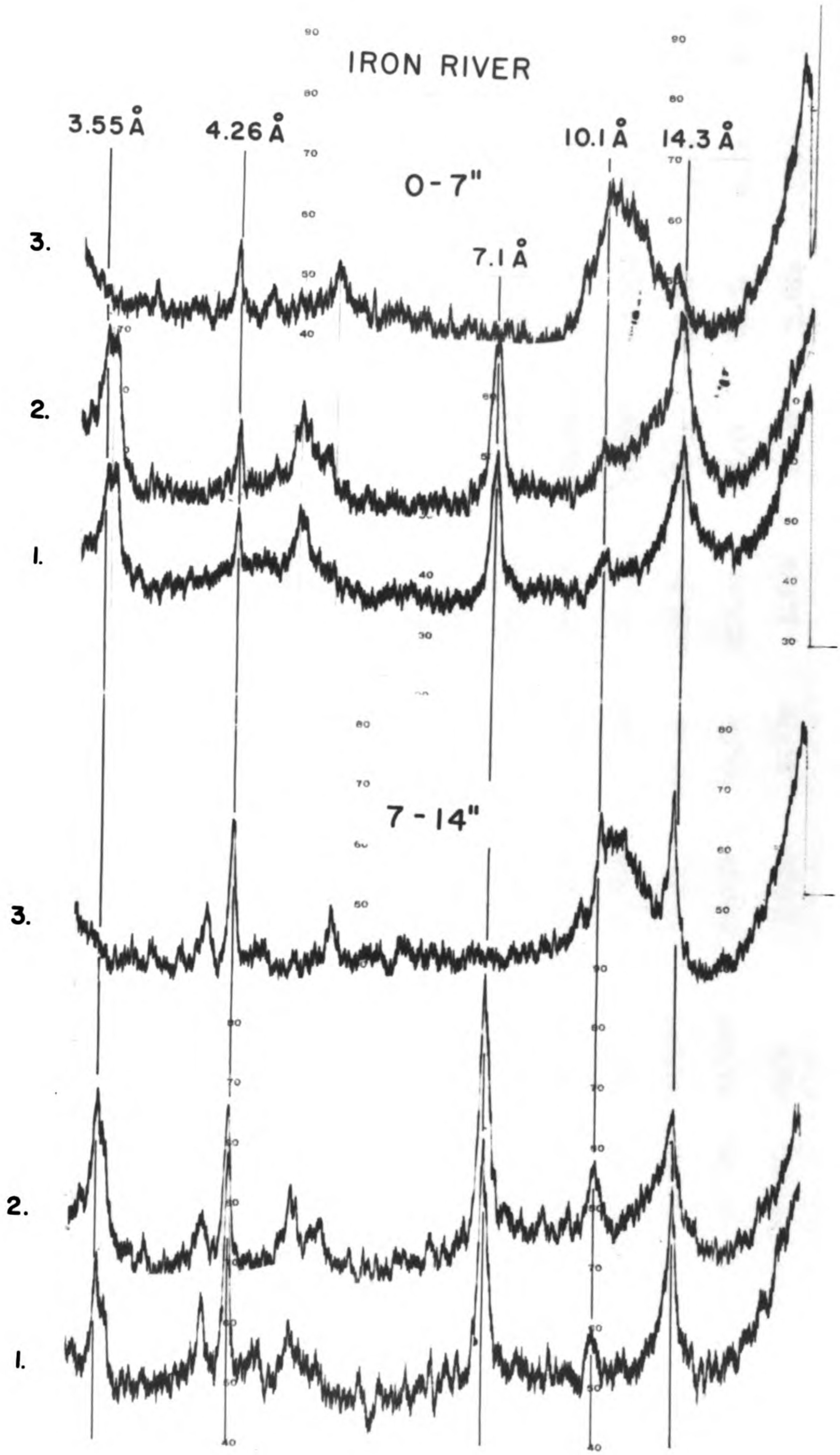
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Table 1. The effect of rate of application of lime on yield, content of calcium, potassium, and phosphorus of alfalfa and uptake of calcium, potassium, and phosphorus by alfalfa grown on a Plainfield loamy sand.

