THE EFFECT OF LIME AND MOLYBDENUM ON SOIL
REACTION AND BASE SATURATION PERCENTAGE
AND ON THE YIELDS AND MOLYBDENUM UPTAKE
OF SEVERAL MICHIGAN CROPS

by

Fred Turner, Jr.

AN ABSTRACT

Submitted to the School for Advanced Graduate Studies of Michigan State University of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Department of Soil Science
1958

	Di	\circ	\mathcal{O}
Approved		C001	/ ₂

ABSTRACT :

There is disagreement in some cases and lack of information in others on the kinds, fineness and rates of application of liming materials and of their effect on the availability to the plant of nutrient elements. Additionally, very little study has been made of either the natural availability of molybdenum in Michigan soils or of the availability as influenced by liming practices.

Studies were undertaken with several Michigan soils to investigate
(1) the optimum soil pH values for maximum crop production, (2) the
relative merits of different liming materials as to composition, degree
of fineness and neutralizing value, and (3) the interaction between lime
and molybdenum and their effects on plant growth.

Various liming materials were applied at three locations at equivalent rates calculated to raise the soil pH to 6.0, 6.5, 7.0 and 7.5.

Molybdenum was applied as a spray to the young plants on one-half of each limed plot. A similar experiment was conducted in the greenhouse on three soils, two mineral and one organic, with cauliflower as the indicator crop.

The yields of oats and a legume hay were not affected by liming a Nester sandy clay loam, although the pH and base saturation percentage of the soil were markedly increased, especially where an acetylene by-product material had been applied. Likewise, no increase in the yield of field corn resulted from liming a Morley clay loam. The pH and base saturation percentage of this soil were increased for less than was the

case with the Nester sandy clay losm, possibly indicating a high residual hydrogen ion concentration.

Lime and molybdenum had no significant effect on the yields of beens and wheat on a Montcalm sandy loam. The residual amounts of these materials markedly increased the yield of red clover grown on this soil. The pH and base saturation percentage also were greatly increased.

In the greenhouse, liming similar soils increased cauliflower yields. Molybdenum application increased the yield of cauliflower and eliminated molybdenum-deficiency symptoms on a Montcalm sandy loam.

In each soil tested, there was a high correlation between pH and base saturation percentage.

Significant increases were also observed in the nolybdenum content of cauliflower, oats and corn leaves with increases in soil pH.

ACKNOTLEDGEDENT

The consideration, advice and assistance of Dr. W. W. McCall in the conduct of these investigations and in the preparation of this manuscript are gratefully acknowledged.

The author is appreciative of the assistance of Dr. E. J. Benne in the molybdenum determinations, and of Dr. J. F. Davis in some photographic phases.

These investigations were supported in part by grants in aid from the Climax Molybdenum Company, Michigan Lime Producers Association and the Linde Air Products Corporation. Snowball "A" cauliflower seed was furnished by the Ferry-Morse Seed Company.

THE EFFECT OF LIME AND MOLYBDENUM ON SOIL

REACTION AND BASE SATURATION PERCENTAGE

AND ON THE YIELDS AND MOLYBDENUM UPTAKE

OF SEVERAL MICHIGAN CROPS

by

Fred Turner, Jr.

Submitted to the School for Advanced Graduate Studies of Michigan State University of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Department of Soil Science

ProQuest Number: 10008550

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.



ProQuest 10008550

Published by ProQuest LLC (2016). Copyright of the Dissertation is held by the Author.

All rights reserved.

This work is protected against unauthorized copying under Title 17, United States Code Microform Edition © ProQuest LLC.

ProQuest LLC. 789 East Eisenhower Parkway P.O. Box 1346 Ann Arbor, MI 48106 - 1346 Fred Turner, Jr.

candidate for the degree of

Doctor of Philosophy

Final examination, July 31, 1958, 10:00 A. M., Room 210, Agriculture Hall.

Dissertation: The Effect of Lime and Molybdenum on Soil Reaction and Base Saturation Percentage and on the Yields and Molybdenum Uptake of Several Michigan Crops.

Outline of Studies

Major subject: Soil Science
Minor subject: Plant Physiology

Biographical Items

Born, January 13, 1920, Paris Crossing, Indiana

Undergraduate Studies, University of Arizona, 1937-40, cont. 1946-48.

Graduate Studies, Washington State College, 1948-1950; Michigan State University, 1954-1957.

Experience: Lt. Col., United States Air Force Reserve, active duty 1941-46 and 1951-53; Graduate Research Assistant, Washington State College, 1948-50; Soil Scientist, Irrigation Experiment Station, Prosser, Washington, 1950-51; Soil Scientist, Northern Great Plains Field Station, Mandan, North Dakota, 1954; Graduate Research Assistant, Wichigan State University, 1954-57; Assistant Agricultural Chemist, University of Arizona, 1957 to date.

Member of Alpha Zeta, Society of the Sigma Xi, Soil Science Society of America, American Society of Agronomy, and the Western Society of Soil Science.

TABLE OF CONTENTS

																						P	age'
INT	RODU	CT.	I 0	N	•	•	•	•	•	•		•	•	•	•	•	•		•	•		•	1
LIT	ERAI	U R.	E	RE	VI	Eν	r	•	•	•	•	•	•	•	•	•	•			•	•	•	2
L	ime	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	2
M	olyb	de.	nu	m	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	9
EXP	ERIN	ŒN	TA	L	Pli	:OC	EI	UF	ŒS	3	•	•	•	•	•	•	•	•	•	•	•	•	13
F	ield	ı s	tu	di	8 8	;	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	13
G	reen	ıho	us	е	St	uc	lie	s	•	•	•	•	•	•	•	•	•	•	•	•	•	•	17
MET	HODS	0	F	AN	AL	ΥS	SIS	3	•	•	•	•	•	•	•	•	•	•	•	•	•	•	19
S	oils	3	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	19
Р	lant	s	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	21
RES	ULTS	A.	ND	D	T S	CU	ISS	SI (N	•	•	•	•	•	•	•	•	•	•	•	•	•	23
F	'ield	1 S	tu	di	Θ.5	;	•	•	•	•	•		•	•	•	•	•	•	•	•	•	•	23
G	reen	ho	us	е	St	uc	di e	s	•	•	•	•	•	•	•	•	•	•	•	•	•	•	38
SUM	MARY	. A.	ND	C	ON	CI	LUS	SIC	N S	3	•	•	•	•	•	•	•	•	•	•	•	•	5 1
LIT	ERAI	'UR	E	CI	TE	D	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	53

LIST OF TABLES

Table		Page
I.	Liming materials added to three Michigan soils on which field studies were conducted	14
II.	Mechanical analysis of Michigan soils on which field studies were conducted	15
III.	Comparison of lime requirement as determined by the incubation and Bradfield-Allison method	20
IV.	Some characteristics of several liming materials	22
V •	The effects of liming materials and rates of application and of molybdenum on the yields of oats and the first cutting of alfalfa hay on a Nester sandy loam	24
•IV	The effects of liming material, applied at various rates, on the base saturation percentage of several Hichigan soils	27
VII.	The effect of liming material and rate of application and of molybdenum on the yields of corn in 1955 on a Morley clay loam	30
VIII•	The effect of liming material, rate of application, and of molybdenum on the yields of cranberry beans, wheat and red clover bay on Montcalm sandy loam	35
IX.	The effect of lime and molybdenum applications on the yields of cauliflower in a greenhouse experiment	40
Х.	The effect of lime upon soil reaction and nolvbdenum content of cauliflower leaves	47

LIST OF FIGURES

Figur	е	Page
1.	The effect of liming materials, applied at equivalent rates, on the soil reaction of a Nester sandy clay loam	25
2.	Correlation between base saturation percentage and soil reaction of a limed Nester sandy clay loam	29
3.	The effect of liming materials, applied at equivalent rates, on the soil reaction of a Morley clay loam	32
4.	Correlation between base saturation percentage and the soil reaction of a limed Morely clay loam	34
5.	The effect of liming materials, applied at equivalent rates, on the soil reaction of a Montcalm sandy loam	3 6
6.	Correlation between base saturation percentage and soil reaction of a limed Montcalm sandy loam	3 9
7.	Molybdenum-deficient cauliflower grown on a Montcalm sandy loam in a greenhouse study	42
8•	Molybdenum-deficient cauliflower in Allegan County, Michigan. Note inward cupping and crinkling of leaves	44
9•	The effect of calcium hydroxide on soil reaction when applied at different rates to three Michigan soils in a greenhouse experiment	45
10.	Correlation between base saturation percentage and soil reaction of three soils from a greenhouse experiment	46
11.	Correlation between molybdenum content of cauliflower leaves and soil pH in a greenhouse experiment	49
12.	Correlation between the molybdenum content of the sixth leaf of corn and the soil reaction of a limed Morley clay loam	50

INTRODUCTION

Many aspects of the chemical and physical relationships of soils to crop production have been investigated over the years, the simplest of these to determine being the soil reaction, or pH. Experimentally, it has been demonstrated that different species of plants have their own optimum, minimum and maximum soil pH values for growth, which must be considered if maximum returns from agricultural ventures are to be realized. Therefore, either the selected crop must be one which is tolerant of the soil pH where it is to be grown, or the pH of the soil must be adjusted to a suitable value.

In the humid regions of the northern United States, the soils are predominately acid. The most economical method for raising the pH values of acid soils is by the application of lime. Although much has been written concerning liming practices, there is disagreement in some cases and lack of information in others of the kinds, fineness and rates of application of liming materials and of their effect on the availability of nutrient elements to the plant.

These studies were undertaken with several Michigan soils to investigate (1) the optimum soil pH values for maximum crop production (2) the relative merits of different liming materials as to composition, degree of fineness and neutralizing value, and (3) the interaction between lime and molybdenum and their effects on plant growth.

LITERATURE REVIEW

Lime

Crop response to soil applications of lime have been observed and studied for centuries. Reviewers, such as Truog (70), found records of its use in the Christian Era. He referred to its early use on this continent in Virginia by Edward Ruffin (1794-1865) and in Rhode Island by Wheeler near the close of the 19th century. Liming has been a permanent general practice in Pennsylvania since that time.

Lime, as used agriculturally, refers to those compounds of calcium and magnesium which are capable of alleviating the harmful effects of an acid soil (56). Liming materials such as calcium and magnesium limestones, marl, hydrated lime, burned lime, wood ashes, shells, etc. have long been used. In more recent years, basic by-products of commercial operations have been applied to soils in increasing amounts. These include blast-furnace and phosphate-furnace slags, sugar-beet processing residues, water-softening plant residues, and by-products of acetylene manufacturing.

Basic elements are continually lost from the soil by leaching and by cropping. Some are returned to soils as crop residues and manures, and some are made available to the plants by decomposition and weathering of the soil minerals. However, there is a net loss of basic elements from the soil, and an acid soil will become increasingly more acid unless lime is applied (70).

