LIME CONTENT OF SOIL IN RELATION TO CROP RESPONSE TO MAGNESIUM

By

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INTRODUCTION

Magnesium is an important constituent of chlorophyll and it constitutes about 2.7 per cent of the chlorophyll molecule. Proper functioning and efficiency of the leaf, therefore, depends to a large extent on the presence of an adequate amount of magnesium. Better and proper utilization of the fertilizers applied to soil requires a large and efficient leaf area. The presence of adequate amount of magnesium plays an important part in this regard. Magnesium is also considered as a carrier of phosphorus. It is associated with seed formation; carbohydrate production and transport. Accumulation of nitrogen by legumes is increased by the presence of magnesium. Thus, the importance of an adequate supply of magnesium in plant and fertilizer economy is evident.

Lime--Magnesia Hypothesis

An excess of magnesium is highly toxic to green plants. Calcium in suitable concentration counteracts this toxicity. Loew (35,36)* in 1892, developed the "Lime--magnesia" hypothesis and proposed that calcium and magnesium should be

*Figures in parenthesis refer to "Literature Cited."

present in a definite ratio for the proper functioning and growth of plants although the optimum ratio would vary with the plant species. This has prompted many investigations in soil, sand and water-cultures. Lipman (34) in an exhaustive summary has shown that all these investigations had not led to a general agreement on the interpretation of this hypothesis.

In all these investigations very little attention was paid to the degree of saturation of the exchange complex of soil in determining the optimum Ca:Mg ratio for the growth of plants and to what extent the variation in the Ca:Mg ratio influenced the mineral and organic composition of the plants. There is a growing tendency to associate the health and well-being of man and animals with the food they eat. Soil is one of the potent factors in determining the composition of plants. So any variation in the Ca:Mg ratio in the soil may influence the composition of plants. Thus a study of the Ca:Mg ratio from these two aspects appears to be warranted.

THE OBJECT OF THE INVESTIGATION

The object of the present investigation is to study the interaction of Calcium and Magnesium as influenced by the degree of saturation of the exchange complex in relation to crop response to magnesium and the extent to which the mineral composition of crops are influenced by such interactions.

REVIEW OF LITERATURE

Gedroiz (20) was one of the first to point out the importance of calcium in the nutrition of plants. It was found that oats could not develop in a H-saturated soil. He then saturated the soil with sixteen different cations and brought them to neutral reactions. None of them could support the growth of oat plants but a slight addition of lime improved the growth to a great extent. With the development of the concept that exchangeable cations held on the surface of soil colloids are generally available to plants, it has been observed that the degree of saturation of the ion determines it's availability provided all other factors are constant. Even though the cations are assimilated directly by plants, lowering the saturation of one with respect to the other will decrease its availability.

Jenny and Cowan (27) found that soybeans did not grow when the calcium saturation in a Ca-H system fell below 30 per cent of the total exchange capacity. Ratner (48) did not succeed in growing oats in a sodium-calcium clay system when calcium saturation fell below 30 - 40 per cent. Albrecht and MacCalla (2) from their sand-colloid cultures found that the availability of Ca from Ca-H system increased regularly with increase in per cent Ca-saturation. Thorne (58) in a sodium-calcium system found that growth of tomato plants was reduced markedly when the calcium saturation fell below 50 per cent of the total saturation capacity. Arnon and Grossenbacher (4), in amberlite-sand mixtures, found that poor growth of tomato was associated with low saturation of divalent cations. Even 46.6 per cent saturation failed to induce good growth. Bower and Turk (10) have shown that alkali soils with high sodium saturation failed to supply calcium to plants despite the presence of free $CaCo_3$.

The Ca-Mg interaction may also be influenced by the kind of complementary ions present. Jenny and Ayres (26) have shown that uptake of K by excised barley roots was influenced by the presence of NH_4, Ca, Na and H ions. Ammonium ion had the greatest and calcium the least effect while sodium and hydrogen occupied intermediate positions. Van Itallie (61) showed that exchangeable calcium had very little influence on the uptake of potassium by the Italian Rye grass while magnesium distinctly depressed the absorption of potassium.

Availability of exchangeable cations in different soils that are at a given degree of saturation varies with the nature of colloids in each soil. Allway (1) and Mehlich and Colwell (42) have shown that greater percentage of release of calcium was obtained from colloids of 1:1 lattice type than from the 2:1 type. Mehlich and Reed (43) have also shown that the organic colloids exert greater influence on the uptake of nutrients than mineral colloids of either 1:1 or 2:1 types.

Thus the mutual replacement or antagonism between calcium and magnesium does not depend upon a definite ratio of the two but rather on the degree of saturation, nature of complementary ions, and the type of colloids present in the soil.

PLAN OF THE EXPERIMENT

No attempt was made to prepare Ca or Mg saturated clays and diluting them with inert quartz sand to get the desired degree of base saturation. Such prepared culture media do not approach the microbiological and natural properties of soil during the growth of the crop.

Alkaline calcareous soil relatively rich in exchangeable calcium and acid sandy soils relatively low in exchangeable calcium and magnesium were used for the present investigation. Wisner loam represents the first type while Plainfield and Fox sand represent the latter type of soil. A subsoil with very low cation exchange capacity and containing very little colloidal material, either mineral or organic, was taken as an intermediate between the loam and the sandy soils. Due to the fact that the delivery of cations is influenced by the original cation exchange capacity of soils these three kinds of soil permitted further investigation of this point. Quartz sand culture was included in order to compare the uptake of nutrients from a solution with that from the soils.

The effect of varying calcium levels on plant growth and composition was determined with four different levels of calcium saturation in combination with four different levels of magnesium saturation at each level of calcium saturation. Calcium was applied in amounts to supply 50, 75, 100 and 150 per cent saturation while magnesium was applied in amounts to supply 10, 25, 50, 75 and 100 per cent saturation of the cation exchange capacity of each soil. The percentage calcium and magnesium saturations were made up by adding quantities of these two elements through suitable salts to the amounts already contained in the exchange complex of each soil. Calcium and magnesium were applied to the sand culture on a milliequivalent basis within a certain ratio comparable to that of each soil. Thus the results can be evaluated on the basis of (1) increasing amounts of magnesium with a constant calcium level and (2) the changes caused by variations in the proportion of the two cations at constant levels of base saturation.

The complementary cations, as well as all other nutrients, were kept constant and in sufficient amount for each type of crop grown. The level of N - P - K was kept constant by checking with the Spurway test (54) at intervals of two weeks during the growth of the crops. Sufficient amounts were added in order to bring the nutrients to the same level as they were at the start of the experiment.

DESCRIPTION OF SOIL TYPES USED FOR THE INVESTIGATION

Detailed description of the soil types used for the greenhouse experiments are to be found in the Soil Survey Report Series No. 19 of 1933, No. 27 of 1929, and No. 12 of 1936 of Saginaw, St. Clair and Clinton Counties of Michigan, respectively. A brief description of each soil type is presented below.

Wisner Sandy Loam. The soil is derived from the old beds of the glacial lakes. It is situated in the river flood plain and is very young and poorly developed. The soil contains free lime carbonate and is darkened with a relatively small amount of organic matter. The surface soil is ordinarily alkaline and lime is invariably abundant at depths of 18 - 24 inches.

Plainfield Sand. The soil is largely outwash and valley train deposits; is light grayish-brown loamy fine sand poorly supplied with organic matter. The surface layer is underlain by incoherent light yellowish brown fine sand. The soil is strongly acid in reaction and the capacity for retention of water is low.

Fox Sandy Loam. It occupies level to undulating outwash plains, terraces, valley-train deposits. Gravel occurs throughout the soil mass. It is low in organic matter and medium to strongly acid in reaction. The rather strongly acid reaction of the surface soil inhibits the growth of some plants, particularly the legumes.

<u>Hillsdale Subsoil</u>. This soil was obtained from a quarry at a depth of 40 - 50 inches. At this depth the material consists of limy yellowish gray friable sandy loam or clayey sandy loam of glacial drift. It contains free carbonates and is alkaline in reaction.

Soil Sampling and Preparation

The samples of Wisner, Plainfield and Fox soils were secured from the A horizon from a depth of 0 to 8 inches, while the Hillsdale subsoil was taken from the B horizon at a depth of 40 - 50 inches. The bulk samples were air-dried and passed through a one-fourth inch sieve and were mixed thoroughly.

The Quartz sand was soaked with 0.05 N HCl for a period of forty-eight hours after which it was washed with distilled water until free of chloride ions. The washed sand was then dried before use.

Analytical Methods

The mechanical composition of the soils was determined by the hydrometer method as described by Bouyoucos (13). Because of the presence of free carbonates in the Hillsdale subsoil and the Wisner soil they were first saturated with hydrogen. These hydrogen saturated soils were used for the determination of their mechanical composition. Free carbonates were determined by the method described by Piper (46) and organic matter content was determined by adopting Walkley and Black's rapid titration method (46). Exchangeable hydrogen was determined by using Triethanolamine buffered at pH 8 as described by Mehlich (41).

Wisner and Hillsdale subsoil contain a large amount of free carbonates. Because of the possible interference of free carbonates with the determination of Base Exchange Capacity by the Neutral Ammonium Acetate method described by Schollenberger and Simon (52), the potentio-metric titration methods of Puri and Uppal (47) were used. The results obtained by the two methods were within 0.5 - 0.8 milliequivalents. The procedure adopted for the potentiometric titration was as follows:

Fifty gram portions of air-dried soils were treated with 2 N HCl to dissolve all carbonates. The soil was then leached with successive 50 cc portions of 0.05 N HCl. The excess acid was washed with distilled water until the leachates were free from chloride ions and finally washed with 100 ml of 95% ethylalcohol. The hydrogen-saturated soils were dried at 80°C for 12 hours.

One gram of barium chloride was added to each of the hydrogen saturated soils and made into a paste with 25 ml. of distilled water. Each sample was then titrated with 0.1 N $Ba(OH)_2$ solution using the glass electrode. The titration curve for each soil is represented in Fig. 1. The milliequivalents of base necessary to adjust the pH to 7.0 was interpolated from the titration curve.