Parameters Measured			Rate of Lime (Pounds per Acre)						
			0	1000	1500	2000	2500	3000	4000
pH of soil at planting time			5.60	6.08	6.39	6.89	7.01	7.11	7.01
Yield	first cutting	g/pot	1.15d	6.99c	7.17bc	8.88ab	8.27abc	8.05abc	8.68a
Yield	second cutting	g/pot	0.48c	5.11b	6.64ab	7.17a	6.51ab	7.80a	7.21a
Yield	third cutting	g/pot	0.86c	4.61b	6.30a	6.40ab	6.63a	7.53a	7.85a
Ca content	first cutting	mg/g	7.70d	10.69c	11.36c	11.96bc	11.46c	14.00a	13.76ab
Ca content	second cutting	mg/g	6.57b	12.00a	12.03a	13.23a	14.46a	14.46a	13.96a
Ca uptake	first cutting	mg/pot	8.7e	75.9d	81.6cd	106.7ab	94.8bc	112.8ab	118.1a
Ca uptake	second cutting	mg/pot	3.1d	62.7c	82.9bc	95.7ab	94.0ab	113.1a	100.8ab
K content	first cutting	mg/g	22.77a	20.30b	20.13b	16.63c	17.93c	17.76c	17.29c
K content	second cutting	mg/g	21.60a	17.60b	16.16bc	12.60d	12.60d	12.19d	11.53d
K uptake	first cutting	mg/pot	26.3b	140.4a	142.8a	147.4a	148.0a	133.1a	149.7a
K uptake	second cutting	mg/pot	10.42b	88.5a	103.6a	89.1a	81.7a	94.2a	83.0a
P content	first cutting	mg/g	1.13b	1.87a	1.67a	1.43a	1.60a	1.67a	1.57a
P content	second cutting	mg/g	2.10a	1.12b	1.37ab	1.50ab	1.50ab	1.83a	1.60ab
P uptake	first cutting	mg/pot	1.24d	11.31bc	10.05c	14.14ab	12.59bc	16.70a	11.75bc
P uptake	second cutting	mg/pot	1.01d	5.86c	8.99b	10.55b	9.74b	14.00a	11.23ab

Table 2. The effect of rate of application of lime on yield, content of calcium, potassium, and phosphorus of Alfalfa and uptake of calcium, potassium, and phosphorus by alfalfa grown on a Kalamazoo loam soil.

Parameters Measured			Rate of Lime (Pounds per Acre						
			0	1000	1500	2000	2500	3000	4000
pH of soil at planting time			5.35	5.32	5.45	5.71	5.77	6.10	6.34
Yield	first cutting	g/pot	6.11bc	5.21c	5.17c	6.50bc	6.72bc	7.42ab	8.56a
Yield	second cutting	g/pot	2.06d	2.14d	3.14bcd	4.98bc	4.39bc	6.55ab	8.34a
Yield	third cutting	g/pot	3.83c	4.35c	4.27c	4.77abc	4.78abc	5.63ab	7.54a
Ca content	first cutting	mg/g	13.49b	14.43ab	15.83a	15.56a	14.36ab	15.43a	15.66a
Ca content	second cutting	mg/g	12.3b	13.6a	15.3a	16.0a	14.6a	16.6a	15.4a
Ca uptake	first cutting	mg/pot	82.3cde	75.4e	81.7de	101.2bc	96.9bcd	114.5ab	134.0a
Ca uptake	second cutting	mg/pot	23.8e	29.5e	48.1de	79.7bc	65.6cd	107.2ab	127.7a
K content	first cutting	mg/g	14.87b	14.53c	13.83d	13.36e	15.10a	12.86f	12.43g
K content	second cutting	mg/g	15.99a	14.93ab	13.33bc	11.83cd	11.87cd	10.27d	9.67d
K uptake	first cutting	mg/pot	91.0a	75.1a	71.5a	86.7a	101.0a	95.2a	106.2a
K uptake	second cutting	mg/pot	31.9a	31.4a	36.9a	59.0a	50.6a	66.8a	80.0a
P content	first cutting	mg/g	1.43c	2.07a	1.97ab	2.03a	1.93ab	1.57abc	1.50bc
P content	second cutting	mg/g	1.97ab	2.06a	1.63abc	1.60abc	1.97ab	1.20c	1.47c
P uptake	first cutting	mg/pot	9.86a	10.87a	10.42a	12.87a	12.84a	10.84a	12.84a
P uptake	second cutting	mg/pot	3.94e	4.60de	4.96cde	8.06bc	8.41b	7.69bcd	11.80a

Table 3. The effect of rate of application of lime on yield, content of calcium, potassium, and phosphorus of alfalfa and uptake of calcium, potassium, and phosphorus by alfalfa grown on a Pence sandy loam soil.