Although general increases in crop yields due to liming acid soils have been common, the reasons for changes in yields have not been so

apparent. The effects of liming the soil may be summarized (34, 53, 70) as affecting: (1) the solubility and availability of nutrient elements, (2) the solubility or effects of toxic elements, (3) the activity of soil microorganisms, (4) the soil structure and (5) root distribution.

Truog (70) charted the general availability of the principal and some of the minor elements in relation to soil reaction. He and others (62) recommended a soil reaction at or near pH 6.5 for maximum availability of nutrient elements. A pH of 6.5 for mineral soils and of 5.5 for organic soils in Michigan are recommended by Porter, et al (56). Arnon and Johnson (5), working with nutrient cultures, found that most plants made normal growth at very low pH values, provided sufficient calcium was supplied.

Calcium and magnesium are added directly as components of the liming material. Calcium, in particular, is considered by Kelley (36) to be as important for plant nutrition as is nitrogen, phosphorus or potassium, especially in the growth of legumes.

Phosphorus in the soil becomes most available to plants at about pH 6.5 (68, 69), and at this pH its availability is preserved (18). An increase in available phosphorus with an increase in base saturation in Michigan soils was noted by Cook (18). In the more highly acid soils, phosphorus is rendered relatively insoluble by combination with aluminum and iron. However, Scarseth and Tidmore (63) found that calcium carbonate decreased the availability of phosphorus, at least until all free carbonates had disappeared from the soil. McGeorge (40) and others have shown that relatively insoluble tricalcium phosphate is formed on the alkaline side of neutral. Black and Goring (12) reviewed the

transformation and availability of organic phosphorus in the scil. In organic soils, the organic forms may constitute 75 to 85 percent of the total phosphorus present (21). However, these forms must become mineralized before the phosphorus is available to the plants (12). McCall (38) found that the soil organic phosphorus in several organic soils of Michigan behaved differently than did organic phosphorus from other sources.

Opinions differ regarding the effect of liming on the availability of potassium. York and Rogers (74) found that the uptake of potassium from limed soils depended on its initial availability, the ability of the soil to fix applied potassium and the solubility of potassium minerals in the soil. Dean (22) and Opitz, et al (52) found that lime or calcium salts increased the amount of exchangeable potassium. Peech and Bradfield (54) observed an increase in potassium in the soil solution when lime was applied to a soil which was already well saturated with calcium, but on slightly acid soils, liming had little effect on the amount of water-soluble potassium. Pretty (58) limed several Michigan soils and found no significant changes in the available potassium.

The soil reaction greatly affects the activities of soil microcrganisms, which in turn affects the availability of nutrient elements, especially nitrogen, sulfur and phosphorus (69). The activity of many soil microorganisms is greatly retarded by an acid reaction, thus reducing the decomposition of soil organic matter and inhibiting the activities of nitrogen-fixing organisms (70).

All of the essential minor elements, with the exception of molybdenum, are rendered less available as the soil pH is increased (62). At lower pH values, aluminum, iron and manganese may be toxic (62, 69, 70). Molybdenum is discussed in more detail later.

The lime requirement of a soil can be defined as the amount of a liming material that must be added to raise the soil pH to some prescribed value (69). Peech and Bradfield (54) have classified lime-requirement determinations according to the methods employed as (a) determination of soil reaction, (b) determination of exchangeable hydrogen, (c) rapid determination of the lime requirement, (d) determination of exchangeable calcium, and (e) determination of readily soluble aluminum, iron and manganese. Extensive reviews of various methods have been made recently (35, 58, 65, 69). Walker, (73) when estimating lime requirement, included observation of the growth of different crop plants and natural vegetation.

Although the pH value of a soil is easily determined and is widely used in estimating the liming needs of a soil, pH is a measure of only the active acidity of a soil. The reserve acidity (hydrogen ions held at the exchange sites and within some clay minerals and organic matter) also has a considerable effect and must also be partially neutralized in considering the liming needs (16, 56). Soils having high clay or organic matter contents usually have a high reserve acidity which must be considered in correlating soil pH with the lime requirement (44).

Walker (73) quotes Hall (1905) that, "any soil with less than one percent calcium carbonate will be benefited by liming," but indicates that modern methods relate soil unsaturation to the amount of lime needed to bring the soil pH to a given level in the laboratory. Mehlich (43) and Thorne and Leatz (69) suggest use of pH-percentage base saturation or unsaturation curves. Jensen (34) obtained good linear

correlation between pH and percent base saturation for fifty Danish soils. Shimp (65) found that the pH-percent base saturation relationship is too imperfect to use as a single factor in lime-requirement determinations of several Michigan soils, and that pH alone is insufficient for determining the requirement of soils varying in texture and exchange capacity. Others (43, 51, 53, 55) also found that soils of the same reaction may vary considerably in their percentage base saturation.

Bray and DeTurk (16) recommended that for most crops the exchange capacity of the soil should be at least 80 percent saturated with bases. Bear and Toth (8) proposed that 65 percent of the exchange capacity be saturated with calcium. Miles (48) found the degree of saturation favorable for most crops to be between 40 and 60 percent for kaolinitic soils. Walker (73) cited the recommendations of Rice-Williams, who estimated that soils of England and Wales which contained higher than 30 percent exchangeable calcium, extractable with 0.5 normal acetic acid, did not need lime. Lipman, et al (37) obtained good yield response with lime applications less than the amount indicated by the lime requirement.

Determination of exchangeable hydrogen as a criteria for lime requirement has been employed, especially for the sandier soils, with good results (42). Shimp (65) observed good correlation between the exchangeable hydrogen in Michigan soils and plant yields.

The nature of the clay minerals present affects the lime response of the soils. Marshall (41) found that montmorillonitic clays saturated below 70 percent with calcium have a higher energy of absorption for that element than do the kaolinitic clays, and so release is slower. Colloids of the 2:1 type require a higher percentage of base saturation

with calcium than do the 1:1 minerals to be equally effective in promoting plant growth.

Once the liming requirement has been determined, the amount and type of liming material to be applied must be considered. Different materials have different neutralizing values, so equivalent amounts should be applied (56). It is not generally economical to use limestone containing less than 80 percent of calcium carbonate equivalent (45).

Investigators disagree on the relative merits of different liming materials. Coarser grades of dolomitic limestone are generally considered less reactive than are similar grades of calcitic limestone (7, 46, 64), although yields in some instances have been highest where the dolomitic form was used (59). Walker (73) and Powers (57) found no differences in yields for calcitic over dolomitic lime applications.

The degree of fineness of the liming material is probably more important than is its composition. In early Michigan experiments,

McCool and Millar (39) obtained higher yields of rye from hydrated

lime treatments than from marl or 10-20 or 40-60-mesh limestone treatments. Later recommendations by Millar (49) were for use of a lime
stone so ground that practically all would pass through a 10-mesh screen and at least one-third would pass through an 80-mesh screen. After a two-year period, Jensen (34) found no difference in effects of different grades of limestone finer than 35-mesh, and that after four years those grades finer than 10-mesh were equally effective in Denmark. Walker (73) related that work in England indicates no differences in the long run between the effects of coarse and fine grades.

Relatively small amounts of lime applied at frequent intervals, such as once in each rotation, have been effective, especially on sandier soils (1, 34, 47, 62). Albrecht (1) contributes this to the proximity of the dispersed lime particles to a portion of one root system, which is selective in its adsorption functions.

Heavy applications of coarser grades of lime have overridden the effects of lighter applications of the finer grades (7, 33). Hydrates are no more effective than are fine grades of limestone, according to results obtained by Beacher (7) and by Jensen (34).

Russel (62) probably resolves the controversy regarding the relative merits of the different degrees of fineness of liming materials in his statement that, "Whether passing a 10-mesh or a 20-mesh sieve is the preferable upper limit of size has not been fully investigated, but for many limestones there appears to be little to choose between them; the important thing is to have a considerable variation in particle size in the material to ensure both rapid action initially and a reason-ably long residual action."

Molybdenum

Although the beneficial effects on plant growth due to the apolication of lime to acid soils have been observed and studied for many centuries, not until 1930 was the biological importance of molybdenum first realized, when Bortels (13) found this element to be highly beneficial in the fixation of gaseous nitrogen by Azotobacter chrococcum. More recently the need for this element in other microbiological species has been established.

Molybdenum deficiency in crop plants. Arnon and Stout (4) were the first to establish the necessity of molybdenum for the growth of a higher plant, the tomato. Anderson (2) reported definite cases of molybdenum deficiency in clover on acid soils in Australia in areas of high winter rainfall, and Davies (19) later demonstrated the deficiency symptoms in cauliflower in New Zealand. Walker (73) first demonstrated molybdenum deficiency on plants grown on a soil in the United States.

Extent of molybdenum deficiency. The symptoms of molybdenum deficiency have been noted in more than 40 plants, both legumes and non-legumes, throughout the world. The plants include cauliflower, cabbage, mustard, alfalfa, clovers, rye, oats, carrot, potato, citrus (trees) and others, including many ornamentals, according to Hewitt (32). Although known deficient areas are most widespread in Australia and New Zealand, deficiencies in the field have been confirmed in many areas of the United States, notably in California, Florida, New Jersey and New York. Rubins (61) cited known field deficiencies in 13 states and suspected deficiencies in three others.

Molybdenum deficiency is often associated with acid soils, because the element becomes less available with decreasing pH. Although the deficiency is more likely to occur in plants grown on the sandier soils, it also has been observed in crops on fine textured soils. Increasing the pH by the addition of lime is an important method of overcoming soil deficiency of molybdenum. Stout, et al (68) found that phosphates greatly increased the uptake of molybdenum, and that sulfates decreased it in acid soils.

Several surveys have been made of the molybdenum status of soils of the United States. Robinson and Alexander (60) found an average of 2.3 ppm total molybdenum in the soils they and others had analyzed, with little variation between soils.

Role of molybdenum in plant nutrition. Molybdenum is required in very small amounts by plants for the physiological reduction of nitrates. Nitrates accumulate in the tissues of molybdenum-deficient plants, and the protein content of the plant is reduced. It is also required in trace quantities for the nodulation of legumes when grown on either nitrate or atmospheric nitrogen.

Molybdenum deficiency symptoms. The symptoms of plant diseases which are now associated with molybdenum deficiency were recognized long before the true cause was known. "Whipteil" of cauliflower and broccoli was recognized in New York state by Clayton (17) and a leaf spotting of citrus in Florida was reported early in the century by Floyd (30). Later investigators found similar symptoms on plants grown in other areas.

Molybdenum deficiency symptoms in many plants were described and pictured by Hewitt (32) and Anderson (3). Legumes exhibit the appearance of nitrogen starvation, with pale yellow foliage, poor or stunted growth, and in some species a pronounced yellowing between the veins which retain some green color. A mottling of the leaves may be evident as is often the case with molybdenum-deficient citrus. Larginal scorching, a rolling or curling inward (cupping) and a withering or orinkling of the leaves occur in many species of broad-leaved plants. In severe cases the leaves may die.