To avoid the depressing influence of calcium in

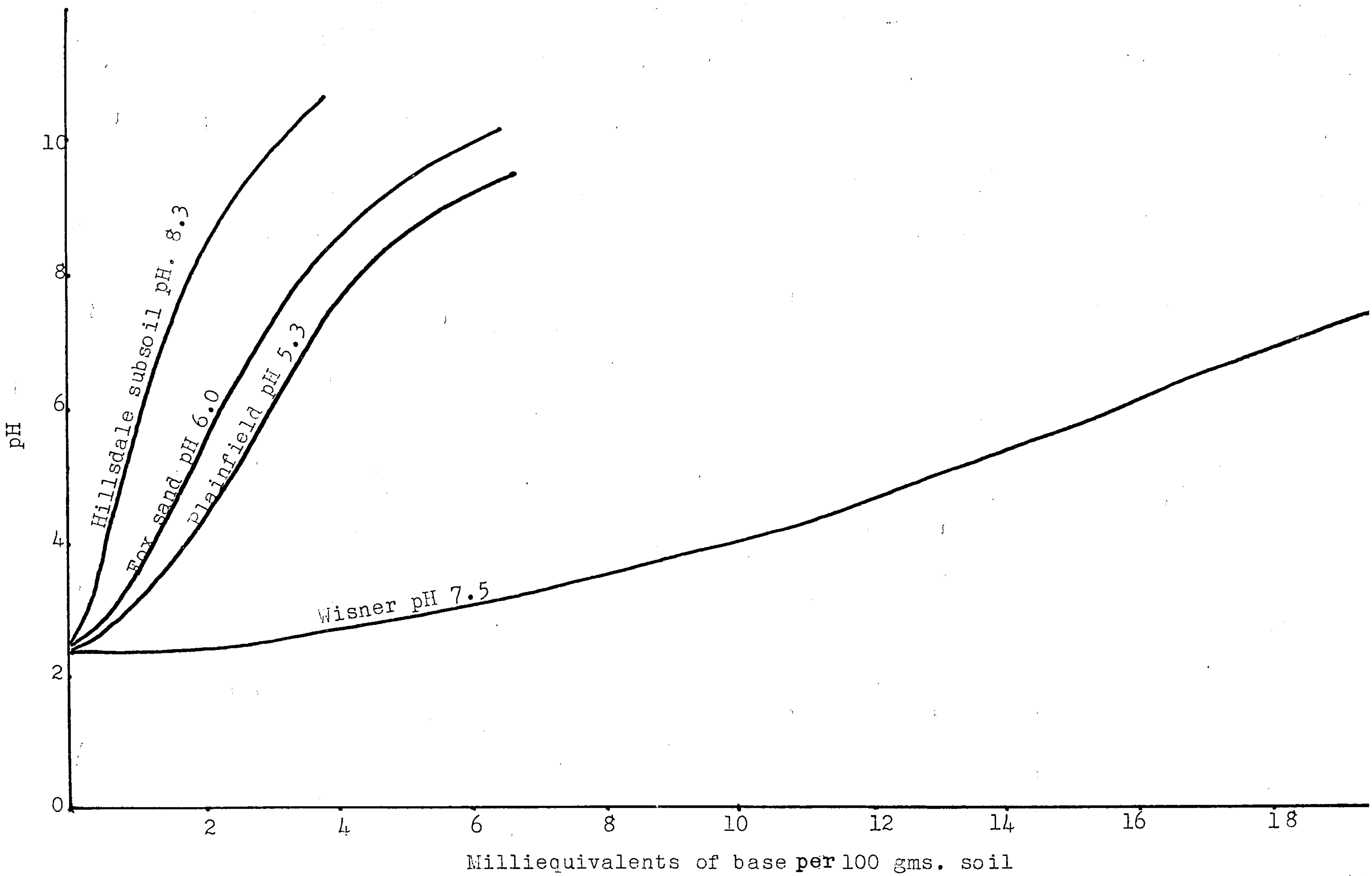

Fig. 1. Electrometric titration for "Base-exchange" and buffering capacity of the soils.

solution, in the soils containing free carbonates, upon calcium replacement from the colloidal complex, extraction of calcium and magnesium was made by using normal sodium chloride solution as suggested by Hissink (23). The difference in the calcium and magnesium content of the first and second liter portions was taken to be the exchangeable calcium and magnesium.

Calcium was precipitated as oxalate on the 10 ml aliquot and was estimated with potassium permanganate following the procedure of Chapman (14). Magnesium was determined photocolorimetrically, using 520 mμ filter in suitable aliquot with proper dilution by Titan yellow method of Peech and English (44).

Exchangeable potassium was extracted by leaching 50 gms of soil with neutral normal ammonium acetate solution (pH 6.9) as described by Schollenberger and Simon (52) and was determined volumetrically by titration of the potassium cobaltinitrite precipitate with standard potassium permanganate according to the method of Volk and Truog (62). Phosphorus was determined by molybdenum-reduced phosphomolybdate blue color method (32). All colorimeter readings were taken with Evelyn Photoelectric Colorimeter.

PHYSICAL COMPOSITION AND CHEMICAL CHARACTERISTICS OF THE SOILS

The physical and chemical determinations were carried out on each soil in an effort to evaluate their respective calcium and magnesium status as well as the fertility levels. The results of the analyses are presented in Tables I and II. The predominating soil separate is sand whereas the silt fraction is very low.

Data presented in Table II show show that all the soils have a higher content of calcium than of magnesium. In the Wisner, the ratio of calcium to magnesium is 17:1 while in the podsolized Plainfield, Fox and the Hillsdale subsoil the ratio is very narrow, varying from 2:1 to 4:1.

The Wisner and the Hillsdale subsoil are alkaline. This condition is generally favorable for calcium supply but unfavorable for phosphate availability. The presence of eight to nine per cent free calcium carbonate further retards phosphate availability. Plainfield and Fox sandy loam are acid in reaction and have a low degree of base saturation. These conditions are not favorable for the supply of bases or for keeping phosphorus available. They need lime and fertilizers for successful growth of crops.

TABLE I

Some Mechanical and Chemical Characteristics of Soils Used

	Wisner	Plainfield	Fox sand	Hillsdale subsoil
	%	%	%	%
Sand[1]	71.2	82.8	87.8	91.8
Silt[2]	5.6	6.0	5.0	2.0
Clay[3]	23.2	11.2	7.2	6.2
Fine Clay[4]	19.2	9.2	5.2	5.2
Organic Matter	4.3	0.07	0.08	0.03
Free Carbonate	9.5	Nil	Nil	9.05

1 2.0 - 0.02 mm

2 0.02 - 0.002 mm

3 .002 mm

4 2 hrs. reading

Table II

Chemical Characteristics of the Soils Used

Soil	pH	Base Exchange Capacity M.E. per 100 gm. Soil	Replaceable Bases M.E. per 100 gm. Soil				Relative proportion of bases. Percent of total				Ratio of the Cations (1)			Total N	Total P ppm
			Ca	Mg	K	H	Ca	Mg	K	H	Ca/Mg	K/Mg	K/Ca		
Wisner	7.5	18.32	16.75	0.98	0.15	0	91.43	5.35	0.82	0	17:1	0.16:1	0.008:1	0.25	0.35
Plainfield	5.3	3.56	1.10	0.63	0.08	1.7	30.89	17.69	2.24	47.75	1.74:1	.13:1	0.07:1	0.04	0.05
Fox Sand	6.0	3.39	1.24	0.31	0.03	1.8	36.57	9.14	0.88	53.10	4:1	1:1	0.02:1	0.05	0.06
Hillsdale Subsoil	8.3	1.32	0.92	0.30	0.02	0	69.69	22.72	1.51	0	3:1	.07:1	.02:1	0.02	Less than 0.02

(1) Calculated on basis of milligram equivalents, rather than weight equivalents.

EXPERIMENTAL PROCEDURE

Fertilizer Application

A summary of the treatments for the four different soils and the quartz sand culture is given in Tables III, IV, V, VI and VII.

Calcium was applied as calcium hydroxide, magnesium as the sulfate and potassium as the chloride. The rate of application of potassium was 10 P.P.M. for tomato and 15 P.P.M. for tobacco and corn. Nitrogen was applied at the rate of 90 milligrams for ten pounds of soil while Phosphorus was applied at the rate of 24 P.P.M. Nitrogen was supplied partly as ammonium nitrate and partly as mono-ammonium phosphate.

Solutions of sodium iodide, copper sulfate, ferrous sulfate, manganous sulfate and sodium borate were applied to the quartz sand to give concentrations of 2, 4, 8, 10, 2 and 8 P.P.M. of iodine, copper, iron, manganese, zinc and boron, respectively. Eight applications of these minor elements were made during the growing period of the crop.

Proper amounts of calcium hydroxide and magnesium sulfate for each treatment were thoroughly incorporated with required amount of soil before placing the soil into the pots. The nitrogen, phosphorus and potassium fertilizers were applied in solution. All chemicals used were of C.P. grade. After the application of fertilizers the soils were kept in a moist condition for two weeks to permit equilibrium adjustments before planting the crops.

Cultural Methods

Glazed earthenware jars were employed throughout the investigation. One trial series was carried out in one gallon jars, each filled with ten pounds of soil or quartz sand. Two crops were grown in containers of 2 gallon capacity, each filled with twenty pounds of soil or quartz sand.

Throughout the experiments, the moisture content of the soils was maintained at approximately their moisture-equivalent capacity while in the case of quartz sand, the moisture was maintained at 8 per cent by weight. Approximately equal moisture conditions were maintained by weighing the pots. Distilled water was used and no drainage was permitted from the pots. Usual precautions were taken to equallize light and temperature conditions in the greenhouse.

The treatments on white quartz sand were replicated three times and all other treatments on mineral soils were replicated five times. All the replicates for a particular soil were arranged in a randomized manner. Of the five replications for each of the treatments, two were utilized for either green tissue study or for study of any nutritional disorders. Growth and yield data were recorded from three replicates of each treatment.

Three crops, tomato, tobacco and corn, were grown in the four mineral soils as well as in quartz sand. These crops were not grown in succession. Each crop was grown in freshly prepared soil and quartz sand.

The experiments were carried out during the spring, summer and early fall of the year 1948. Tomatoes were grown in the period from April 5th to July 30th, 1948; tobacco from July 15th to October 5th, 1948; while corn was grown from August 15th to October 15th, 1948. No artificial illumination of the greenhouse was used. As it was not possible to grow each crop in the four different soils and in quartz sand at the same time, seeding was so adjusted that the period of growth of a particular crop in each soil was the same. The exact date of seeding and harvesting of each crop is shown in Tables III, IV, V, VI and VII.

Tomato. Tomato, Master Marglobe variety procured from the Horticultural Department, M.S.C., was the first crop grown. Three seeds were sown in each pot. Two weeks after germination the plants were thinned to one per pot. The plants were allowed to grow for 105 days.

Tobacco. Yellow special, a flue-cured tobacco secured from Bright Tobacco Field Station, Chatham, Virginia, was grown as the second test crop. Sufficient seedlings were grown in quartz sand to permit selection for size and uniformity. The seedlings were transplanted after the development of the second pair of leaves. A single plant was grown in each pot. Harvesting was done after a growth period of 70 days.

Corn. Michigan hybrid 51B, a midseason variety of corn, was sown as the third crop. Three grains of corn of uniform weight were planted in each pot. The stand was thinned to one plant per pot one week after germination. The crop was allowed to grow for a period of eight weeks, after which the above ground portion was harvested.

Soil samples were taken following the removal of each crop. Soils of the three replicated pots were mixed together and a composite sample from this was taken for analysis.

Preparation of Plant Materials

After the harvest of the crops, the materials were dried in paper bags for two days in the greenhouse and then dried at 70°C for three days, after which the dry weights were taken. Usually two weighings at an interval of two days were made as a check to insure constant weight.

The dried plant materials of the three replicated pots for each treatment were mixed and ground in a Wiley mill to pass through a 40 mesh sieve. These were then carefully mixed and sampled for analysis. Two gram portions of the oven dry tissue were dry-ashed in an electric furnace at 350°C for eight hours. The ash was taken up in hydrochloric acid and the extract diluted to 50 milliliters. Aliquots of this extract were taken for analysis of calcium, magnesium, potassium and phosphorus.

Calcium and magnesium were determined by the methods described under the "Ahalysis of Soil." Potassium was determined by the dipicrylamine procedure as described by Lawton (33).

Nitrogen Fractions

Total nitrogen, including nitrates, was determined in appropriate aliquots of dried tissue by the modified Kjeldahl-Gunning method. Hot water extracts of the dried tissue were used for the determination of total soluble nitrogen. The extracts were obtained by boiling appropriate aliquots in about 60 cc of water for five minutes. The suspension was cooled, allowed to stand overnight and the supernatant liquid was filtered through a dry filter paper. A total nitrogen analysis was made on the filtrate representing the total soluble nitrogen (15).