Parameters Measured			Rate of Lime (Pounds per Acre)						
			0	1000	1500	2000	2500	3000	4000
pH of soil at planting time			5.50	5.70	5.80	5.91	6.09	6.17	6.41
Yield	first cutting	g/pot	6.25a	6.17a	5.87a	6.49a	6.86a	7.36a	6.52a
Yield	second cutting	g/pot	3.98b	5.47ab	4.89ab	5.01ab	6.40a	5.64ab	5.24ab
Yield	third cutting	g/pot	5.75ab	6.73ab	5.69ab	5.78ab	7.43a	6.20ab	5.16b
Ca content	first cutting	mg/g	13.67c	14.10bc	16.57a	16.53a	15.63ab	15.27abc	16.63a
Ca content	second cutting	mg/g	12.50c	13.20bc	12.87c	15.07abc	16.93a	15.57abc	16.20ab
Ca uptake	first cutting	mg/pot	83.9b	87.1b	97.1ab	106.5a	106.6a	112.3a	107.8a
Ca uptake	second cutting	mg/pot	45.9c	72.7b	63.2bc	75.4b	107.3a	87.3ab	84.6ab
K content	first cutting	mg/g	15.27d	17.10a	16.03b	15.27d	15.03e	15.20d	15.73c
K content	second cutting	mg/g	17.50a	14.00b	13.86b	11.67bc	11.27c	10.60c	10.67c
K uptake	first cutting	mg/pot	96.1a	105.9a	97.0a	98.8a	103.0a	111.2a	101.6a
K uptake	second cutting	mg/pot	65.4a	75.4a	67.7a	57.3a	71.1a	59.1a	55.6a
P content	first cutting	mg/g	1.47a	1.83a	1.63a	1.33a	1.37a	1.46a	1.43a
P content	second cutting	mg/g	2.10a	1.73ab	1.50bc	0.97c	1.30bc	1.10c	1.47bc
P uptake	first cutting	mg/pot	9.20a	11.20a	9.78a	8.41a	9.35a	10.75a	9.50a
P uptake	second cutting	mg/pot	7.09a	8.91a	7.32a	4.87b	7.73a	5.96a	7.52a

Table 4. The effect of rate of application of lime on yield, content of calcium, potassium, and phosphorus of alfalfa and uptake of calcium, potassium, and phosphorus by alfalfa grown on a Montcalm sandy loam soil.

Parameters Measured			Rate of Lime (Pounds per Acre)						
			0	1000	1500	2000	2500	3000	4000
pH of soil at planting time			5.40	5.67	6.30	6.37	6.42	6.55	6.78
Yield	first cutting	g/pot	5.19b	5.84ab	6.04ab	7.00a	7.41a	7.05a	6.56ab
Yield	second cutting	g/pot	2.80b	4.60a	5.52a	6.03a	5.81a	5.96a	6.53a
Yield	third cutting	g/pot	5.92a	5.76a	5.82a	6.98a	6.73a	6.14a	7.09a
Ca content	first cutting	mg/g	11.80b	14.07a	14.80a	14.63a	14.03a	15.17a	15.97a
Ca content	second cutting	mg/g	10.27c	11.40c	11.83bc	14.20ab	13.83ab	14.67ab	15.90a
Ca uptake	first cutting	mg/pot	60.3c	82.3bc	89.5ab	102.2a	104.1a	106.9a	104.7a
Ca uptake	second cutting	mg/pot	29.1d	52.2cd	64.7bc	85.6ab	80.3ab	87.5ab	103.2a
K content	first cutting	mg/g	16.67bc	18.43a	17.60ab	15.17c	14.50d	15.43c	15.53c
K content	second cutting	mg/g	17.93a	13.77b	11.67bc	10.43c	10.93c	10.60c	11.00c
K uptake	first cutting	mg/pot	85.9a	107.5a	105.9a	106.1a	107.5a	108.5a	101.4a
K uptake	second cutting	mg/pot	51.1a	65.0a	64.0a	62.9a	63.4a	63.0a	72.2a
P content	first cutting	mg/g	1.60a	2.03a	1.80a	1.63a	1.60a	1.73a	1.93a
P content	second cutting	mg/g	1.60abc	1.80ab	1.27c	1.20c	1.89a	1.37abc	1.43abc
P uptake	first cutting	mg/pot	8.31b	11.97ab	10.82ab	11.41ab	12.01ab	12.25a	12.53a
P uptake	second cutting	mg/pot	4.55c	8.13ab	7.00b	6.94b	10.97a	7.83ab	9.39ab