Some of the crucifers, such as cauliflower, broccoli, cabbage and brussels sprouts have characteristic secondary symptoms of more severe molybdenum deficiency, which is commonly termed "whiptail." Leaf tissue develops irregularly from the midrib to produce long, narrow leaves, often having edges which are pleated or otherwise contorted in appearance. Also, leaves may form in the curd of cauliflower, rendering the head unmarketable. In very severe cases no head is formed (Gammon et al, 31).

Effects of molybdenum excess. Although no symptoms of molybdenum excess in plants have been described, cattle and sheep grazing on pasture herbage of high molybdenum content are affected by the disease "Molybdenosis", variously termed as "teart" or "teartness", peat scours of beef and dairy cattle, and ataxia of lambs. Symptoms in cattle are acute scouring, change in coat color, general unthriftiness and poor growth of calves. Dick (24) and others have shown that there is an antagonism between copper and molybdenum in the metabolism of ruminants, especially where the sulfate intake is high. Where the molybdenum

content of the forage is high, over 10 ppm (20), copper retention by the animal is low, thus causing the disease. It is readily cured by supplementing the animal's diet with copper salts. Excess molybdenum in forage has been found in Florida, California and Oregon (61).

Research on molybdenum in Michigan. The role of molybdenum in agriculture has been explored very little in Michigan. Benne and Jerrim (9, 10) reported the molybdenum content of some plants, and Bergman and Kenworthy (11) reported on studies with Concord grapes grown with nutrient solutions. Van Arsdell and associates (72) suggested a possible excess of molybdenum in a reed canary grass pasture. Field studies on lime and molybdenum relationships were initiated by the author in the fall of 1954 and greenhouse studies in May 1956.

EXPERIMENTAL PROCEDURES

Field Studies

General treatments. At three locations several types of liming materials were applied at the rates determined by the method of Bradfield and Allison (15) to raise the soil pH to 6.0, 6.5, 7.0 or 7.5 (Table I). Calcitic and dolomitic meals were applied at all four rates. A pulverized dolomite was applied at rates to raise the soil pH to 6.5 and 7.0. In addition an acetylene by-product lime was applied at the four rates on soils in Ogemaw County and at one rate, to pH 7.0, in Washtenaw County. A Montcalm sandy loam received one treatment, to pH 7.0, with blast-furnace slag. A sodium molybdate solution was sprayed on the young plants on one-half of each limed plot.

Nester sandy clay loam. The experimental area is located near Rose City, Ogemaw County, in the NN_{4}^{2} of section 30, township 23N, range 3E. The mechanical analysis of this and other soils investigated in field experiments are given in Table II.

No manure or mineral fertilizer had been added to this soil prior to 1949. In that year, 200 pounds per acre of 3-18-9 were drilled with barley and alfalfa at planting time. 1950 was the second year for the alfalfa, and in 1951 a top dressing of 300 pounds per acre of 0-20-0 was applied. Ten loads of manure were spread on the area in early 1952, and pasturing was continued until the alfalfa was plowed under in the fall of 1953. In the spring of 1954, ten loads of manure per acre were again spread, incorporated into the soil with a field cultivator, 100 pounds of 10-10-10 was drilled in, and field corn was planted.

Table I. Liming materials added to three Michigan soils on which field studies were conducted.

		Pounds	per acre	to attain	n pH of
Soil	Liming material	6.0	6.5	7.0	7.5
Nester sandy	Calcitic meal	, o1	2700	5500	8200
clay loam	Dolomitic meal	o o	2200	4300	6500
· ·	Pulverized dolomite	0	2200	4300	4
	By-product ²	O	2000	4000	6100
Morley clay	Calcitic meal	1300	4600	8000	11300
loam	Dolomitic meal	1000	3700	5300	7800
	Pulverized dolomite	our our War Sile.	2900	6300	
	By-product ²			5300	
	,				
Montcalm sandy loam	Calcitic meal	2200	3300	4900	6300
TACM	Dolomitic meal	1700	3000	3900	5200
	Pulverized dolomite		2800	3700	
	By-product ³		***	5000	~~~

¹ Determined by the lime-requirement method of Bradfield and Allison

² By-product of acetylene manufacturing process. Linde Air Corporation, Hammond, Indiana

³ Water-quenched blast-furnace slag. The Granalite Company, East Chicago, Illinois

⁴ Not applied at this rate

Table II. Mechanical analysis of bichigan soils on which field experiments were conducted.

Series	Texture	Sand	Silt	Clay
		%	%	%
Nester	Sandy clay loam	51.0 ¹	25.8	23.2
Morley	Clay loam	44.0	27.8	28.2
Montcalm	Sandy loam	72.0	14.8	13.2

 $^{^{1}}$ 3y the Bouyoucos hydrometer method

The experiment was laid out for 15 treatments, each replicated four times, and one-half of the required lime was spread on the soil surface and was plowed under on November 11, 1954. The remaining lime was spread on November 16 and 17 and was incorporated with a field cultivator. After 200 pounds of 6-24-12 per acre had been drilled in on May 2, 1955, cats were planted. Sixteen ounces per acre of sodium molybdate were sprayed on the cats plants on June 22. The cats were harvested on August 9, and whole plant samples, excluding roots, were taken for analysis.

An alfalfa-clover-grass mixture was seeded with the oats in 1955 and was pastured in the spring of 1956. After removal of the stock, 8 ounces of sodium molybdate per acre was applied. The first and only cutting was made on August 3.

Morley clay loam. The experimental area is located near Whitmore
Lake in the Sw1 of section 16, township 18, range 6E in Washtenaw County.
The experiment consisted of 12 treatments, each replicated four times.
One-half of the required lime was spread on a heavy crop of clover and grass and was plowed under on May 4, 1955. On May 17, the remainder of the lime was applied and disked in, and corn was planted the next day.
Eight ounces per acre of sodium molybdate was sprayed on the young corn plants July 31.

Leaf samples were taken on September 2 from all unsprayed plots in replication IV. The sixth leaf of each corn plant was pulled and washed in DREFT and distilled water before drying. The mature corn was harvested on October 20.

Ohio M-15 variety of corn was planted on May 30, 1956. The farmer

used a special shoe to place 200 pounds per acre of a 6-24-12 fertilizer latinches below the seed at planting time. The corn did not mature before the first frost and so was not harvested. It was damaged by a 2,4D weed control spray which was applied when the corn plants were about 10 inches high.

Montcalm sandy loam. The same experimental design as that used in Washtenaw County was used near Edmore in the Wa of the Swa of section 2, township 12N, range 6W in Montcalm County. The first half of the required lime was spread on May 14, 1955 and was disked under. The remainder, applied May 19, was harrowed in prior to planting cranberry beans on May 20. Sodium molybdate was applied July 6 at the rate of 4 ounces per acre to the young plants. The mature plants were pulled August 26, piled outside the field, and threshed when dried.

Wheat was planted in the late fall of 1955, sprayed with 8 ounces per acre of sodium molybdate on May 31, and harvested on August 8, 1956. Three hundred pounds per acre of 5-20-20 fertilizer was drilled in the fall, and 100 to 150 pounds per acre of ammonium nitrate were broadcast in the spring.

Red clover had been seeded in the wheat and the first cutting was harvested on June 19, 1957. Yield data were taken, although no plant or soil samples were taken at that time.

Greenhouse Studies

Soil samples from the plow layers of three soils, a Montcalm sandy loam from the vicinity of Edmore, a Nester sandy clay loam from a former apple orchard at the Graham Experimental Station near Grand Rapids, and a Houghton muck from the Michigan State University Muck Experimental

Farm were used in this study. The initial pH values were 5.2, 4.5 and 5.5, the cation exchange capacities were 4.63, 6.99 and 138.86 milliequivalents per 100 grams, and the total exchangeable bases were 1.42, 0.54 and 112.88 milliequivalents per 100 grams, respectively. Mutrient requirements were determined by a soil test using the methods of Spurway and Lawton (66) and the lime requirements by the Bradfield-Allison method (15). The amounts of calcium hydroxide (hydrated lime) determined to bring each soil to pH values of 6.5 and 7.5 are hereafter called rate 1 and 2 respectively for the particular soil (Table IX). Optimum levels of c.p. salts containing all of the essential elements except molybdenum, and the calcium hydroxide, where required, were mixed with 4325 grams of Montcalm, 3775 grams of the Nester and 1250 grams of the Houghton soil. The treated soils were then placed in one-rallon metal cans lined with polyethylene bags. Each treatment was replicated three times. The soils were brought to field capacity with distilled water and were incubated for one week. Seeds of "Snowball A" variety of cauliflower were planted on May 7, and the resulting plants were later thinned to one plant per container. Distilled water was added as needed to keep the soils near field capacity.

Sodium molybdate was dissolved in water, to which one teaspoon of DREFT had been added to each gallon of water as a spreader, to give proper concentrations at the rates of 0, 2, 4 and 8 ounces of sodium molybdate per acre when applied in two applications. The solutions were applied to the leaves with a plastic sprayer on June 22 and 29. The plants were harvested on August 12 before flowering.

METHODS OF ANALYSIS

Soils

Soil sampling and preparation. Samples of the 0 to 8 inch depth were taken from all plots and from the greenhouse soils prior to treatment and at periodic intervals thereafter. All samples were crushed with a wooden rolling pin and were sieved through a 2-millimeter plastic screen prior to analysis.

Analysis. A mechanical analysis of each soil was made by the hydrometer method of Bouyoucous (14).

The field capacity of the soils was approximated from the amount of water retained by the soils, which had been saturated and then permitted to drain for 12 hours.

The pH of a 1:1 soil:water suspension was measured with the glass electrode, using a Beckman Model N pH meter. The centrifuge methods described by the United States Salinity Laboratory (71) were found to be most satisfactory in determining the exchange capacity and the exchangeable cations of the soil.

The lime requirement was determined both by incubation with varying amounts of calcium hydroxide and by the titration method of Bradfield and Allison (15). The results obtained by these two methods, as shown in Table III, were very nearly the same. Therefore, the most rapid method, the titration method, was utilized for further determinations.

A quick test of the available soil nutrients was made using the method of Spurway and Lawton (66).

Table III. Comparison of lime requirement as determined by the incubation and Bradfield-Allison methods.

	lbs.
Incubation	2300
Bradfield-Allison	2850
Incubation	5 3 00
Bradfield-Allison	4820
Incubation	73 20
Bradfield-Allison	7770
	Bradfield-Allison Incubation Bradfield-Allison Incubation

A sieve analysis was made of each liming material. The neutralizing value of each was determined (6), and the determinations are reported in Table IV.

Plants

Preparation. Fresh samples were washed in DREFT and distilled water and then rinsed. All plant samples were oven-dried at 70°C., ground in a Wiley mill with stainless steel hopper and number 20 screen, and stored in Flint-class bottles.

Analysis. Molybdenum determinations on the plant samples were made by the method of Dick and Bingley (23) as modified by Benne and Jerrim (3, 10). Referee samples furnished by Dr. Benne were analyzed to insure accuracy of the method.