TABLE III

Summary of Treatments of the Greenhouse

Experiments on Quartz Sand

Treatment M.E. of Ca	Mg	Ca:Mg	pH At start	At Harvest Tomato	Tobacco	Corn
0.75			9.0	8.2	8.1	Corn not grown
1.50			9.2	8.4	8.3	
2.25			9.2	8.3	8.4	
3.00			9.4	8.5	8.8	
	0.06		6.6	6.5	6.5	
	0.12		6.4	6.3	6.2	
	0.24		6.2	6.2	6.2	
	0.60		6.2	6.2	6.2	
0.75	0.06	12.5:1	9.4	6.7	7.4	6.5
	0.12	6.25:1	9.2	6.7	7.4	6.5
	0.24	3.1:1	9.3	6.3	7.0	6.9
	0.60	1.25:1	9.3	6.5	7.5	6.9
1.50	0.06	25:1	8.7	7.5	8.5	8.0
	0.12	12.5:1	8.7	7.4	8.3	8.4
	0.24	6.25:1	9.0	7.3	8.3	8.2
	0.60	2.5:1	9.0	7.3	8.4	8.2
3.00	0.06	50:1	9.0	8.1	8.5	8.6
	0.12	25:1	8.9	8.0	8.7	8.4
	0.24	12:1	8.8	8.0	8.7	8.6
	0.60	5:1	8.8	7.9	8.6	8.6

Crops Grown: Tomato - 5th April to 19th July
Tobacco - 21st July to 28th Sept.
Corn - 20th Aug. to 14th Oct.

Equivalent amount of fertilizer applied:

0.75 M.E. Ca	=	1/2	ton	$CaCO_3$
1.50 "	=	1	"	"
2.25 "	=	1-1/2	"	"
3.00 "	=	2	"	"
0.06 M.E. Mg	=	100	lb.	$MgSo_4$
0.12 "	=	200	"	"
0.24 "	=	400	"	"
0.60 "	=	1000	"	"

TABLE IV

Summary of Treatments of the Greenhouse

Experiments on Wisner Soil

Degree of Saturation			pH			
				At Harvest		
Ca	Mg	Ca:Mg	At start	Tomato	Tobacco	Corn
%	%					
91.43	5.35	17:1	7.8	7.2	7.4	7.2
100	10	10:1	8.3	7.5	7.5	7.4
	25	4:1	8.0	7.4	7.3	7.4
	50	2:1	8.0	7.4	7.4	7.4
	75	1.3:1	8.1	7.2	7.4	7.4
	100	1:1	8.1	7.3	7.4	7.7
150	10	15:1	8.8	7.7	7.8	7.7
	25	6:1	8.6	7.5	7.7	7.5
	50	3:1	8.5	7.6	7.5	7.6
	75	2:1	8.7	7.7	7.8	7.7
	100	1.5:1	8.7	7.8	7.8	7.7

Crops Grown: Tomato - 5th April to 18th July
Tobacco - 15th July to 21st Sept.
Corn - 10th Aug. to 4th October

Amount of fertilizer added per acre to bring to desired saturation percentage:

100% Ca Sat. = 960 lb. $Ca(OH)_2$
150% " = 6,580 " "

10% Ma Sat. = 1,488 lb. $MgSO_4 3H_2O$
25% " = 6,312 " "
50% " =14,271 " "
75% " =22,291 " "
100% " =30,253 " "

TABLE V

Summary of Treatments of the Greenhouse Experiments on Plainfield Sand

Degree of Saturation			pH			
				At Harvest		
Ca %	Mg %	Ca:Mg	At start	Tomato	Tobacco	Corn
30.89	17.69	1.74:1	5.3	4.1	5.1	4.6
50	25	2:1	5.5	4.5	5.0	4.9
	50	1:1	5.3	4.5	4.7	4.8
	75	.75:1	5.3	4.6	5.1	4.9
	100	.5:1	5.3	4.7	4.7	4.7
75	25	3:1	6.1	5.3	5.4	5.5
	50	1.5:1	6.0	5.2	5.3	5.3
	75	1:1	5.9	5.0	5.2	5.3
	100	.75:1	5.9	5.1	5.1	5.9
100	25	4:1	6.6	5.6	6.0	5.9
	50	2:1	6.5	5.5	5.9	5.9
	75	1.3:1	6.3	5.5	6.1	5.8
	100	1:1	6.5	5.6	5.9	5.7
150	25	6:1	7.1	6.4	6.5	6.5
	50	3:1	7.1	6.1	6.4	6.5
	75	2:1	7.0	6.2	6.5	6.4
	100	1.5:1	7.0	6.2	6.6	6.9

Crops Grown: Tomato - 17th April to 30th July
Tobacco - 31st July to 9th October
Corn - 15th August to 15th October

Amount of fertilizer added per acre to bring to desired saturation percentage:

50% Ca Sat. = 400 lb. $Ca(OH)_2$
75% " = 960 " "
100% " = 1,500 " "
150% " = 2,580 " "
25% Mg Sat. = 453 lb. $MgSO_4 3H_2O$
50% " = 2,000 " "
75% " = 3,550 " "
100% " = 5,112 " "

TABLE VI

Summary of Treatments of the Greenhouse Experiments on Fox Sand

Degree of Saturation			pH			
				At Harvest		
Ca %	Mg %	Ca:Mg	At start	Tomato	Tobacco	Corn
36.57	9.14	4:1	5.6	5.3	5.0	5.5
50	25	2:1	5.9	5.0	5.1	5.4
	50	1:1	5.9	4.9	5.1	5.3
	75	.75:1	5.7	5.1	5.4	5.3
	100	.5:1	5.7	5.0	5.3	5.1
75	25	3:1	6.6	5.7	6.0	6.0
	50	1.5:1	6.5	5.6	5.9	6.0
	75	1:1	6.4	5.5	5.9	5.8
	100	.75:1	6.5	5.4	6.4	5.7
100	25	4:1	7.1	6.2	6.4	6.5
	50	2:1	7.0	6.0	6.4	6.3
	75	1.3:1	6.9	6.0	6.5	6.3
	100	1:1	6.9	6.0	6.4	6.5
150	25	6:1	7.7	6.9	7.1	7.1
	50	3:1	7.6	6.7	7.0	7.0
	75	2:1	7.5	6.8	6.9	7.2
	100	1.5:1	7.5	6.7	7.0	7.1

Crops Grown: Tomato - 15th April to 28th July
Tobacco - 25th July to 5th October
Corn - 15th August to 15th October

Amount of fertilizer added per acre to bring to desired saturation percentage:

50% Ca Sat.	=	336	lb.	$Ca(OH)_2$
75% "	=	963	"	"
100% "	=	1,591	"	"
150% "	=	2,845	"	"
25% Mg Sat.	=	937	lb.	$MgSO_4 3H_2O$
50% "	=	2,416	"	"
75% "	=	3,895	"	"
100% "	=	5,373	"	"

TABLE VII

Summary of Treatments of the Greenhouse Experiments on Hillsdale Subsoil

Degree of Saturation			pH		
				At Harvest	
Ca %	Mg %	Ca:Mg	At Start	Tomato	Tobacco
69.69	22.74	3:1	8.0	7.6	7.4
75	50	1.5:1	7.9	7.7	7.6
	75	1:1	7.9	7.7	7.6
	100	.75:1	7.7	7.6	7.3
100	50	2:1	8.1	7.8	7.6
	75	1.3:1	8.0	7.7	7.5
	100	1:1	7.8	7.7	7.4
150	50	3:1	8.7	7.8	7.6
	75	2:1	8.4	7.9	7.7
	100	1.5:1	8.2	7.8	7.6

Crops Grown: Tomato - 18th April to 29th July
Tobacco - 7th August to 15th October

Amount of fertilizer added per acre to bring to desired saturation percentage:

75% Ca Sat. = 51 lb. $Ca(OH)_2$
100% " = 296 lb. "
150% " = 784 lb. "

50% Mg Sat. = 645 lb. $MgSO_4 3H_2O$
75% " = 1,220 lb. "
100% " = 1,796 lb. "

PRELIMINARY EXPERIMENTS

Mobility of Applied Calcium and Magnesium Ions in the Different Soils

The relative concentration of exchangeable cations and their mobility or reactivity is affected by their degree of saturation on the absorption complex (25). The activity is also affected by the concentration of the ions in the soil solution and their ionization. The cations added to a system do not necessarily react with the exchange complex. Some of them might exist in the system as free cations and would not be absorbed by the colloids as exchangeable cations. In an effort to determine the actual amount of adsorption of calcium and magnesium added through fertilizers by different soils, the following experiments were carried in the laboratory.

Calculated amounts of calcium hydroxide and magnesium sulfate were mixed with 250 grams of each soil on the basis of degree of saturation of the exchange complex desired for the greenhouse experiments. They were kept at their proper moisture equivalents for a period of two weeks. Complementary potassium ions were not added to the soil. After this period the soils were air dried and both exchangeable calcium and magnesium were determined by the procedures already described. The results of the analyses are presented in Tables VIII and IX.

From Tables VIII and IX, it is evident that applications

TABLE VIII

Extent of Ionic Exchange Reactions Following the Application of Calcium and Magnesium to the Soil after two weeks of Incubation.

			Wisner					Hillsdale Subsoil				
Percentage Saturation			M.E.added		pH after incubation	M.E. Recovered		M.E.added		pH after incubation	M.E. Recovered	
Ca	Mg	Ca:Mg	Ca	Mg		Ca	Mg	Ca	Mg		Ca	Mg
Check			16.75	0.98	7.6	16.58	0.95	0.92	0.03	8.1	0.9	0.029
100	25	4:1	18.30	4.58	7.6	16.2	3.0					
	50	2:1	"	9.16	7.6	15.8	5.5	1.32	0.66	8.1	1.3	0.32
	75	1.3:1	"	13.74	7.5	15.5	6.8	"	0.99	8.1	1.2	0.49
	100	1:1	"	18.32	7.5	15.0	9.0	"	1.32	7.9	1.1	0.95
150	25	6:1	27.48	4.58	7.9	20.8	2.9					
	50	3:1	"	9.16	7.9	16.8	5.0	1.98	0.66	8.7	0.99	0.28
	75	2:1	"	13.74	7.8	16.7	6.3	"	0.99	8.3	1.50	0.47
	100	1.5:1	"	18.32	7.8	18.8	8.8	"	1.32	8.3	1.40	0.68

TABLE IX

Extent of Ionic Exchange Reactions following the Application of Calcium and Magnesium to the Soil after two weeks of Incubation