Table 5. The effect of rate of application of lime on yield, content of calcium, potassium and phosphorus on alfalfa and uptake of calcium, potassium, and phosphorus by alfalfa grown on a Munising sandy loam soil.

Parameters Measured			Rate of Lime (Pounds per Acre)						
			0	1000	1500	2000	2500	3000	4000
pH of soil at planting time			5.50	5.64	5.67	5.71	5.80	5.98	6.21
Yield	first cutting	g/pot	3.38b	3.62b	4.18b	3.84b	4.06b	4.17b	6.27a
Yield	second cutting	g/pot	0.63c	2.85b	3.91ab	3.34ab	3.35ab	3.61ab	4.92a
Yield	third cutting	g/pot	3.13b	3.48b	5.07ab	3.56b	4.24ab	5.11ab	6.03a
Ca content	first cutting	mg/g	11.57b	15.97a	14.40a	15.70a	15.47a	15.87a	15.70a
Ca content	second cutting	mg/g	11.37b	9.63b	11.03b	11.83b	11.73b	12.77b	18.50a
Ca uptake	first cutting	mg/pot	39.0c	57.7b	59.3b	60.2b	63.1b	65.7b	98.2a
Ca uptake	second cutting	mg/pot	7.2c	27.5bc	43.9b	43.8b	39.2b	47.2b	90.4a
K content	first cutting	mg/g	22.50a	20.00bc	22.70a	20.66b	19.00c	19.66bc	18.66c
K content	second cutting	mg/g	19.83ab	21.10a	16.83c	15.67c	16.20c	17.77bc	12.33d
K uptake	first cutting	mg/pot	75.5b	72.5b	95.3ab	79.3b	76.7b	82.0b	115.9a
K uptake	second cutting	mg/pot	11.6a	58.9a	65.6a	52.1a	53.8a	62.1a	60.4a
P content	first cutting	mg/g	2.43ab	2.10abc	1.97bc	2.30abc	2.13abc	2.57a	1.80c
P content	second cutting	mg/g	2.83a	2.00a	1.70a	1.63a	1.53a	1.70a	1.90a
P uptake	first cutting	mg/pot	8.37a	7.74a	8.09a	8.79a	8.87a	10.99a	11.02a
P uptake	second cutting	mg/pot	1.79d	5.42b	6.71a	5.48b	5.18b	5.99b	9.45a

Table 6. The effect of rate of application of lime on yield, content of calcium, potassium, and phosphorus of alfalfa and uptake of calcium, potassium, and phosphorus by alfalfa grown on a Nester sandy loam soil.