Table IV. Some characteristics of several liming materials.

Location of experiment	Type	Grade	Source	Neutral- izing value	Sc Percent through 8 mesh	Screen analyses Percent Perthrough the	yses Percent through
Ogemaw County	Calcitic Dolomitic Dolomitic By-productl	Meal Meal Pulverized	Bayport, Mich. Drummond Is., Mich. Woodville, Ohio Hemmond, Ind.	81.6 106.8 106.4 115.3	99 99 100	50 66 100 98	21 91 89
Washtenaw County	Calcitic Dolomitic Dolomitic By-productl	Weal Weal Pulverized	Monroe, Mich. Woodville, Ohio Woodville, Ohio Hammond, Ind.	102.9 103.1 106.4 115.3	99 95 100 100	47 56 100 98	30 36 91 89
Montcalm County	Calcitic Dolomitic Dolomitic By-product ²	Weal Weal Pulverized Granulated	Bayport, Mich. Drumnond Is., Mich. Woodville, Ohio East Chicago, Ill.	79.6 107.2 106.4 87.4	100 93 100	54 37 100 46	21 80 91 22
Greenhouse	$\mathtt{Ca}(\mathtt{OH})_2$!	135.1	100	001	100

1 By-product of acetylene manufacturing process. Linde Air Corporation, Hammond, Indiana

2 Blast-furnace slag. East Chicago, Illinois

RESULTS AND DISCUSSION

Field Studies

Nester sandy clay loam. The soil variability found between plots in Openaw County on the Nester sandy clay loam partially obscures the effects of the treatments. The data in Table V show that the type of liming material, the rate of its application, and the addition or nonaddition of molybdenum had no apparent significant effects on the yields of oats and hay. However, the soil reaction was markedly affected by the liming materials, especially by the acetylene by-product. Soil samples of the plow depth were taken prior to the application of liming materials and at periodic intervals thereafter up to 22 months. As shown in Figure 1, the decreasing order of effectiveness in raising the soil pH was acetylene by-product, high calcium meal, reference dolomite, and the dolomitic meal. The lowest liming rates had little effect on the soil reaction. Greater differences due to different liming materials were evidenced at the higher rates of application. The desired pH of 6.5 was reached with all liming materials except the dolomitic meal. However, the desired pH of 7.0 was reached only with the acetylene by-product, and with none of the liming materials was the desired pH of 7.5 attained. In the latter instance, the pH had increased over the 22 month period Trong 3.1 to 7.5, in contrast to an increase in the check plots from 6.0 to 6.1. Where the high calcium and dolomitic meals had been applied at the highest rates, a final pH of 6.7 was attained by both materials. However, 8200 pounds per acre of the calcitic meal was no more effective in raising the ph than was 5500 pounds per acre of the same material.

Table V. The effect of liming materials and rates of application and of molybdenum on the yields of cats and the first cutting of alfalfa hay on a Nester sandy clay loam.

Liming mater	ial	0a 198		Alfal:	fa h ay 56
Type	Rate	No Mo	Mo ¹	No Mo	Mol
	lbs/ac	bu/ac	bu/ac	T/ac	T/ac
Calcitic meal	0	43.6 ²	40.7	1.68	1.84
	2700	41.5	50.9	1.69	1.76
	5500	34.1	40.9	1.70	1.78
	8200	40.7	43.3	1.93	1.75
Dolomitic meal	0	48.6	44.8	1.70	1.67
	2200	43.1	39. 0	1.62	1.72
	4300	49.0	35.6	1.95	1.86
	6500	41.3	44.0	1.87	1.92
cetylene	0	45.7	47.1	1.67	1.74
oy-product	2000	36.0	3 6.3	1.77	1.83
	4000	45.4	35.8	1.64	1.54
	610 0	35.9	41.1	1.73	1.83
Pulverized dolomite	2200	32.7	39.0	1.86	1.90
	4300	43.0	33.9	1.58	1.51
No lime	*****	39.8	42.5	1.66	1.60

Applied 16 cumces per acre and 8 cumces per acre of sodium molybdate in 1955 and 1956, respectively

² Average of three replications

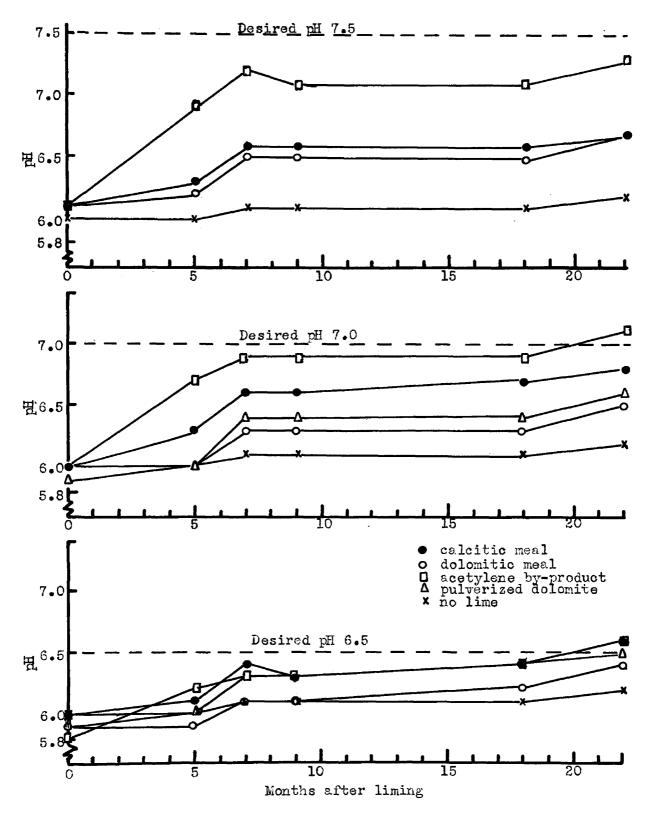


Figure 1. The effect of liming materials, applied at equivalent rates, on the soil reaction of a Nester sandy clay loam.

The base saturation percentages were determined on soil sampled in the fall 1955 and the fall 1956 and are reported in Table VI. Where 2200 pounds per acre of the dolomitic meal had been applied, the base saturation percentage was increased from 73.7 percent to 77.1 percent in 22 months, an increase of 3.3 percent. The increase was similar where 6500 pounds per acre of this material had been added. However, 4300 pounds per acre of the material resulted in a net increase of 6.5 percent, a figure nearly double that obtained from either the higher or the lower rates. A larger and more rapid increase was obtained with the high calcium meal, the greatest increase being 16.7 percent with an application of 5500 pounds per acre of this material. In the case of the acetylene by-product material, much higher increases in the base saturation percentage were obtained, being nearly linear with the amount of the material applied. The base saturation percentage obtained with the two higher rates of this latter material was greater than 100 percent, there being little difference in effect between the two rates of application. During this same period, the base saturation percentage of the unlimed soil decreased 0.7 percent.

As shown in Figure 2, there was a significant correlation of 0.892 between the pH and the base saturation percentage, regardless of the kind of liming material or the rate of application, during the observation period. Similar correlation was observed by Jensen (34) in Danish soils.

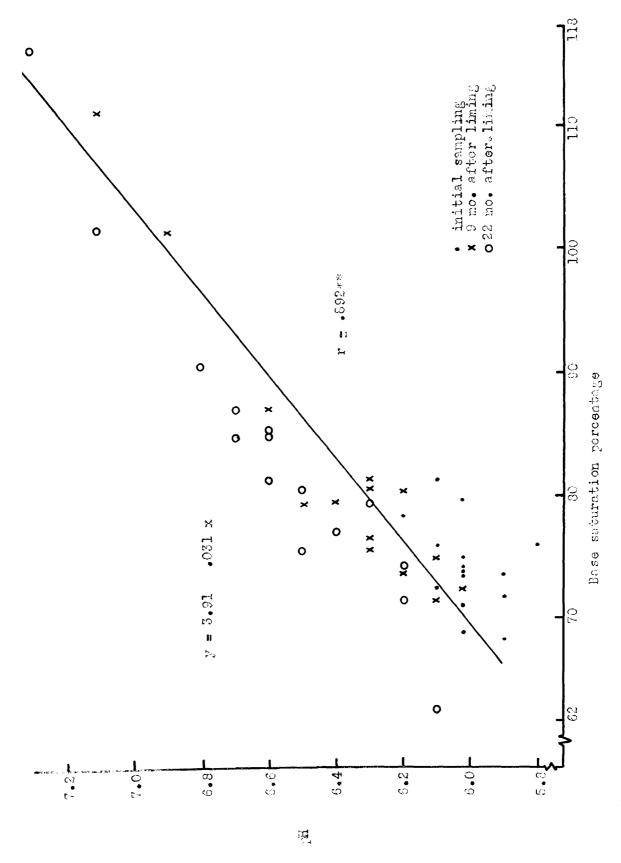
Morley clay loam. There were no significant differences in the 1955 yield of corn on the Morley clay loam due to liming materials or to molybdenum, as shown in Table VII. Living the soil did decrease

Table VI. The effects of liming materials, applied at various rates, on the base saturation percentage of several Michigan soils.

	Desired	de – 1901, albertelle undkandelle betterholde nyglernelle med der beldt in 1904 dette ille in dessenden meterselle nyssele ande			Incr	·ease
Liming material	pН	Months	after	liming	Fall '55	Fall 56
Nester sandy clay	y loam					
		0	9	22		
Calcitic meal	6.0	68.7	72.2	62.5	3.5	- 6.2
	6.5	7 0•9	81.4	85.0	10.5	14.1
	7.0	73.6	85.6	90.3	12.0	17.7
	7.5	75. 9	86.9	86.9	11.0	11.0
Dolomitic meal	6.0	73.8	73.8	71.6	0.0	- 2.2
	6.5	73.7	71.3	77.1	- 2.4	3.4
	7.0	74.1	76.5	80.6	2.4	6.5
	7.5	81.3	79.2	84.6	- 2.1	3 •3
Acetylene	6.0	78.3	80.3	79.2	2.0	0.9
by-product	6.5	76.0	80.5	85.5	4.5	9.5
0 1	7.0	79.6	101.6	101.6	22.0	22.0
	7.5	72.3	110.7	115.9	38.4	43.6
Pulverized	6.5	68.2	75.4	77.5	7.2	9.3
dolomite	7.0	71.8	79.4	81.3	7.6	9.5
No lime		74.9	74.7	74.2	- 0.2	- 0.7
Morley clay loam		0	6	15		
		-			C 77	4 72
Calcitic meal	6.0	56 • 2	61.9	60 . 5	5•7 5•2	4.3 7.3
	6 . 5	55•6 55•5	60.8 59.8	62•9 64•3	5•≥ 4•3	8.8
	7.0	55.7	63.6	69.7	7.9	14.0
	7.5	99 • ≀	00.0	05•1	1 • 3	1400
Dolomitic meal	6.0	54.7	58.2	62.5	3.5	7.8
DOZOM2 02 0 340 142	6.5	51.5	56.6	61.0	5.1	9.5
	7.0	63.2	70.4	72.6	7.2	9.4
	7.5	58.2	67.3	69.6	9.1	11.4
Pulverized	6.5	57.0	64.5	67.4	7.5	10.4
dolomite	7.0	54.7	68.9	71.7	14.2	17.0
MOTOUT 00	. • -					
Acetylene by-product	7.0	53 . 6	69.5	73.6	15.9	20.0
No lime	as at M	51.9	5 0.5	51.9	- 1.4	0.0

Table VI. Continued

	Desired				Incr	ease
Liming material	pН	Mon th:	s after l	iming	Fall '55	Fall '56
Montcalm sandy	loam					
		0	4	15		
Calcitic meal	6.0	41.2	63.4	68.9	22.2	27.7
	6.5	44.3	72.4	76.0	28.1	31.7
	7.0	44.0	74.0	77.6	30.0	3 3.6
	7.5	37.8	77.2	84.6	39.4	46.8
Dolomitic meal	6.0	44.1	56.8	61.6	12.7	17.5
	6.5	43.8	55.4	59.5	11.6	15.7
	7.0	41.7	63.8	67.7	22.1	23.0
	7.5	43.6	62.1	69.1	18.5	25.5
Pulveri zed	6.5	47.0	78.8	83.9	31.8	36.9
dolomite	7.0	44.5	78.8	78.8	34.3	34.3
Slag	7.0	45.0	56.2	61.4	11.2	16.4
No lime		47.3	47.3	44.4	0.0	- 2.9



Correlation between base saturation percentage and soil reaction of a limed Nester sendy clay loam. Figure 2.