Percentage Saturation			Plainfield					Fox				
			M.E.added		pH after incuba-tion	M.E. Recovered		M.E.added		pH after incuba-tion	M.E. Recovered	
Ca	Mg	Ca:Mg	Ca	Mg		Ca	Mg	Ca	Mg		Ca	Mg
Check			1.1	0.63	5.2	1.05	0.60	1.24	0.31	5.7	1.24	0.31
50	25	2:1	1.78	0.89	5.2	1.3	0.80	1.70	0.85	5.6	1.70	0.60
	50	1:1	"	1.78	5.2	1.5	0.92	"	1.70	5.6	1.62	0.80
	75	.75:1	"	2.67	4.9	1.5	1.60	"	2.55	5.5	1.60	1.20
	100	.5:1	"	3.57	4.9	1.56	2.20	"	3.40	5.4	1.16	1.40
100	25	4:1	3.56	0.89	5.8	2.49	0.92	3.40	0.85	6.7	2.88	0.61
	50	2:1	"	1.78	5.6	3.3	1.00	"	1.70	6.6	3.20	0.85
	75	1.3:1	"	2.67	5.5	3.2	1.65	"	2.55	6.3	3.40	1.3
	100	1:1	"	3.57	5.4	3.1	1.75	"	3.40	6.1	3.30	1.25
150	25	6:1	5.34	0.89	6.1	4.2	0.85	5.10	0.85	7.0	3.2	0.62
	50	3:1	"	1.78	6.0	4.4	1.70	"	1.70	6.8	3.5	0.85
	75	2:1	"	2.67	5.9	4.9	2.50	"	2.55	6.8	3.9	1.30
	100	1.5:1	"	3.57	5.9	4.8	2.90	"	3.40	6.7	4.2	1.28

of calcium hydroxide and magnesium sulfate invariably raised the pH. At each level of calcium saturation the change in pH was influenced by the concentration of magnesium ions. The variation in pH was only one tenth unit with Wisner soil while it was two to three tenths units with Plainfield, Fox sand and Hillsdale subsoil. Anderson (3) and Kardos and Joffe (30) have shown that colloids with high SiO_2/R_2O_3 ratio show greater variation in pH when saturated with Ca and Mg ions than those with a low ratio. Colloids saturated with Ca had a lower pH than that of the colloids saturated with Mg. The stronger affinity of Mg for the silicate ion as compared with the Ca ion makes the former more effective in reducing the quantity of silicate available for hydrolytic cleavage as measured by the increase in pH. The data presented in Table I show that the Wisner has less sand in comparison with Plainfield, Fox or the Hillsdale subsoil. Therefore, the reduction in pH due to concentration of magnesium ions is less in the Wisner than in the other three soils that have more siliceous matter. Thus there is a tendency for the conversion of the magnesium ions into magnesiummsilicates with increasing concentration of the former in the soil solution. This is further supported by the amount of total magnesium recovered after an incubation period of two weeks as shown by the data in Tables VIII and IX. The recovery of added magnesium ion was less in proportion to the amount added in the case of the Wisner soil. There was less magnesium recovered with the higher concentrations of calcium and higher pH. Ray and Ganguly (49) have demonstrated that silicic acid sol becomes very unstable in the range of pH 6 to 9 and the sensitivity range narrows as the concentration of silicate decreases. With increasing concentration of Ca in the exchange complex, the pH of the medium increases (Tables VIII and IX). Thus at high pH more magnesium combines with silicate ions and are tied up. This may be an explanation why in alkaline soil the availability of magnesium is low as noted by Bower and Turk (10).

There was less recovery of added Ca from the acid than the alkaline soils. In some instances the calcium was added in excess of the saturation capacity of the exchange complex. It should be recalled that the soils are very low in organic as well as mineral colloids. Generally the added calcium reacts with organic or the mineral colloids. In the absence of these substances, the Ca reacts with the H_2SiO_3 which is in greater concentration and replaces the H ions, $CaSiO_3$ is formed, and the pH is increased. These facts emphasize the importance of the degree of calcium saturation or the available calcium content of the soil as a major factor influencing the effect of magnesium in plant growth and nutrition.

Effect of Magnesium on the Structure of Soils

Increasing amounts of magnesium at a constant level of calcium saturation was found to bring about a puddled and compact consistency of the Wisner soil. The soil was sticky and water tight when moist but became very hard on drying. It resembled somewhat the morphological characteristics of a solonetz soil. Swelling of soil on wetting was in proportion to the concentration of magnesium. Such a change in the structure of the soil was reflected in poor growth of tomato seedlings as can be seen from the photograph in Fig. 2. The "check" plants which did not receive calcium or magnesium grew better than those which received increased amounts of magnesium at a constant level of calcium. McGeorge and Breazeale (40) have suggested oxygen deficiency as a factor responsible for poor growth and wilting of plants in a puddled soil.

Plainfield, Fox sand and Hillsdale subsoil with low organic matter and clay content showed compaction near the surface. A coarser textured soil with large pores is usually associated with easy permeability of water. A white incrustation was found when the soil started drying after each watering. The intensity of the white incrustation increased as the concentration of magnesium increased. During the growth of the tomato and tobacco plants it was noticed that although all the treatments were maintained at a uniform moisture level, plants receiving a high rate

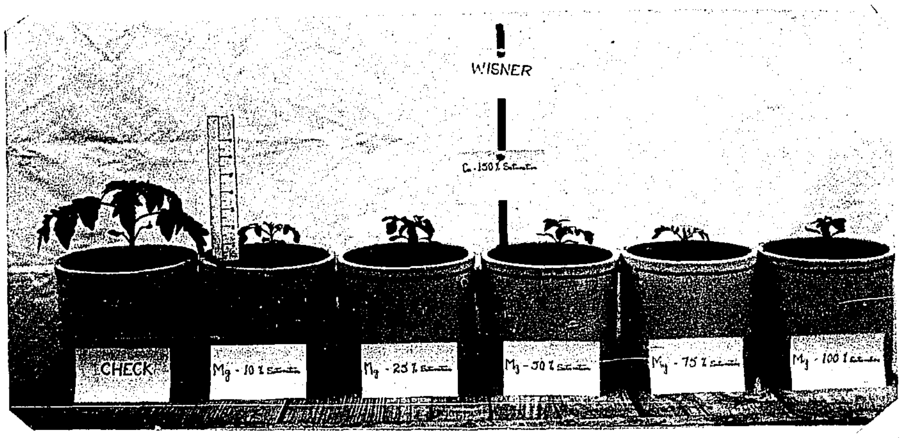

Fig. 2. Growth of 17 days old tomato seedlings showing the effect of poor tilth of Wisner soil as a result of increasing Mg saturation at a constant level of Ca saturation.

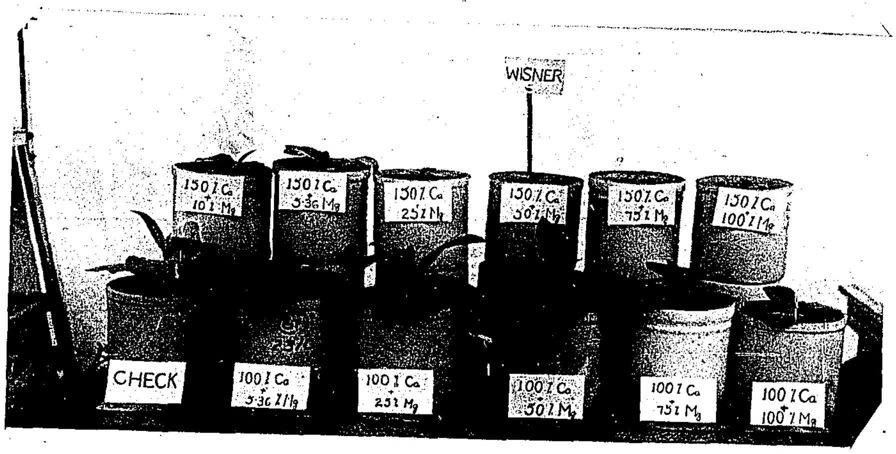

Fig. 3. Tobacco seedlings after four weeks of transplantation showing the effect of poor physical condition of soil as a result of increasing Mg saturation at a constant level of Ca saturation.

of magnesium showed symptoms of more marked moisture stress than the plants receiving small amounts of magnesium. The pronounced rolling of leaves of corn and wilting of the leaves of tobacco were evident symptoms of moisture stress. Recovery from such moisture stress was quick with all of the sandy soils but very slow with Wisner upon watering.

Electrical conductivity measurements were made on 1:2 extracts (1 part of soil to 2 parts of distilled water) on all soils after the application of the required amount of calcium hydroxide and magnesium sulphate. The measurements were confined to the clear supernatant liquid with "Solubridge." The electrical resistance readings thus obtained were corrected to 25°C. The results are summarized in Table X. Bradfield (11) has shown that after the saturation point is reached any amount of calcium added is converted to solid-phase calcium carbonate and the calcium ion concentration, as measured by the conductivity of the solution, becomes constant and is independent of the amount of calcium hydroxide added to the system.

Taking for granted that the same situation holds true for magnesium as for calcium, any excess magnesium added above the saturation capacity of the exchange complex, will be precipitated as magnesium carbonate or reacts with silica to form insoluble magnesium silicate. But this latter process is slow. Hence, after application of high amounts of Mg salt, the tendency is for the conversion of

TABLE X

Electrical Conductivity of Soil Solution as Influenced by the Calcium and Magnesium Ratio in Soils. (Conductivity values expressed as $MhoSx10^5$ at 25°C).

Degree of Saturation			Wisner			Plainfield			Fox			Hillsdale		
Ca	Mg	Ca:Mg	M. E. of Ca	M. E. of Mg	Conductivity	M. E. of Ca	M. E. of Mg	Conductivity	M. E. of Ca	M. E. of Mg	Conductivity	M. E. of Ca	M. E. of Mg	Conductivity
%	%													
Check					52	1.10	0.63	3	1.24	0.31	5			12
50	25	2:1	--	--	--	1.78	0.89	10	1.70	0185	14	--	--	--
"	50	1:1	--	--	--	"	1.78	16	"	1.70	20	--	--	--
"	75	.75:1	--	--	--	"	2.67	28	"	2.55	34	--	--	--
"	100	.5:1	--	--	--	"	3.56	42	"	3.40	36	--	--	--
100	25	4:1	18.32	4.58	160	3.56	0.89	10	3.40	0185	22	--	--	--
"	50	2:1	"	9.16	380	"	1.78	24	"	1.70	42	1.32	0.66	19
"	75	1:3	"	13.74	440	"	2.67	40	"	2.55	55	"	0.99	20
"	100	1:1	"	18.32	575	"	3.56	40	"	3.40	50	"	1.32	24
150	25	6:1	27.48	4.58	360	5.34	0.89	16	5.10	0.85	24	--	--	--
"	50	3:1	"	9.16	380	"	1.78	26	"	1.70	36	1.98	0.66	20
"	75	2:1	"	13.74	450	"	2.67	38	"	2.55	44	"	0.99	22
"	100	1.5:1	"	18.32	475	"	3.56	55	"	3.40	48	"	1.32	36

the salt to the carbonate form. In a system with calcium and magnesium carbonate, the latter is 10 times more soluble than the former, (16).

Magnesium sulphate is 25 times more soluble than the calcium sulfate, although calcium chloride is 1.5 times more soluble than magnesium chloride. Thus in the soil solution at equal total concentrations of Ca and Mg salts there is a preponderance of magnesium ions and magnesium salts. The conductivity value was, therefore, largely due to magnesium salt. Thus, high applications of magnesium, in excess of calcium, increase the salt concentration and thereby the osmotic value of the soil solution. Richards (50) has stated that the range in 'capillary' force with which water is held by soil particles between field capacity and permanent wilting point is approximately 0.1 - 1.5 atmospheres of tension. If water is held above this tension it will not be equally available in the range between field capacity and wilting point. Thus the amount of soluble salt affects the amount of water available to plants. This accounts for the incipient wilting of the tomato and tobacco plants in the high concentration of magnesium salts in the Wisner soil.

The amount of water added at each watering, so as to bring the soil moisture to the original level, was less with high magnesium application than that with low magnesium application. Higher concentrations of magnesium resulted in a corresponding reduction in plant growth, thereby lowering the rate of water removal from the soil. Frequency of irrigation was closely related to the concentration of magnesium in the medium.