Parameters Measured			Rate of Lime (Pounds per Acre)						
			0	1000	1500	2000	2500	3000	4000
pH of soil at planting time			5.15	5.53	5.85	6.18	6.40	6.58	6.73
Yield	first cutting	g/pot	6.81c	8.29bc	9.04ab	8.48b	8.26bc	7.92bc	10.49a
Yield	second cutting	g/pot	6.13a	6.26a	7.08a	7.28a	6.99a	7.67a	7.46a
Yield	third cutting	g/pot	6.23b	7.71b	8.74a	9.73a	9.23a	8.24a	8.33a
Ca content	first cutting	mg/g	9.90c	9.09c	10.20c	12.93b	14.13ab	14.97a	13.73ab
Ca content	second cutting	mg/g	8.67c	9.93bc	12.60abc	12.80ab	11.90ab	12.63ab	15.03a
Ca uptake	first cutting	mg/pot	67.4d	75.5cd	91.9bc	109.6b	116.9b	118.0b	144.4a
Ca uptake	second cutting	mg/pot	52.5d	62.1cd	80.3bc	93.2ab	83.1bc	95.3ab	112.5a
K content	first cutting	mg/g	18.63ab	19.20a	18.20ab	17.4bc	16.00dc	17.93ab	15.69d
K content	second cutting	mg/g	18.10a	15.77ab	13.67bc	13.67bc	12.93c	13.77bc	12.50c
K uptake	first cutting	mg/pot	128.0b	158.9ab	164.1a	146.6ab	132.0b	141.7ab	165.0a
K uptake	second cutting	mg/pot	110.0a	98.3a	96.7a	99.6a	90.2a	104.2a	93.3a
P content	first cutting	mg/g	2.10a	2.07a	1.90a	1.80a	1.87a	2.00a	2.03a
P content	second cutting	mg/g	1.77a	1.83a	1.33ab	1.77a	1.57ab	1.17b	1.63ab
P uptake	first cutting	mg/pot	14.25b	16.99a	17.21a	15.00a	15.34a	15.77a	21.11a
P uptake	second cutting	mg/pot	10.53abc	11.46abc	9.39bc	12.86a	10.65abc	8.85c	12.46ab

Table 7. The effect of rate of application of lime on yield, content of calcium, potassium and phosphorus on alfalfa and uptake of calcium, potassium, and phosphorus by alfalfa grown on a Warsaw loam soil.

Parameters Measured			Rate of Lime (Pounds per Acre) 0	1000	1500	2000	2500	3000	4000
pH of soil at planting time			5.50	5.45	5.60	5.68	5.75	5.85	6.25
Yield	first cutting	g/pot	2.59c	6.97ab	7.29a	8.82a	7.94a	8.01a	7.55a
Yield	second cutting	g/pot	0.44b	6.09a	6.48a	6.01a	6.90a	7.19a	7.51a
Yield	third cutting	g/pot	2.19b	7.23a	7.33a	8.45a	7.51a	8.11a	8.06a
Ca content	first cutting	mg/g	7.50d	10.57bc	12.37b	9.80c	9.80c	11.17abc	12.70a
Ca content	second cutting	mg/g	7.27b	8.00ab	9.13ab	9.93ab	9.87ab	10.93a	11.10a
Ca uptake	first cutting	mg/pot	18.5c	73.5b	81.6ab	80.2ab	75.8ab	89.3ab	95.3a
Ca uptake	second cutting	mg/pot	3.2c	48.5b	56.2ab	60.3ab	67.9ab	78.5a	83.5a
K content	first cutting	mg/g	19.53c	23.76ab	22.20bc	22.77ab	22.77ab	22.93ab	24.13a
K content	second cutting	mg/g	26.67a	21.33b	22.33b	22.10b	21.10b	19.77b	19.03c
K uptake	first cutting	mg/pot	51.00c	164.6b	158.2b	195.9a	178.6ab	183.2ab	181.3ab
K uptake	second cutting	mg/pot	12.0b	130.0a	140.1a	131.5a	144.0a	142.2a	141.9a
P content	first cutting	mg/g	2.50a	2.30ab	2.13abc	2.17abc	1.97bc	1.87c	1.97bc
P content	second cutting	mg/g	1.87a	1.63a	1.97a	1.83a	1.80a	1.83a	1.63a
P uptake	first cutting	mg/pot	6.5c	15.9ab	15.3ab	18.8a	15.6ab	15.2ab	14.7b
P uptake	second cutting	mg/pot	0.9b	9.9a	11.8a	11.2a	12.3a	12.8a	12.5a

Table 8. The effect of rate of application of lime on yield, content of calcium, potassium and phosphorus on alfalfa and uptake of calcium, potassium, and phosphorus by alfalfa grown on an Ontonagon clay soil.