Table VII. The effect of liming material and rate of application and of molybdenum on the yields of corn in 1955 on a Morley clay loam.

Liming material		Cor	n
Type	Rate	No Mo	Mol
	lb/ac	bu/ac	bu/ac
Calcitic meal	1300	67.0 ²	67.3
	4600	71.9	72.6
	8000	74.2	79.3
	11500	68.4	73.4
Dolomitic meal	1000	64.2	69.2
	3700	71.5	66.2
	5300	77.0	78.1
	78 00	74.0	75.5
Pulverized dolomite	2900	61.4	65.3
	6300	70.7	71.1
Acetylene by-product	5300	70.0	68•4
No lime	ages state attent	80•4	71.2

^{1 8} oz/ac of sodium molybdate

² Average of four replicates

yields somewhat, and molybdenum decreased yields where no lime had been applied. The 1956 crop was not harvested as the corn was frosted before maturity. The soil was sampled before the lime applications and at periodic intervals thereafter up to 15 months. As shown in Figure 3, there was much less change in the soil reaction due to liming this soil than was the case with the Mester sandy clay loam, although liming rates were based on lime-requirement determinations. The greatest increase was with the acetylene by-product applied at the rate of 5300 pounds per acre. The dolomitic meal and the reference dolomite both gave lower, although nearly equal increases in the soil pH. The smallest changes were observed where the high calcium meal had been applied. Although the lowest liming rates had little effect on the soil reaction, an increase in the rate of the liming material applied resulted in a corresponding increase in the soil pH.

The effects of the applied liming materials on the base saturation percentage are shown in Table VI. At the lowest liming rate, the smallest increase in the base saturation percentage, 4.4 percent, was obtained with the high calcium meal. With increasing lime the base saturation percentage of the soil increased with all materials, the greatest increase being with the acetylene by-product material applied at the rate of 5300 pounds per acre, a net increase of 20.0 percent. At the higher rates of application the effects were nearly the same for both the high calcium and dolomitic meals, with a net increase of 14.0 percent where 11,300 pounds per acre of the calcitic meal had been applied. Over this 15 month period there was no change in the base saturation percentage of the unlimed plots.

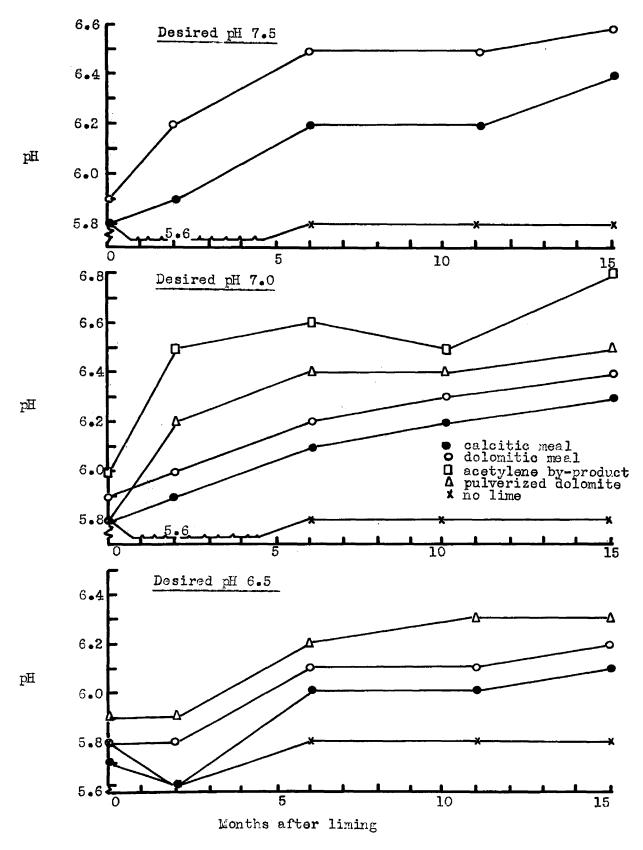


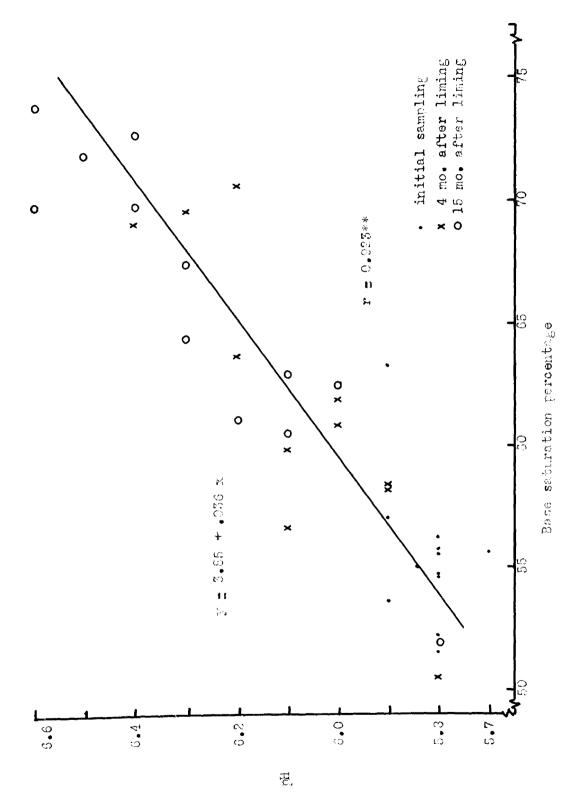
Figure 3. The effect of liming materials, applied at equivalent rates, on the soil reaction of a Morley clay loam.

Figure 4 shows the highly significant correlation coefficient of 0.923 between the base saturation percentage and the soil reaction over the pH range of 5.7 to 6.6, regardless of liming material or of the rates of application.

Montcalm sandy lcam. The data in Table VIII show that on Montcalm sandy loam there were no significant differences caused by treatments in the yields of field beans and wheat. However, residual sodium molybdate and lime had an effect on the red clover yields in Montcalm County similar to that observed on cauliflower grown on this soil in the green-house. The yield response to lime alone, regardless of the type or rate of liming material applied, was highly significant. The average yield on a dry-weight basis was increased from 0.34 tons per acre where no lime was applied to 1.58 tons from the limed plots. The increase with molybdenum alone was from 0.34 tons to 1.02 tons, and with lime plus molybdenum alone, yields were increased the most where lime at the lower rates plus molybdenum had been applied.

Molybdenum-deficient clover plants were smaller than normal, the leaves were pale-green and few nodules were observed on the roots. The stand was thinnest where no lime or molybdenum had been applied.

As shown in Figure 5, the pulverized dolomite had the greatest effect on the soil reaction, increasing the pH from 5.2 to 6.8 over a 15 month period where 2800 pounds per acre of the material had been applied. Thirty-seven hundred pounds per acre of this material was similar in its effect. The desired pH levels were attained or exceeded with the two rates of the high calcium meal. However, additions of 4900 and 6300 pounds per acre were little more effective than 3300



Correlation between hese saturation percentage and the soil reaction of a limed Korloy clay leam. Figure 4.

The effect of liming material, rate of application and molybdenum on the yields of cranberry beans, wheat and red clover hay on Montcalm sandy loam. Table WIII.

Liming material		Cranber 1	Cranberry beans 1955	W	Wheat 1956	Red clover hay 1957	er hay 7
${\rm Typ} {\bf e}$	Rate	No Mol	Mo	No Mo	Mo	No Mo	Mo
	lbs/ac	bu/ac	pn/ac	pn/ao	bu/ao	T/ac	T/ac
Calcitic meal	2200	9.72	9•6	45.7	40.4	1.70	1.60
	3300	10.9	11.6	45.2	45.3	1.39	1.62
	4900	0.6	10.0	45.3	42.4	1.72	1.96
	6300	10.0	10.4	42.4	41.9	1.52	1.69
Dolomitic meal	1700	8.00	0•6	44.0	41.6	1.24	1.76
	2000	10.1	11.2	43.3	42.4	1.48	1.78
	3900	0.6	10.6	43.9	45.5	1.56	1.72
	5200	2. 6	7.0	41.0	39.2	1.97	1.63
Pulverized dolomite	2800	9 6	9•1	39.4	41.1	1.83	1.89
	3700	10.7	10.2	44.6	45.1	1.68	1.90
Blast-furnace slag	2000	10.3	10.2	44.8	44.6	1.32	1.67
No lime	† ! !	9.1	10.1	42.3	43.7	0.34	1.05

l Applied to young plants as sodium molybdate solution at rates of 4 ounces on the beans, 8 ounces on the wheat and no application on red clover

2 Averages of four replications

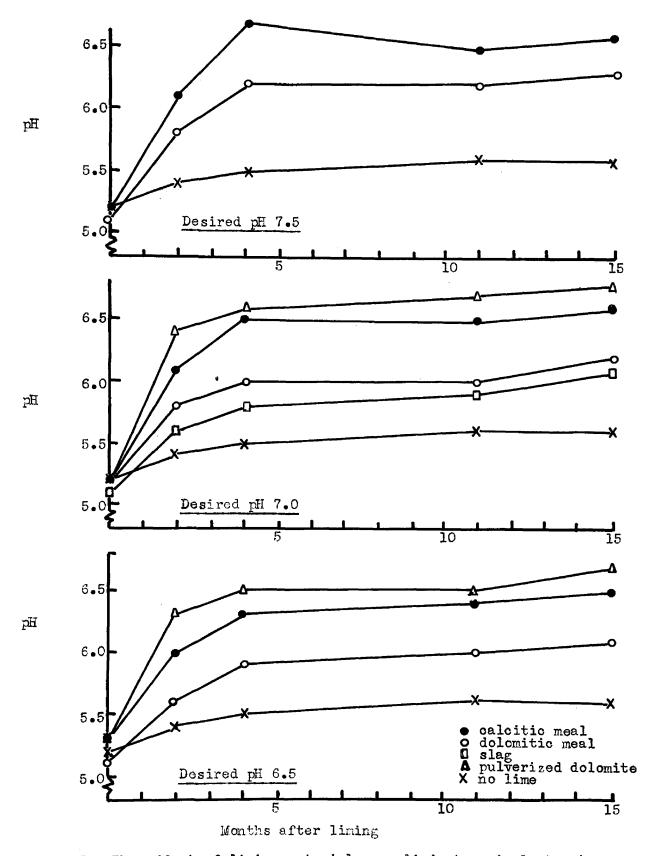


Figure 5. The effect of liming materials, applied at equivalent rates, on the soil reaction of a Montealm sandy loam.

pounds per acre, an additional increase of 0.1 pH units resulting from the higher rates. Dolomitic meal was similarly effective to the high calcium meal at the low rate of application. However, additional amounts of this dolomitic material increased the pH only slightly more, 5200 pounds per acre giving a net increase of only 0.2 pH units over that obtained with 3000 pounds per acre. During the observation period, the unlimed plots increased 0.4 pH units. The effect of the slag was equal to that of dolomitic meal where both had been applied at the same equivalent rate.