EXPERIMENTAL RESULTS

Growth Response in Quartz Sand Culture

Magnesium without Calcium. Germination of tomato seeds appeared to be normal in the sand cultures in the absance of calcium but after two weeks the seedlings started to damp off. The young leaves on the upper part of the tomato as well as tobacco plants turned yellow while the lower leaves remained green. The terminal bud died and no further growth took place. The series received all the nutrients except calcium. Hence, magnesium in the absance of calcium does not insure the healthy growth of plants. (Fig. 4)

Calcium without Magnesium. Growth of both tomato and tobacco plants was very slow and retarded in the absence of magnesium. Leaves were dull green, small, narrow and very rough. As growth advanced the lower leaves became blanched. Some of them turned brown, died, and fell off. Flower differentiation of tomato plants was much delayed. The few fruits which developed were small, tough, and contained few seeds.

High Calcium and Low Magnesium. Retarded growth was noticed with high calcium and low magnesium applications. Tomato seedlings showed phosphorus deficiency symptoms and it was intensified with wide ratios of calcium to magnesium. As growth advanced, potassium deficiency symptoms began to appear. The young leaves of tomato and tobacco became crinkled, whereas the older leaves turned grayish green with a yellow tinge along the margin. With a 50:1 and 25:1 ratio of calcium to magnesium a bronzing of leaf tissues was followed by many light colored spots between the larger veins.

Low Calcium and High Magnesium. With a narrow ratio of calcium to magnesium, toxicity symptoms began to appear four weeks after growth. The young leaves of both tomato and tobacco showed curling and rolling of the lamina with many sunken brown patches.* A careful examination of the cross section of the affected leaf through the brown blotches showed the lower epidermis and spongy regions to be somewhat disorganized and collapsed. The pallisade region in these areas was not markedly affected. The lower side of the leaf in these affected areas was somewhat depressed below the level of the adjacent areas. Sorokin and Sommer (55) working with Pisum Sativum found that the absence of calcium had a direct effect on the disintegration of the cell-wall. They have suggested that the absence of calcium disturbs the normal mitosis of the meristematic cells and the appearance of aberrant type of division as calcium is withdrawn. This indicates that a small amount of calcium is needed as a constituent of the

*This microtonic cross section and examination was done in the laboratory of Dr. E. F. Woodcock of the Department of Botany.

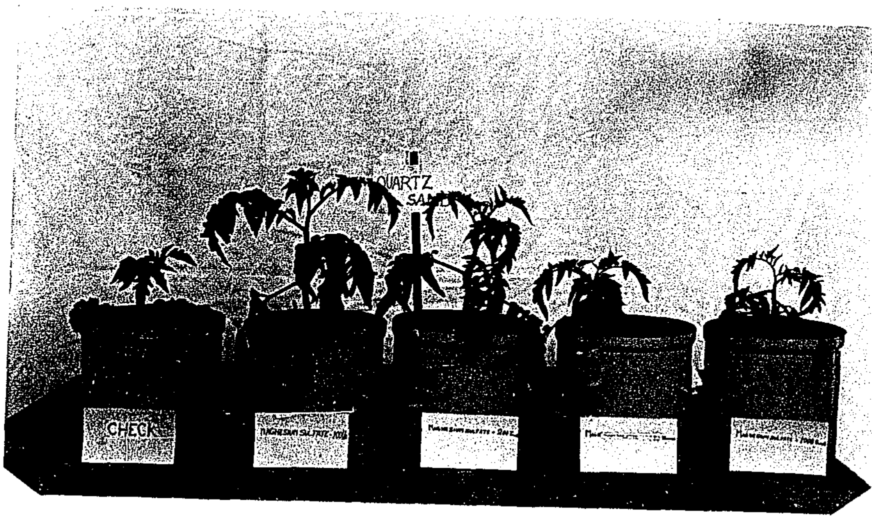

Fig. 4. Growth of 4 weeks old tomato seedlings with increasing amount of Mg in absence of Ca application.

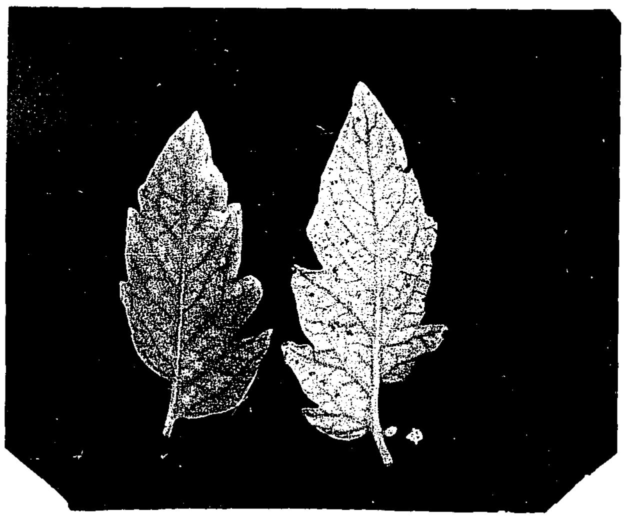

Fig. 5. Tomato leaves under low Ca and high Mg treatments, showing sunken patches on the lamina. Narrow ratio of Ca:Mg brought about disorganization of cell walls due to which the sunken patches became prominent.

Fig. 6. Growth of flue cured tobacco at the end of 7th week as related to the interaction of Calcium and Magnesium in Quartz sand culture.

Treatments of jars, from left to right:

1. 100 lbs. of $MgSO_4$ (0.06 M.E. Mg). No Calcium.
2. 400 lbs. of $MgSO_4$ (o.24 M.E. Mg). " "

3.	1/2 ton $CaCo_3$	400 lb. $MgSO_4$	(Ca:Mg	= 3.1:1)
4.	1 " "	" " "	("	= 6.25:1)
5.	1-1/2 " "	" " "	("	= 9:1)
6.	2 " "	" " "	("	= 12:1)

protoplasts while a large amount is needed for the formation of the cellwalls. Thus, a narrow ratio of calcium to magnesium in the substratum brought about magnesium toxicity in the plant. (Fig. 5).

Corn plants showed toxicity symptoms with the narrow calcium:magnesium ratio. With high level of calcium in the substratum the fourth leaf emerged with a tightly rolled basal portion. This rolling was more pronounced than the normal leaf grown with a wider calcium to magnesium ratio. Old leaves exhibited rolled apices. Due to the fact that the rolled leaves were observed under a constant level of calcium, with increasing levels of magnesium saturation, this could be called magnesium toxicity. As the available supply of magnesium was increased the absorption of magnesium by the plants was also increased. Thus, a high concentration of magnesium, associated with a relatively low concentration of calcium, is toxic to plant growth.

Growth Response in Wisner Soil

The poor physical condition of the Wisner soil, brought about by high concentrations of Mg, was reflected in the growth of tomato, tobacco and corn plants. This is illustrated by photographs of these plants (Fig. 2, 9, 10). There appeared to be a direct relationship between the color of the tomato, tobacco and corn leaves with the magnesium content of the soil. With the wider Ca:Mg ratios the leaves

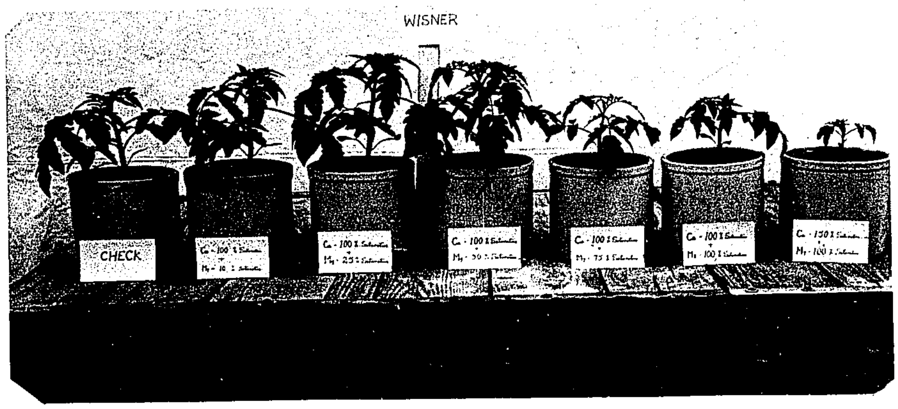

Fig. 7. Tomato crop at the end of fifth week of germination showing the effect of increasing saturation of Mg at a constant level of Ca saturation. (Increased amount of Mg application is from left to right).

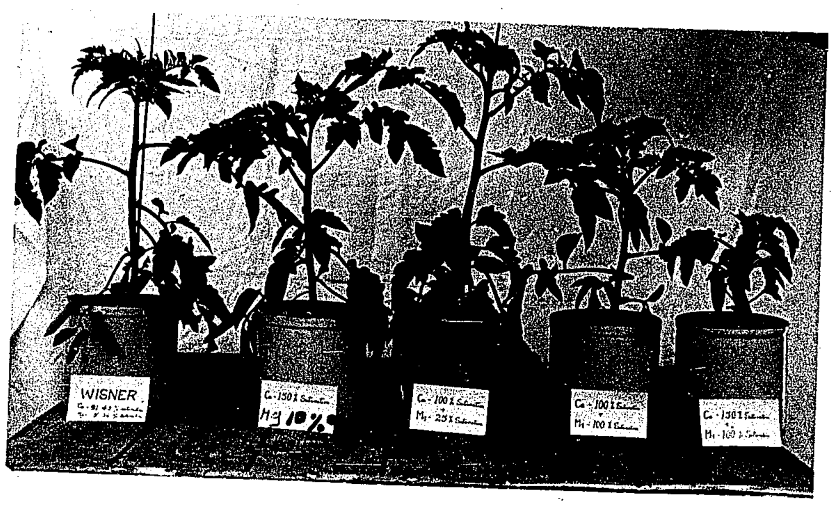

Fig. 8. Growth of tomato plants just before blossoming as influenced by different levels of Ca and Mg saturation. From left to right:

Jar 1 -	Check			
" 2 -	150% Ca sat.	10% Mg sat.	(Ca:Mg	15:1)
" 3 -	100% "	25% "	("	4:1)
" 4 -	100% "	100% "	("	1:1)
" 5 -	150% "	100% "	("	1.5:1)

Fig.9. Growth of tomato crop before harvest as related to varying Ca and Mg saturation. Top row 100% Ca sat. with varying amount of Mg sat., from left to right:

Jar 1 - 10% (Ca:Mg 10:1)
" 2 - 25% (" 4:1)
" 3 - 50% (" 2:1)
" 4 - 75% (" 1.3:1)
" 5 -100% (" 1:1)

Bottom row, left to right:

Jar 1 - Check
" 2 - 100% Ca 10% Mg
" 3 - 100% " 100% "
" 4 - 150% " 10% "
" 5 - 150% " 100% "

As Ca:Mg becomes narrower, there is more vine growth and less fruiting.

Fig. 10. Growth of tobacco crop prior to the harvest as was influenced by the degree of Ca and Mg saturation in Wisner soil. Top row, 150% Ca sat. and bottom row, 100% Ca sat., and increasing rate of Mg sat. from left to right.