Parameters Measured			Rate of Lime (Pounds per Acre)						
			0	1000	1500	2000	2500	3000	4000
pH of soil at planting time			5.50	5.41	5.48	5.50	5.53	5.74	5.87
Yield	first cutting	g/pot	12.82a	7.73b	7.85b	7.88b	8.20b	8.55b	8.81b
Yield	second cutting	g/pot	7.95b	8.53abc	7.78c	7.25c	9.87ab	9.08abc	10.02a
Yield	third cutting	g/pot	8.27d	9.33bcd	8.71cd	9.19cd	11.63a	10.55abc	11.37ab
Ca content	first cutting	mg/g	10.77b	12.40ab	12.90a	12.93a	13.63a	12.87a	13.10a
Ca content	second cutting	mg/g	11.33a	10.53a	11.23a	10.80a	10.33a	10.50a	9.23a
Ca uptake	first cutting	mg/pot	135.6a	95.7c	101.3bc	102.1bc	111.79bc	109.69bc	115.28b
Ca uptake	second cutting	mg/pot	83.1a	87.5a	87.6a	78.2a	100.8a	94.6a	92.4a
K content	first cutting	mg/g	23.37b	23.80ab	22.87b	25.10a	22.77b	23.53ab	23.77ab
K content	second cutting	mg/g	23.43a	24.63a	24.43a	24.83a	24.76a	24.50a	24.77a
K uptake	first cutting	mg/pot	297.7a	184.6b	179.1b	196.9b	186.2b	201.3b	209.2b
K uptake	second cutting	mg/pot	188.6a	210.3a	190.2a	179.1a	246.5a	223.6a	247.7a
P content	first cutting	mg/g	1.43a	1.53a	1.60a	1.53a	1.53a	1.77a	1.50a
P content	second cutting	mg/g	1.43a	1.30a	1.20a	1.20a	0.96a	0.93a	1.03a
P uptake	first cutting	mg/pot	17.96a	11.82b	12.58b	12.08b	12.48b	14.99a	13.08b
P uptake	second cutting	mg/pot	11.28a	11.06a	9.21a	8.42a	10.01a	8.66a	10.29a

Table 9. The effect of rate of application of lime on yield, content of calcium, potassium and phosphorus on alfalfa and uptake of calcium, potassium, and phosphorus by alfalfa grown on an Iron River silt loam.

Parameters Measured			Rate of Lime (Pounds per Acre)						
			0	1000	1500	2000	2500	3000	4000
pH of soil at planting time			5.50	5.32	5.40	5.50	5.58	5.65	6.00
Yield	first cutting	g/pot	7.00ab	5.85c	7.03abc	5.70c	6.81abc	7.15abc	8.16a
Yield	second cutting	g/pot	4.08b	5.35a	5.13a	5.21a	5.87a	6.73a	6.68a
Yield	third cutting	g/pot	6.86a	7.51a	7.50a	6.51a	8.00a	8.49a	7.91a
Ca content	first cutting	mg/g	17.43b	18.83ab	18.37b	20.77a	19.30ab	18.97ab	20.50a
Ca content	second cutting	mg/g	12.63d	14.57c	17.17bc	19.43ab	17.13bc	18.17b	22.17a
Ca uptake	first cutting	mg/pot	132.4b	109.8c	129.0b	117.9bc	128.6b	135.5b	165.8a
Ca uptake	second cutting	mg/pot	53.3d	76.2c	87.8c	100.3bc	99.4bc	121.0ab	127.9a
K content	first cutting	mg/g	9.70b	12.70a	12.10a	12.37a	12.30a	11.93a	11.10a
K content	second cutting	mg/g	13.53a	10.27b	9.67bc	8.43bc	8.50bc	7.50c	7.87bc
K uptake	first cutting	mg/pot	73.7a	73.6a	85.0a	70.1a	83.1a	85.0a	90.8a
K uptake	second cutting	mg/pot	53.3a	54.3a	50.0a	43.7a	49.5a	50.3a	48.6a
P content	first cutting	mg/g	1.43a	1.80a	1.83a	1.93a	1.77a	1.73a	1.47a
P content	second cutting	mg/g	1.67a	1.33a	1.50a	1.43a	1.50a	1.40a	1.13a
P uptake	first cutting	mg/pot	10.71a	10.50a	12.76a	11.21a	12.10a	12.28a	11.72a
P uptake	second cutting	mg/pot	6.81a	7.07a	7.77a	7.37a	8.69a	9.37a	7.53a