As shown in Table VI, the 16.3 percent increase in the base saturation percentage where the slag had been applied was half of that where equivalent amounts of the high calcium meal and the pulverized dolomite had been applied, and was considerably less than the change due to the dolomitic meal. Additions of the pulverized dolomite increased the base saturation percentage the most, followed by the high calcium meal and the dolomitic meal in that order. The high calcium meal was only slightly less effective than was the pulverized dolomite in this respect. The base saturation percentage increased directly with the amount of calcitic meal applied, the increases ranging from 27.7 percent with 2200 pounds per acre of this material to 46.9 percent with 6300 pounds per acre. The increases were little different for the 1700 and 3000 pounds per acre applications of the dolomitic meal, being 17.5 and 15.7 percent, respectively. Where 3900 and 5200 pounds per acre had been added, the increases were 26.0 and 25.5 percent, respectively. After 15 months the percent base saturation of the unlimed soil had decreased 2.9 percent.

As shown in Figure 6, there was a highly significant correlation coefficient of 0.951 between the base saturation percentage and the pH of the Montcalm sandy loam for pH values of 5.5 and above for the limed plots. The correlation would be less if the base saturation percentage in the unlimed plots was included in the determination.

Greenhouse Studies

The dry-weight yields of cauliflower are given in Table IX. Liming affected the yield on all soils. Germination was excellent in all cases but plants grown in the Nester orchard soil to which no lime had been applied failed to grow beyond the single leaf stage. Lime added at rate 1 resulted in an average yield of 9.7 grams; however, lime added at rate 2 did not give an additional significant increase in yield. Additional molybdenum had little effect on the growth of plants in this soil, regardless of lime treatment.

Liming the Montcalm sandy loam increased cauliflower yields from 9.6 grams for the check to 12.4 and 13.1 grams for lining rates 1 and 2, respectively (significant at the one percent level). The average yield of cauliflower due to the lime treatments was 11.4 grams. Two ounces per acre of sodium molybdate significantly increased the average yield to 12.2 grams. Higher rates of molybdenum had little additional effect on the yields.

The average increase on the Houghton muck from 30.8 for the check to 32.8 grams where lime was added at rate 1 was highly significant.

Liming to a higher pH resulted in yields which were lower than those from the unlimed muck. According to Porter, et al (56) and others, liming organic soils in Michigan to a pH higher than 5.5 reduces yields.

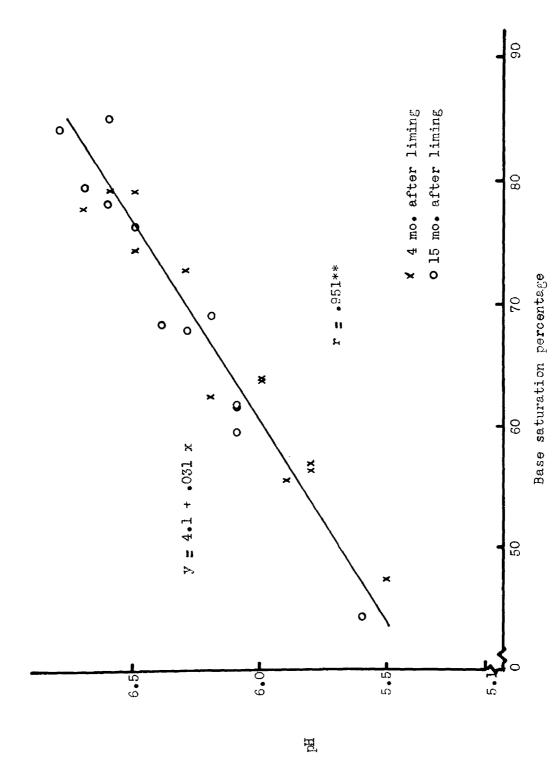


Figure 6. Correlation between base saturation percentage and soil reaction of a limed Wontcalm sandy loam.

Table IX. Effect of lime and molybdenum applications on the yields of cauliflower in a greenhouse experiment.

•	Lime	treatment		Moly	bdenum	
Soil	Rate	Amount	01	2	4	8
		lbs/ac				
Montcalm	0		9.62	10.1	9.3	9.6
sandy loam	1	1600 ³	11.9	13.0	12.0	12.5
	2	3200	12.8	13.6	13.0	12.8
Nester sandy	0		n.h.4	n.h.	n.h.	n.h.
clay loam	1	3800	10.0	9.2	9.9	9.6
v	2	5800	11.1	10.3	10.7	10.2
Houghton muck	0		30.4	31.5	31.2	30.3
	1	4000	32.2	33.3	33.8	31.5
	1 2	10800	30.5	30.6	30.2	29.3

¹ Ounces of sodium molybdate per acre

² Dry-weight yield in grams per pot. Average of three replications

³ Calcium hydroxide. Neutralizing value 135.1

⁴ Not harvested. Plants did not develop beyond the primary-leaf stage

No significant changes in yield were obtained by the addition of molybdenum to the plants grown in this soil, regardless of lime treatment.

Total dry weights of cauliflower from the Nester clay loam, where limed, were slightly less than those from similarly treated Montcalm soil, but yields from the muck were two and one-half times larger than were those from either of the mineral soils. In all cases, significance was determined by use of Duncan's multiple range tables (26).

As shown in Figure 7, typical molybdenum deficiency symptoms were exhibited by cauliflower grown on the Montcalm soil to which no lime or molybdenum was applied. Necrotic areas appeared at the tips of the second and other well-developed leaves of the young plants, later extending toward the petioles along the leaf margins. Leaves cupped up along the margins, exhibited a pale green or yellow color between the veins, and became slightly crinkled. The cotyledons developed necrotic spots. Nearly all of the deficiency symptoms had disappeared by harvest time. The secondary deficiency symptoms of "whiptail" were never evidenced by these plants, which contained 0.41 ppm molybdenum at harvest. Evans (27) found that alfalfa plants containing less than 0.5 ppm molybdenum responded to applications of the element. However, this critical value does not necessarily hold true for cauliflower.

Molybdenum-deficient cauliflower plants wilted at higher soil moisture levels and recovered more slowly than did plants which had apparent adequate amounts of the element. This possibly was due to a reduction in total root area of the deficient plants, to physiological changes, or to a combination of these or other factors.





Figure 7. Molybdenum-deficient cauliflower grown on a Montcalm sandy loam in a greenhouse study.

Molybdenum-deficient cauliflower of the Snowball "M" variety was observed in Allegan county in 1954 (Figure 8). Typical leaf cupping and crinkling were noted. Adjacent plants which had been sprayed with a sodium molybdate solution at the rate of 8 ounces of the salt per acre did not exhibit these symptoms.

It was essential to increase the pH of the very acid Nester orchard soil before growth of cauliflower past the first-leaf stage was obtained. However, when seedlings from the unlimed soil were transplanted into a greenhouse soil, they resumed apparent normal growth. Bear and Toth (8) found in New Jersey that soil to which hydrated lime had been applied had its highest pH immediately after application, with rapid reduction the first day and more gradual reduction throughout a three-week period. Jorgensen (35) achieved maximum pH on a sandy loam soil within one or two days following application of hydrated lime.

Soil pH changes are shown in Figure 9. The desired pH levels were not attained. Maximum pH values were attained most quickly in the sandy loam, but at the end of 88 days were highest in the muck.

Figure 10 shows that the high correlation observed between the base saturation percentage and the soil reaction of individual limed soils in the field was also evidenced with the greenhouse soils. The initial base saturation percentage of the muck was three to eight times that of either of the mineral soils.

Although growth of cauliflower plants in the unlimed Nester soil was insufficient for collection of plant samples, an increase in the molybdenum content of the cauliflower plants with increased soil pH was found in both the Montcalm and Houghton soils, as shown in Table X and



Figure 8. Molybdenum-deficient cauliflower in Allegan County, Michigan. Note inward cupping and crinkling of leaves.

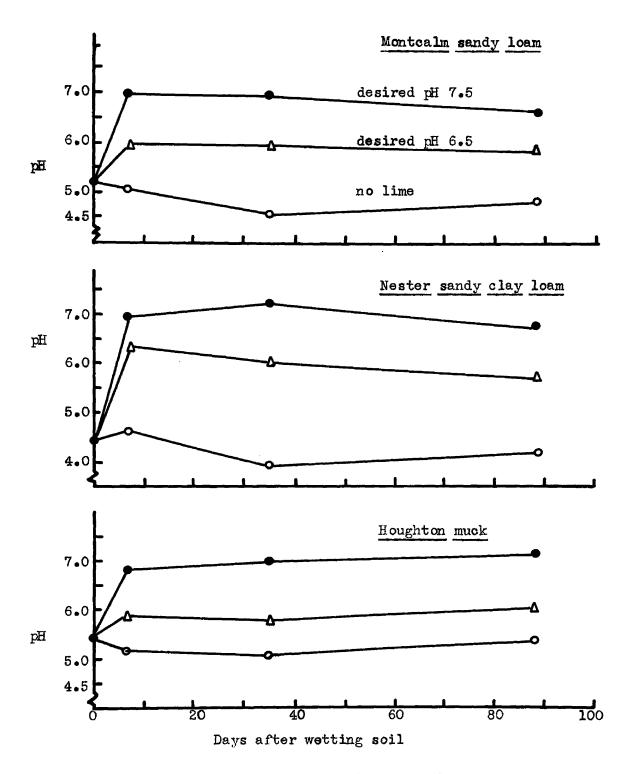


Figure 9. The effect of calcium hydroxide on soil reaction when applied at different rates to three Michigan soils in a greenhouse experiment.