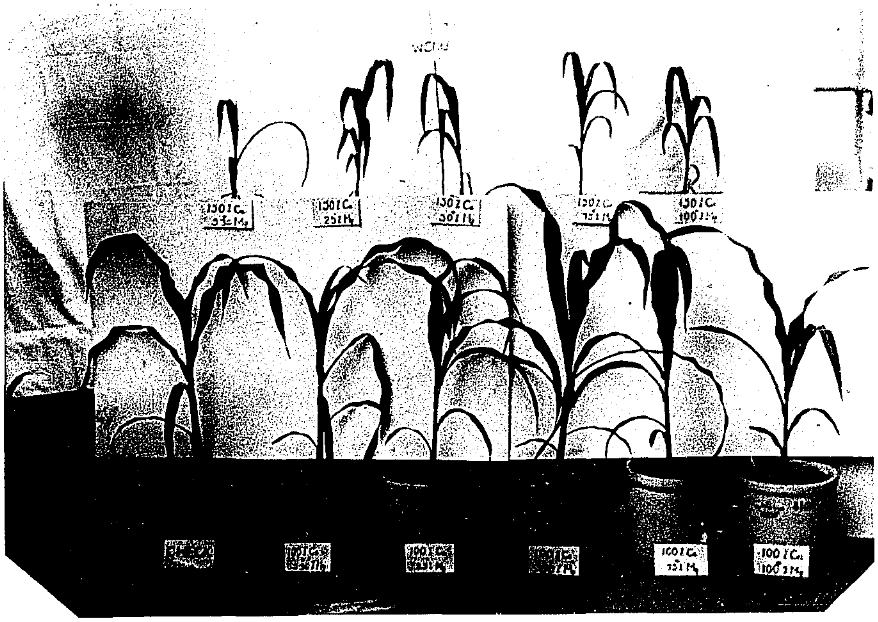

Fig. 11. Three weeks old corn crop showing the effect of different levels of Ca and Mg saturation. Top row, 150% Ca sat. with increasing levels of Mg. sat. Bottom row, 1st jar--check; 2nd through 5th, 100% Ca sat. with increasing levels of Mg sat.

Fig. 12. Corn crop just before harvest showing the growth condition more directly related to Ca sat. 1st jar--check; 2nd through 5th, 100% Ca sat.; 6th through 9th, 150% Ca Sat. Each group receiving increased amount of Mg sat. from left to right.

were thinner, smoother and darker green than with narrower Ca:Mg ratios.

Tomato. With the wider Ca:Mg ratios, the tomato plants were more profusely branched and blossoms appeared earlier. There were two sets of flower clusters with an average of five flowers. Setting of fruits was proportional to the amount of vine growth. With the narrow Ca:Mg ratios there was more vegetative growth but the appearance of blossoms was delayed. Vines were large but fruit setting was not proportional to vine growth.

Tobacco and Corn. From Figs. 9, 10, 11, and 12, a decided decrease in size of tobacco and corn plants due to high concentrations of magnesium is apparent. At 100 per cent level of calcium saturation the addition of magnesium stimulated growth until a concentration equivalent to 50 per cent saturation level of the total exchange capacity was reached. Beyond this ratio of 2:1 a marked decline in growth was observed.

At 150 per cent saturation of calcium the response to magnesium applications was very little. The poor physical condition, accompanying the increased saturation with magnesium, and the high pH had a retarding effect on plant growth. The germination of corn was good but within three weeks severe phosphorus deficiency symptoms were observed. As growth advanced the plants exhibited symptoms of serious potassium deficiency. Leaves became yellowish green, the tips started to die back and gradually the edges of the leaf died. Conspicuous red areas on the upper surface of the mid-rib appeared.

Growth Response in Plainfield and Fox sand

An inspection of Figs. 13 through 17 discloses that increased concentration of calcium in an acid soil was conducive to increased growth of tomato, tobacco and corn; but at very high concentrations growth was retarded. Data presented in Tables V and VI show that a decrease in acidity, accompanied by increasing calcium saturation, was associated with increasing absorption of this element. A further reduction in acidity had no particular effect on the absorption of calcium and other nutrients.

The quality of tobacco leaves was greatly influenced by the Ca:Mg ratio in the soil. A ratio of 2:1 favored smooth, thin and well shaped leaves which developed a bright yellow color towards maturity. Ratios narrower than 2:1 induced dark, thick and long leaves which did not develop the yellow color at the time of harvest.

Response of corn to magnesium was better at lower than at higher concentrations of calcium.

Growth Response in Hillsdale Subsoil

Soil reaction and poor physical condition of the subsoil appeared to be important factors in governing the response of crops to magnesium fertilization. Phosphorus deficiency was acute with all the treatments although it was applied as soluble ammonium phosphate. The low availability of phosphorus was more with increased calcium saturation above 75 per cent of the exchange capacity. The other limiting factors of high calcium concentration appeared to be unavailability of essential minor elements.

A comparison of the tomato plants in Fig. 19 under different levels of calcium saturation reveals that at 75 per cent saturation level of calcium, magnesium fertilization induced better vegetative growth as well as fruit formation. At higher level of calcium saturation there was very little balance between vegetative growth and fruit formation. Therefore, the response of crop to magnesium fertilization in presence of high calcium saturation was very little.

As seen from Figs. 18 and 19, while at 100 and 150 per cent calcium saturation better growth was associated with increasing magnesium saturation. This favorable effect of magnesium concentration at high calcium saturation was probably due to lowering of pH brought about through the application of magnesium as soluble magnesium sulfate. Data presented in Table VII show that a reduction of 3 to 5 tenths units in pH was brought about by the application of higher amounts of magnesium sulfate. This leads to the conclusion that in soils with low exchange and buffering capacity, the response of crop to magnesium fertilization was better at a soil reaction approaching to slightly acid side.

Fig. 13. Growth of tomato crop in Plainfield soil. Top row, 1st jar--check; 2 through 5, 50% Ca sat., increasing level of Mg sat. Bottom row:

Jar 1	- 100% Ca sat	25% Mg sat.	(Ca:Mg 4:1)
2	- 100% "	50% "	(" 2:1)
3	- 100% "	100% "	(" 1:1)
4	- 150% "	25% "	(" 6:1)
5	- 100% "	150% "	(" 1.5:1)

Response of crop to Mg was better with higher level of Ca saturation than at lower level.

Fig. 14. Growth of tobacco crop in Plainfield soil just before harvest showing effect of interaction of Ca and Mg. Top row, 150% Ca sat. with increasing Mg sat. from left to right. Bottom row, Jar 1--Check; Jars 2 through 5, 100% Ca sat., with increasing Mg sat. from left to right. Response of tobacco crop to Mg fertilization was better at low level of Ca sat. than at higher level.

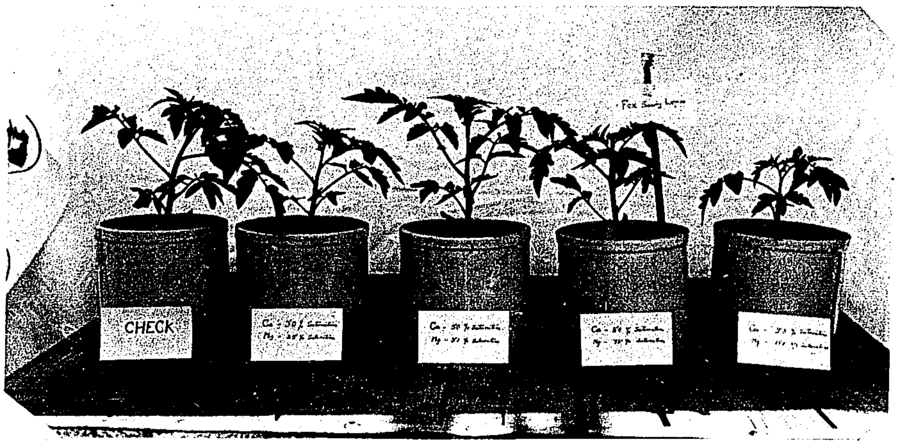

Fig. 15. One month old tomato crop in Fox sand showing the response of crop to different levels of Mg sat. at a constant level of Ca sat. Increasing Mg sat. is shown from left to right.

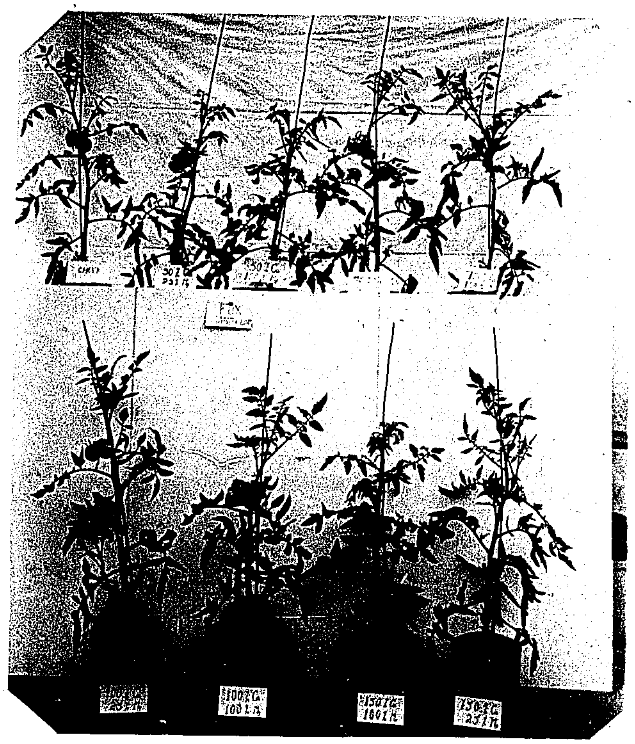

Fig. 16. Tomato crop in Fox sand just before harvest showing the response of crop to Mg fertilization in presence of different levels of Ca saturation.

Jar No.	Top Row		Bottom Row	
1	Check		100% Ca sat.	25% Mg sat.
2	50% Ca sat.	25% Mg.	100% "	100% "
3	50% "	100% "	150% "	100% "
4	75% "	25% "	150% "	25% "
5	75% "	100% "		

Response of crop to Mg was best at 100% Ca saturation.

Fig. 17. Growth of corn in Plainfield soil at the end of eight weeks showing the response of crop to Mg fertilization.

From left to right:

Jar 1 - Check			
" 2 -	50% Ca sat.	25% Mg Sat	(Ca:Mg 2:1)
" 3 -	50% "	50% "	(" 1:1)
" 4 -	50% "	75% "	(" .75:1)
" 5 -	50% "	100% "	(" .5:1)
" 6 -	150% "	25% "	(" 6:1)
" 7 -	150% "	50% "	(" 3:1)
" 8 -	150% "	75% "	(" 2:1)
" 9 -	150% "	100% "	(" 1.5:1)

Response of corn to Mg fertilization was better at slightly lower Ca saturation of soil than that of tomato.

Fig. 18. Three weeks old tomato seedlings in Hillsdale subsoil showing the response of crop to increasing Mg saturation at a constant level of Ca saturation.

Fig. 19. Tomato crop in Hillsdale subsoil before harvest. Top row, left to right, 1st through 3rd, 100% Ca sat.; 4th through 6th, 150% Ca sat., with increasing levels of Mg sat. Bottom row, 1st, check; 2nd through 4th, 75% Ca sat. with increasing level of Mg sat.

Foliar Analysis of Crops During Growth

To determine the relationship between the external concentration of calcium and magnesium and their uptake by the plants and the relationship of the internal concentrations to other elements of growth, a foliar analysis of each crop was made at the flowering stage. Antagonistic action between elements may take place not only at the absorbing membrane but also at the metabolic centers within the plant.