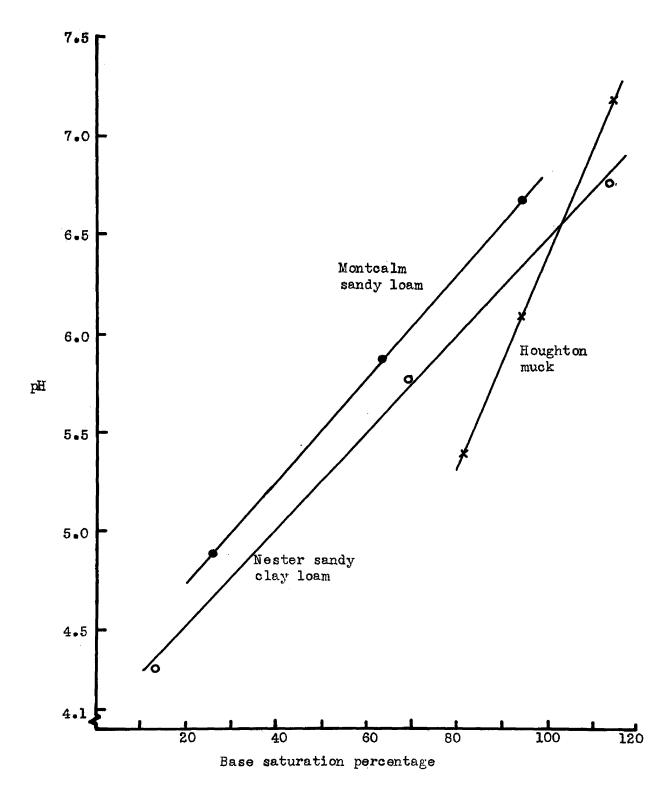


Figure 10. Correlation between base saturation percentage and soil reaction of three soils from a greenhouse experiment.

Table X. The effect of lime upon soil reaction and molybdenum content of cauliflower leaves.

Soil	Lime rate	Molybdenum in leaves	Soil pH
•		ppm	•
Montcalm sandy loam	Ö	0.411	4.9 ¹
	1	1.11	5.9
	2	2.12	6.7
Nester sandy	0	2	4.3
clay loam	1	1.41	5.8
	2	1.99	6.8
Houghton muck	0	2.02	5.4
	1	3.94	6.1
	2	7.32	7.2

¹ Average of three replications

² Plants did not develop beyond the primary-leaf stage

and Figure 11. Moore (50), Evans, et al (28) and others have found similar relationships.

A highly significant correlation of 0.932, as shown in Figure 12, was also found between pH and molybdenum in the leaves of corn grown in 1955 in Washtenaw County on the Morley clay loam, regardless of the liming material. The molybdenum content varied from 1.08 ppm at pH 5.9 to 2.00 ppm at pH 6.4.

Possibilities of excess molybdenum. An excess of molybdenum in herbage for livestock feed should be avoided. Davies (20) recommends a five to six year period between molybdenum applications. In the greenhouse, liming alone did not raise the molybdenum content of the cauliflower grown on the mineral soils to more than 2.12 ppm as shown in Table X. However, on the muck which was limed to pH 7.2, molybdenum content of the cauliflower leaves increased to 7.2 ppm. Fiskell, et al (29) found 11 ppm molybdenum in corn grown on an Everglades peat. Although less than the 10 ppm previously suggested as a maximum for forage plants, added molybdenum to Michigan organic soils under such conditions might increase the molybdenum content of the plants above the danger level insofar as livestock feed is concerned. However, liming to high pH values on muck decreased yield, so this practice ordinarily would not be followed. An increase from 2.4 to 6.20 ppm in mature oats grown in Ogemaw County on the limed Nester soil resulted from spraying the young plants with a molybdenum solution. Generally, spraying doubled the molybdenum content of the oat plants. Fiskell, et al (29) reported similar effects in corn grown on a Norfolk loamy fine sand to which had been added four ounces per acre of sodium molybdate.

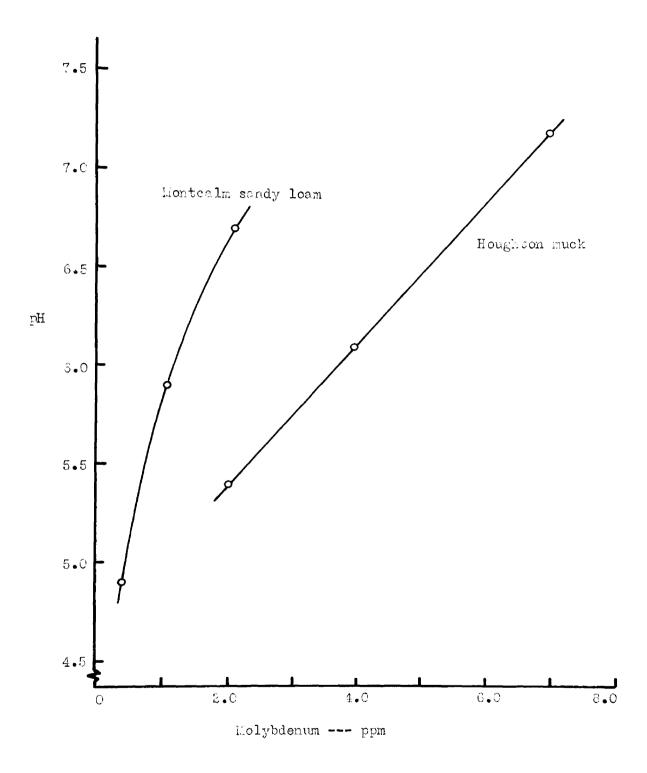


Figure 11. Correlation between molybdonum content of cauliflower leaves and soil pH in a greenhouse experiment.

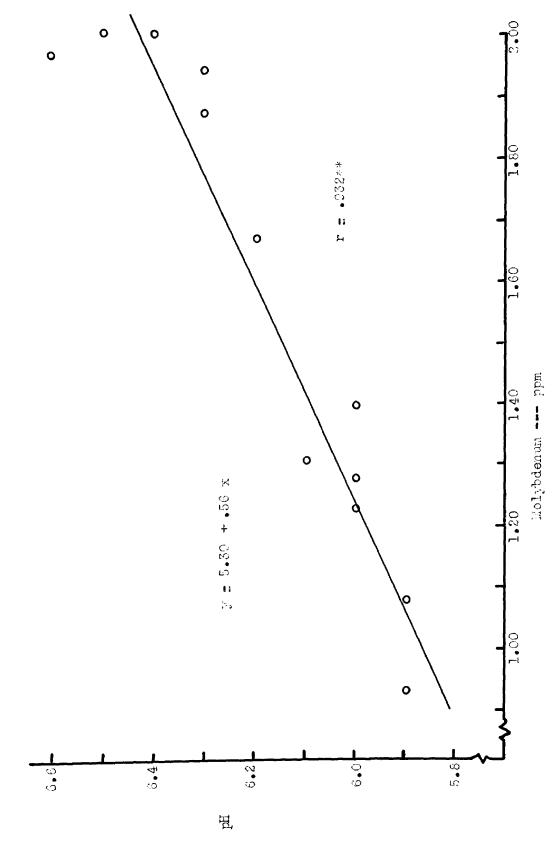


Figure 12. Correlation between the molybdanum content of the sixth leaf of command the soil reaction of a limed Lorley clay loam.

SUMMARY AND CONCLUSIONS

Field and greenhouse studies were conducted during the period of 1954 to 1957. The effects of lime and molybdenum applications upon the soil reaction and base saturation percentage and upon the yields of several crops grown on different Michigan soils were determined. These included oats and alfalfa-grass hay from a Nester sandy clay loam, corn from a Morley clay loam, field beans, wheat and red clover from a Montcalm sandy loam, and cauliflower from a Nester sandy clay loam orchard soil, a Montcalm sandy loam and a Houghton muck.

Acetylene by-product lime increased both the soil pH and the base saturation percentage faster and to higher values than did the other liming materials which were investigated.

Similarly, calcitic meal was the most effective when applied to a Nester sandy clay loam and a Montcalm sandy loam, whereas dolomitic meal was the most effective on a Morley clay loam. Pulverized dolomite was more effective than dolomitic meal. Water-quenched blast furnace slag was the least effective form of liming material.

A high degree of correlation was found between the soil reaction and the base saturation percentage within each limed soil, regardless of the liming material and the rates of application.

No significant increases occurred in the yields of crops grown on the limed soils which had an initial pH near 6.0 or above.

A high degree of correlation was found between the molybdenum content of plants and the soil reaction, expressed in some cases as the pH and in others as the log of the hydrogen ion concentration.

Yields of cauliflower and of red clover were significantly increased by soil applications of lime to a Montcalm sandy loam.

Yields of the plants grown on a Montcalm sandy loam were increased significantly by residual and direct spray applications of molybdenum.

Molybdenum-deficiency symptoms observed on cauliflower grown in Allegan County did not appear on plants which were sprayed with molybdenum.

Although the yields of cauliflower and of red clover were increased more by lime alone than by molybdenum alone on the Montcalm sandy loam, the highest yields were obtained by the application of molybdenum plus low rates of lime, irrespective of the lime source. Yields were not further increased by higher rates of lime plus molybdenum.

The molybdenum content of cauliflower, corn and oats increased with an increase in soil pH. Molybdenum treatment doubled the molybdenum content of oat plants.

Additional research on the molybdenum status of crops and soils in Michigan is needed to further explore the molybdenum-supplying capabilities of these soils and of crop varieties which are less susceptible to molybdenum deficiency when grown on these soils.

LITERATURE CITED

- 1. Albrecht, W. A. Plant nutrition and the hydrogen ion. V. Relative effectiveness of coarsely ground and finely pulverized limestone. Soil Sci. 61:265-271, 1946.
- Anderson, A. J. Molybdenum deficiency on a South Australian ironstone soil. Jour. Aust. Inst. Agr. Sci. 8:73-75, 1942.
- 3. Molybdenum deficiencies in legumes in Australia. Soil Sci. 81:173-182, 1956.
- 4. Arnon, D. I. and P. R. Stout. Molybdenum as an essential element for higher plants. Plant Physiol. 14:599-601, 1939.
- 5. Arnon, D. I. and C. M. Johnson. Influence of hydrogen-ion concentration on growth of higher plants under controlled conditions. Plant Physiol. 17:525-539, 1942.
- 6. Association Official Agricultural Chemists. Methods of Analysis. Ed. 7, Washington, D. C., 1950.
- 7. Beacher, R. L., D. Longnecker and F. G. Merkle. Influence of form, fineness, and amount of limestone on plant development and certain soil characteristics. Soil Sci. 73:75-82, 1952.
- 8. Bear, F. E. and S. J. Toth. The pH values of lime requirements of 20 New Jersey soils. N. J. Agr. Expt. Sta. Circ. 446. 15 pp., 1942.
- 9. Benne, E. J. and Doris M. Jerrim. Report on molybdenum in plants. Jour. Assoc. Official Agr. Chemists 39:412-419, 1956.
- 10. Report on molybdenum in plants. Jour. Assoc. Official Agr. Chemists 40:370-373, 1957.
- 11. Bergman, E. L. and A. L. Kenworthy. Molybdenum deficiency and nitrate toxicity on Concord grapes. Mich. Agr. Expt. Sta. Quart. Bul. 38:524-527, 1956.
- 12. Black, C. A. and C. A. I. Goring. Organic phosphorus in soils. In Soil and Fertilizer Phosphorus in Crop Nutrition. Agron. Monograph 4:123-152, 1953.
- 13. Bortels, H. Molybdenum as a catalyzer in biological nitrogen-fixation. Arch. Mikrobiol. 1:333-342, 1930.