Leaves from the upper halves of the plants were taken for analysis. To measure the reaction and conductivity of the tomato leaf saps, the leaves, after harvest, were put in cellophane bags and immediately frozen with solid carbon dioxide. Before extracting the juice, they were dipped in tepid water to allow thawing of the tissues. The plant materials were then ground in a Warring Blender and the extract was filtered through a muslin cloth. Where the quantity of sap obtained was small it was diluted with an equal volume of water. Determination of pH was made with a Beckman pH meter while conductivity measurements were made with a "Solubridge." Leaves from similar positions of another plant were brought to the laboratory and the soluble constituents were extracted with hot water by adopting the method described by Burkhart and Page (12). Total nitrogen and nitrate nitrogen were determined from representative fractions of each sample by the methods described previously (15). The results are presented in Tables XI, XII and XIII.

The hydrogen ion concentration and leaf analysis data reveal that at lower concentrations of magnesium in the soil the calcium content of leaf sap is high and pH is low, while with the higher magnesium concentrations at a constant level of calcium saturation, calcium content of leaf is low while pH of the sap is high. In the latter case magnesium and potassium contents are higher than that of calcium. This is in line with the observation of Clevenger (17) who suggested that an increase in lime uptake stimulated the life process in the plant and caused an increased production of organic acids. In the leaves where the hydrogen ion concentration of the sap was not increased by the limited absorption of calcium, it seems possible that magnesium and potassium play similar functions in neutralizing organic acids. Both of these cations have replaced calcium in the organic salts as the ratio of these two to calcium was increased.

The conductivity of leaf sap increased with increased magnesium and potassium concentration and decreased calcium concentration. Higher conductivity was associated with depressed growth. True and Bartlet (59) while studying the effect of varying concentration of calcium and magnesium nitrate on pea roots found that where the concentration of Mg was high and the conductivity was 900×10^{-6} mhos per liter, characteristic injury to the pea roots was well marked. Calcium in high proportion never resulted in injury, while injury from magnesium was frequent. Thus, high concentrations of magnesium was associated with higher conductivity of leaf sap which could account for the depressed plant growth.

Increased accumulation of nitrates in the leaves of tomato, tobacco and corn plants accompanied higher magnesium concentrations both in the soil and in the leaf sap. The higher the concentration of nitrate the lower was the concentration of potassium. This inverse relationship between nitrogen and potassium seemed to be associated with concentrations of magnesium beyond the 75 per cent saturation level of the exchange complex at all calcium levels.

The level of nitrate nitrogen in the plants provides an index of the difference between the rate of absorption and the rate of assimilation of nitrogen. As seen from Table XII, there was a decided increase of NO_3 N with increasing concentration of magnesium at each level of calcium saturation. Therefore, concentration of magnesium in soil favors the rate of absorption of nitrogen while any increment of magnesium either above a certain minimum level or above that of calcium level in the leaf inhibited the rate of assimilation.

The data, also, suggest that there was adequate nitrogeneus reserve for higher rate of cell formation and better growth. Data in Table XIII indicates that production of dry matter decreased while hydration of the leaf tissue

Table XI

pH, Conductivity of Tomato Leaf Sap and Percentage Composition of Tomato Leaf

% Saturation in Soil		pH of Leaf Sap			Conductivity mho 8×10^{-5}			% Composition of Leaves (on dry matter basis)														
								Wisner					Plainfield					Fox				
Ca	Mg	Wisner	Plain Field	Fox	Wisner	Plain Field	Fox	Ca	Mg	K	NO_3 N	Tot. N	Ca	Mg	K	NO_3 N	Tot. N	Ca	Mg	K	NO_3 N	Tot. N
Check		5.8	5.8	5.0	150	195	200	1.16	0.55	.73	.32	1.0	.52	.30	.65	.30	1.15	2.2	.36	1.1	.34	1.15
50	25	----	5.9	5.1	----	250	260						.58	.38	.44	.31	1.10	2.1	.85	.75	.32	1.1
	50	----	6.0	5.3	----	253	265						.37	1.13	.65	.34	1.20	1.7	2.03	1.65	.33	1.2
	75	----	6.5	5.2	----	380	400						.29	1.38	.76	.42	1.40	1.4	2.05	1.75	.45	1.50
	100	----	6.5	5.3	----	420	450						.32	1.68	.70	.46	1.42	1.3	2.38	1.25	.48	1.5
100	10	5.8	----	----	230	----	----	0.93	1.35	0.53	.36	1.12	----	----	----	----	----	----	----	----	----	----
	25	6.3	6.0	5.0	250	325	320	.81	1.70	.56	.36	1.12	.72	.33	.38	.33	1.28	2.8	1.13	.75	.38	1.16
	50	6.4	6.2	5.1	280	337	340	.75	1.85	.56	.32	1.10	.55	1.03	.32	.36	1.30	2.2	1.60	.90	.36	1.08
	75	6.4	6.2	5.3	285	380	390	.63	2.40	.58	.48	1.23	.46	1.38	.36	.56	1.36	1.9	1.90	.85	.47	1.30
	100	6.5	6.4	5.4	300	418	425	.40	2.75	.50	.51	1.32	.40	1.48	.31	.58	1.41	1.4	2.18	.80	.49	1.3
150	10	6.9	----	----	145	----	----	.87	1.90	.56	.33	1.25	----	----	----	----	----	----	----	----	----	----
	25	6.9	5.2	5.1	201	230	220	.75	2.10	.67	.34	1.25	1.4	.60	.32	0.4	1.40	3.2	1.0	.60	.38	1.20
	50	7.2	5.3	5.0	218	325	320	.63	2.25	.75	.36	1.36	0.72	1.10	.35	0.42	1.40	2.9	1.63	.84	.37	1.17
	75	7.5	5.3	5.2	220	333	340	.53	2.65	.80	.49	1.41	.55	1.85	.35	0.56	1.48	2.4	1.85	1.50	.49	1.3
	100	7.5	5.4	5.3	230	342	350	.50	3.25	.67	.56	1.73	.52	1.90	.30	0.59	1.90	2.3	1.90	1.20	.51	1.48

Table XII

Composition of Corn Leaf As Influenced by the Level of Ca and Mg Saturation of Soil (Percentage on Dry Matter)

Degree of Saturation Ca	Mg	WISNER Ca	Mg	K	NO_3 N	Total N	PLAIN FIELD Ca	Mg	K	NO_3 N	Total N	FOX Ca	Mg	K	NO_3 N	Total N
Check		.81	.45	1.4	–	1.54	0.85	0.28	1.65	0.04	0.78	1.1	0.5	1.6	0.03	0.9
50	25	–	–	–	–	–	1.70	0.35	1.15	0.08	0.55	2.1	0.83	1.20	0.06	1.20
	50	–	–	–	–	–	0.70	0.90	1.60	0.06	0.51	2.0	0.90	2.0	0.07	1.17
	75	–	–	–	–	–	0.70	0.93	1.10	0.14	0.68	1.8	0.91	2.4	0.32	1.17
	100	–	–	–	–	–	0.50	0.63	1.35	0.16	1.10	1.6	1.20	2.0	0.39	1.62
100	25	.87	.85	0.69	0.09	1.69	–	–	–	–	–	–	–	–	–	–
	50	.81	.98	1.00	0.31	1.74	0.9	0.93	1.50	0.09	1.10	2.1	0.65	2.5	0.07	2.10
	75	.80	1.10	1.82	0.48	1.82	0.65	0.98	1.50	0.16	1.30	2.0	0.83	2.7	0.40	2.10
	100	.75	1.40	1.30	0.52	1.94	0.60	1.00	1.18	0.19	1.44	2.0	1.23	2.2	0.42	2.30
150	25	1.07	0.80	1.01	0.10	1.82	1.2	0.45	1.50	0.10	1.35	3.0	0.45	1.0	0.08	1.80
	50	0.82	0.83	1.20	0.15	1.82	0.9	0.70	1.60	0.13	1.38	2.4	0.75	1.8	0.40	2.30
	75	0.81	0.97	1.27	0.46	1.97	0.8	0.83	2.10	0.16	1.62	2.1	0.80	1.8	0.43	2.30
	100	0.84	1.30	1.10	0.51	2.17	0.8	1.15	1.10	0.21	2.00	2.0	0.85	1.5	0.45	2.60

Table XXIII

Yield of Dry Matter and Degree of Hydration of Tomato Crop As Influenced by the Level of Ca and Mg Saturation of Soil.

Degree of Saturation		WISNER				HILLSDALE SUBSOIL				PLAIN FIELD				FOX			
Ca %	Mg %	Green Wt. gm.	Dry Wt. gm.	% Dry Matter	% Water	Green Wt. gm.	Dry Wt. gm.	% Dry Matter	% Water	Green Wt. gm.	Dry Wt. gm.	% Dry Matter	% Water	Green Wt. gm.	Dry Wt. gm.	% Dry Matter	% Water
Check		197	36.6	18.5	81.5	58	10.1	17.4	82.6	90	16.1	171	82.9	75	13	17.3	82.7
50	25	-	-	-	-	-	-	--	-	118	20.0	18.9	81.1	103	17	16.4	83.6
	50	-	-	-	-	-	-	-	-	134	23.0	17.1	82.9	133	21	16.8	83.2
	75	-	-	-	-	-	-	-	-	130	22.0	16.8	83.2	115	16	13.9	86.1
	100	-	-	-	-	-	-	-	-	106	16.0	15.1	84.9	100	15	15	85.0
100	10	220	42.2	19.2	80.8	-	-	-	-	-	-	-	-	-	-	-	-
	25	215	43.0	20.0	80.0	-	-	-	-	133.0	24.0	18.0	82.0	160	25	15.6	84.4
	50	220	49.0	22.3	77.7	111	17.0	15.3	84.7	157.0	28.0	17.8	82.2	170	27	15.8	84.2
	75	200	36.0	18.0	82.0	117	17.5	14.9	85.1	146.0	24.0	16.4	83.6	181	28	12.7	87.3
	100	199	28.0	14.0	86.0	117	17.0	14.5	85.5	126.0	20.0	15.8	84.2	200	20	10.0	90.0
150	10	200	38.0	19.0	87.0	-	-	-	-	-	-	-	-	-	-	-	-
	25	229	45.0	19.7	80.0	-	-	-	-	128	26.0	20.3	79.7	165	29	17.8	82.2
	50	228	45.8	20.1	79.9	89	12.6	16.1	85.9	148	29.0	19.6	80.4	221	38	17.2	82.8
	75	200	29.2	14.6	85.4	101	14.3	14.1	85.9	145	25.0	17.2	82.8	220	30	13.6	86.4
	100	188	25.0	13.3	86.7	108	13.6	12.6	87.4	124	20.0	16.1	83.9	180	18	10.0	90.0

increased with increased magnesium concentration in the leaf. The general effect of a salt on hydration of the tissue depends upon its concentration and also its presence in chemical union or in absorption with colloidal material. The data in the Table XII indicates that magnesium was not in chemical union with cell content, but was present as a luxury consumption product. A large portion of water was bound with magnesium as hydrated water. The hydration of protoplasmic protein and vacuolation of cells due to this stress in water relation could not proceed normally and this resulted in reduced growth of the plant.