- 14. Bouyoucos, G. J. Directions for making mechanical analyses of soils by the hydrometer method. Soil Sci. Soc. Amer. 42:225-229, 1936.
- 15. Bradfield, R. and W. H. Allison. Criteria of base saturation in soils. Trans. Second Comm. Internat. Soc. Soil Sci. A:63-79, 1933.
- 16. Bray, R. H., and E. E. DeTurk. Field method for lime requirement of soils. Soil Sci. 32:329-341, 1931.
- 17. Clayton, E. E. Investigations of cauliflower diseases on Long Island. N. Y. State Agr. Expt. Sta. Bul. 506. 15pp. with plates, 1924.
- 18. Cook, R. L. Divergent influence of degree of base saturation of soils on the availability of native, scluble, and rock phosphates. Jour. Amer. Soc. Agron. 27:297-311, 1935.
- 19. Davies, E. B. A case of molybdenum deficiency in New Zealand. Nature 156:392, 1945.
- 20. Introduction to symposium on molybdenum. New Zealand Soil News No. 3, 1953.
- 21. Dean, H. L. Some bacteriological and chemical effects of calcium and magnesium limestones on certain acid Iowa soils. Iowa State Col. Jour. Sci. 10:69-71, 1935.
- 22. Effects of liming on the liberation of potassium in some Towa soils. Iowa Agr. Expt. Sta. Res. Bul. 197, 1936.
- 23. Dick, A. T., and J. B. Bingley. The determination of molybdenum in plant and in animal tissue. Aust. Jour. Expt. Biol. Med. Sci. 25: 193-202, 1947.
- 24. Further observations on the determination of molybdenum in plant and animal tissue. Aust. Jour. Exp. Biol. Med. Sci. 29:459, 1951.
- 25. Dick, A. T. Molybdenum in animal nutrition. Soil Sci. 81:229, 1956.
- 26. Duncan, D. B. Multiple range and multiple F tests. Biometrics 2: 1-42, 1955.
- 27. Evans, H. J. The importance of molybdenum in fertilizers. Agr. Chemicals 5(8):31-32, 72-75, 1950.

- 28. Evans, H. J., E. R. Purvis and F. E. Bear. Effect of soil reaction on availability of molybdenum. Soil Sci. 71:117-124, 1951.
- 29. Fiskell, J. G. A., L. G. Thompson, Jr., H. Winsor and T. L. Yuan. Relative availability to corn of nutrient elements as affected by minor element sources applied to Everglades peat and Norfolk loamy fine sand. Agron. Jour. 49:300-306, 1957.
- 30. Floyd, B. F. Leaf spotting of citrus. Florida Agr. Expt. Sta. Ann. Report 91, 1908.
- 31. Gammon, N., Jr., G. M. Volk, E. N. McCubbin and A. H. Eddins. Soil factors affecting molybdenum uptake by cauliflower. Soil Sci. Soc. Amer. Proc. 18:302-305, 1954.
- 32. Hewitt, E. J. Symptoms of molybdenum deficiencies in plants. Soil Sci. 81:159-171. 1956.
- 33. Hoyert, J. H. and J. H. Axley. Influence of liming materials on pH values of six Maryland soils. Soil Sci. 73:61-69, 1952.
- 34. Jensen, S. Torborg. The liming problem. Int. Soc. Soil Sci. I: 93-106, 1952.
- 35. Jorgensen, J. R. The effect of kind, amount and particle size of lime on reaction, residual carbonates and exchangeable calcium, magnesium and potassium in an organic and a mineral soil. Unpublished M. S. thesis, Mich. State Univ., pp 73, 1957.
- 36. Kelley, W. P. The agronomic importance of calcium. Soil Sci. 39: 103-109, 1935.
- 37. Lipman, J. G., A. W. Blair, H. C. McLean and A. L. Prince. A comparison of magnesium and non-magnesium limestone in some 5-year rotations. Soil Sci. 15:307-328, 1923.
- 38. McCall, W. W. A study of the effect of mineral phosphates upon the organic phosphate content of organic soils. Unpublished Ph.D. thesis, Mich. State College, 1953.
- 39. McCool, M. M. and C. E. Millar. Some general information on lime and its uses and functions in soils. Mich. Agr. Coll. Expt. Sta. Spec. Bul. 91, 1918.
- 40. McGeorge, W. T. Factors influencing the availability of native soil phosphate and phosphate fertilizers in Arizona soils. Ariz. Agr. Expt. Sta. Tech. Bul. 82, 1939.

- 41. Marshall, C. E. Ionization of calcium from soil colloids and its bearing on soil-plant relationships. Soil Sci. 65:57-68, 1948.
- 42. Mehlich, A. Use of triethanolamine acetate barium hydroxide buffer for the determination of some base exchange properties and lime requirement of soil. Soil Sci. Sco. Amer. Proc. 3: 162-166, 1938.
- Soil Sci. Soc. Amer. Proc. 6:150-156, 1941.
- Base saturation and pH in relation to liming and nutrient conservation of soil. Soil Sci. Soc. Amer. Prod. 7: 333-361. 1942.
- 45. Mehring, A. L. Fertilizers. In F. C. Blanck, ed. Handbook of Food and Agriculture. Reinhold Publishing Co., New York, 1955.
- 46. Meyer, T. A. and G. W. Volk. Effect of particle size of limestones on soil reaction, exchangeable cations, and plant growth. Soil Sci. 73:37-52, 1952.
- 47. Midgley, A. R. Lime its importance and efficient use on soils. Soil Sci. Soc. Amer. Proc. 8:329, 1944.
- 48. Miles, I. E. Available calcium supply in poorly buffered soils. Soil Sci. 65:97-102, 1948.
- 49. Millar, C. E. Lime for Michigan soils. Mich. State Coll. Ext. Bul. 57 (revised), 1932.
- 50. Moore, C. W. E. Pot culture studies of the copper and molybdenum content of certain pasture plants. Aust. Jour. Agr. Res. 1:43-57, 1950.
- 51. Morgan, M. F. Base exchange capacity and related characteristics of Connecicut soils. Soil Sci. Soc. Amer. Proc. 4:145-149, 1939.
- 52. Opitz, K., E. Mergenroth and W. Knies. Relation between lime and potash in the soils of the Bornim permanent experiments. Fersch Dienst 7:243-254, 1939; Bib. of Minor Elements, ed. 4, 1:232, 1948.
- 53. Peech, M. Availability of ions in light sandy soils as affected by soil reaction. Soil Sci. 51:473-486, 1941.
- 54. Peech, M. and R. Bradfield. Chemical methods for estimating needs of lime. Soil Sci. 65:35-55, 1948.

- 55. Pierre, W. H. and G. D. Scarseth. Determination of the percentage base saturation of soils and its value in different soils of definite pH values. Soil Sci. 31:99-114, 1931.
- 56. Porter, J. A., P. J. Rood and E. D. Longnecker. Lime and its uses. Mich. Agr. Expt. Sta. Ext. Bul. 314. 36 pp., 1952.
- 57. Powers, J. F. Effects of lime and fertilizer on plant growth and composition. Unpublished Ph.D. thesis, Mich. State Coll., 1954.
- 58. Pretty, K. M. The effect of certain liming practices upon the chemical composition and properties of several Michigan soils. Unpublished M. S. thesis, Mich. State Univ., 84 pp., 1955.
- 59. Ririe, D., S. J. Toth and F. E. Bear. Movement and effect of lime and gypsum in soil. Soil Sci. 73:23-35, 1952.
- 60. Robinson, W. O. and L. T. Alexander. Molybdenum content of soils. Soil Sci. 75:287-291, 1953.
- 61. Rubins, E. J. Molybdenum deficiencies in the United States. Soil Sci. 81:191-197, 1956.
- 62. Russel, E. J. Soil conditions and plant growth. 8th ed. rev. Longmans, Green and Co., New York, 1954.
- 63. Scarseth, G. D., and J. W. Tidmore. The fixation of phosphates by clay soils. Jour. Amer. Soc. Agron. 26:152-162, 1934.
- 64. Schollenberger, C. J. Lime requirement and reaction of lime materials with soil. Soil Sci. 11:261-276, 1921.
- 65. Shimp, N. F. A study of the relationship between pH, exchangeable calcium, percent base saturation, and lime requirement in some Michigan soils. Unpublished M. A. thesis, Mich. State Coll., 42 pp., 1951.
- 66. Spurway, C. H. and K. Lawton. Soil Testing. A practical system of soil fertility diagnosis. 4th rev. ed. Mich. Agr. Expt. Sta. Tech. Bul. 132. 32 pp., 1949.
- 67. Stewart, Robert and F. A. Wyatt. The comparative value of various forms of limestone. Soil Sci. 1:273-278, 1919.
- 68. Stout, P. R., W. R. Meagher, G. A. Pearson and C. M. Johnson. Molybdenum nutrition of crop plants. I. The influence of phosphate and sulfate on the absorption of molybdenum from soils and solution cultures. Plant and Soil III:51-86, 1951.

- C9. Thorne, D. W. and L. F. Seatz. Acid, alkaline, alkali, and saline soils. Chemistry of the soil, F. E. Bear, editor. ASC Monograph No. 126. Reinhold Pub. Comp., New York, 1955.
- 70. Truog, E. Soil acidity and living. USIA Fourtook of Agriculture, 583-580, 1938.
- 71. United States Salinity Laboratory. Diagnosis and improvement of saline and alkali soils. USDA Handbook No. 60. Gov. Frint. Office, Wash. D. G., 1954.
- 72. Van Arsdell, W. J., G. A. Branaman, C. M. Harrison and J. F. Davis. Pasture results with stears on Read Connry Grass. Mich. Agr. Exat. Sta. Quart. Bul. 37:125-131, 1854.
- 73. Walker, R. B. Molyèdenum deficiency in serpentine barren soils. Science 108:473-475, 1948.
- 74. York, E. T. and R. T. Rogers. Influence of lime on the solubility of potassium in soils and on its availability to plants. Soil Sci. 03:467-477, 1947.