CROP YIELDS

Yields of tomato, tobacco and corn crops grown in quartz sand and in the four mineral soils are given in Table XIV and are shown in Figs. 20 and 21. The results of the quartz sand culture emphasize that neither calcium nor magnesium alone can give satisfactory growth and yield of crops. The response of the crops is well marked only when both calcium and magnesium are present in the culture media. The declining growth occurring at heavier calcium applications indicates that a higher level of calcium saturation at constant level of potassium and other essential nutrients favors the onset of magnesium deficiency. At lower level of calcium saturation, yield of tomato, tobacco and corn gradually increases for each additional

TABLE X IV

Effect of Different Levels of Calcium and Magnesium on the Yield of Tomato, Tobacco and Corn in Quartz Sand

M.E. of			Tomato*				Tobacco*		Corn*	
Ca	Mg	Ca:Mg	Ht.	Vine	Fruit	Total Yield	Ht.	Total Yield	Ht.	Total Yield
			Cm.				Cm.		Cm.	
0.75	--		35	4	0.5	4.5	20	6.0		
1.50	--		31	9	0.5	9.5	25	7.0		
2.25	--		27	7	1.0	8.0	19	4.0		
3.00	--		26	6	0.5	6.5	16	4.0		
--	0.06		4	0.5	--	0.5	3	0.5		
--	0.12		4	0.5	--	0.5	3	0.5		
--	0.24		2	0.25	--	0.25	--	--		
--	0.60		--	--	--	--	--	--		
0.75	0.06	12.5:1	38	10	1.6	11.6	27	19.0	80	32.6
	0.12	6.25:1	39	12	1.7	13.7	32	20.0	83	34.1
	0.24	3.1:1	35	12	1.5	13.5	34	20.9	93	34.0
	0.60	1.25:1	33	8	2.2	10.2	30	15.0	106	37.0
1.50	0.06	25:1	34	18	3.9	21.9	32	17.0	81	26.0
	0.12	12.5:1	33	22	2.0	24.0	37	18.0	85	28.0
	0.24	6.25:1	38	24	4.7	28.7	39	20.0	104	34.0
	0.60	2.5:1	34	14	1.5	15.5	32	21.0	93	29.0
3.00	0.06	50:1	30	11	0.9	11.9	35	15.0	86	22.0
	0.12	25:1	30	14	2.5	16.5	40	17.0	100	25.0
	0.24	12:1	33	18	5.0	23.0	37	18.0	105	29.0
	0.60	5:1	35	19	5.8	24.8	37	21.0	85	25.0

* Figures represent average of three replicated pots. Weights are dry weight in grams.

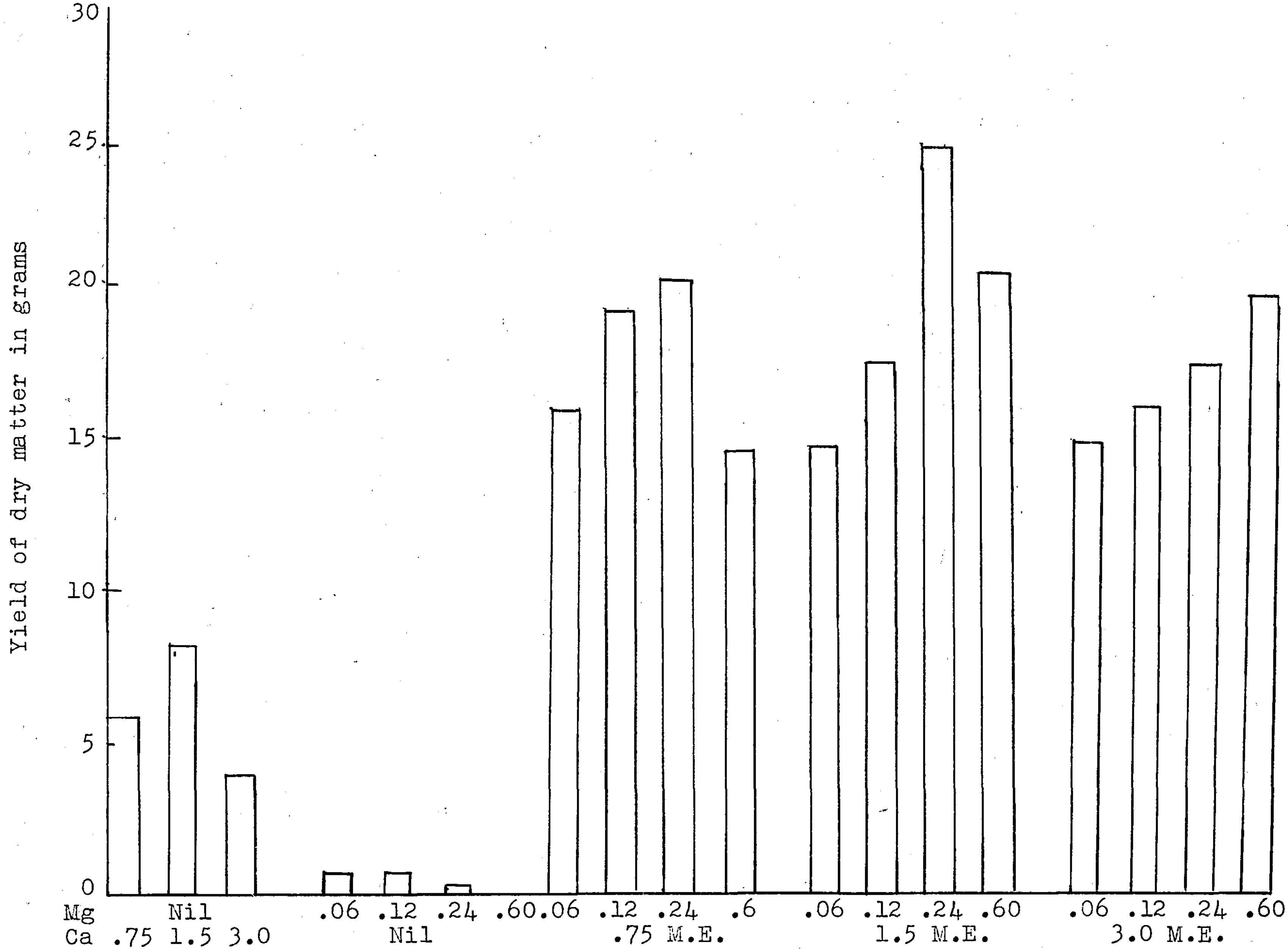

Fig. 20. Effect of interaction of different levels of Ca and Mg on the yield of tomato plants in Quartz sand culture.

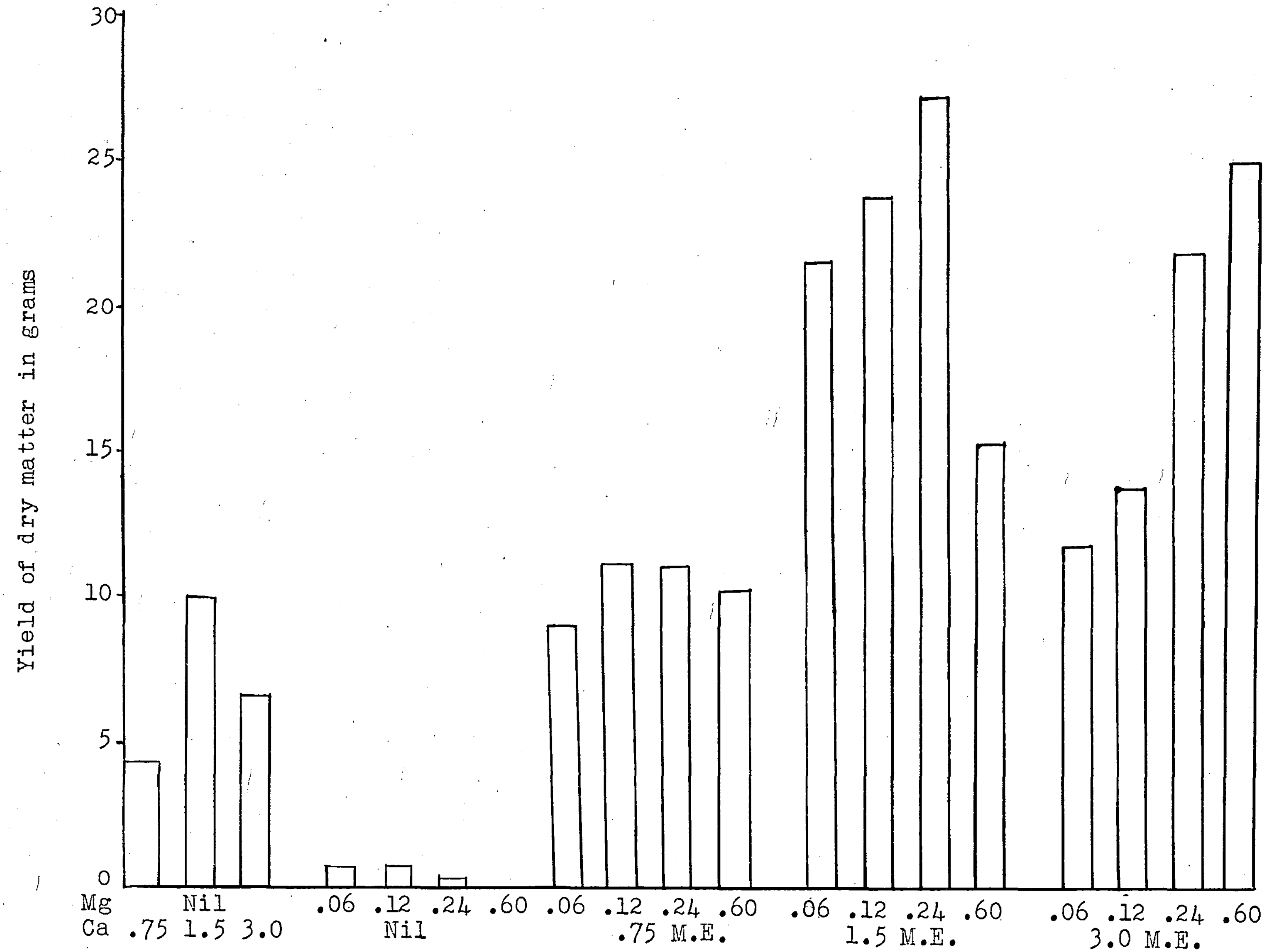

Fig. 21. Effect of interaction of different levels of Ca and Mg on the yield of Tobacco in sand culture.

increment of magnesium and the highest yield of tomato and tobacco was obtained when the ratio of calcium to magnesium was within the range of 3:1 and 6:1. With a wider ratio there was little or no further rise in yield. However, corn responded to a narrow Ca:Mg ratio of 3:1 to 2.5:1.

Wisner Soil. As shown in Table XV and Figs. 22, 23 and 24, the yield data of tomato and tobacco show the same trend on the Wisner soil. Growth and yield of these two crops in this calcareous soil was higher when the Ca:Mg ratio was within the range of 3:1 to 2:1. Beyond this ratio growth as well as yield was depressed. Good tilth and better moisture relations were essential for the success of the tobacco crop. High concentrations of magnesium destroyed the tilth, restricted root growth, and thereby lowered the yields.

The data for the yield of corn in Table XV and Fig. 24 indicate that in this calcareous soil the application of magnesium gave better growth with 100% calcium saturation. At the higher concentrations of calcium, potassium appeared to be the limiting factor. The analysis of corn plants presented in Table XXII shows that, in comparison with the check, the uptake of potassium increased with increased magnesium concentration while an appreciable reduction took place in the absorption of calcium. The total absorption of the two divalent cations was practically constant. Thus, the ratio $\frac{Ca + Mg}{K}$ was

TABLE XV

Effect of Different Levels of Calcium and Magnesium on the Yield of Tomato, Tobacco and Corn in Wisner Soil*

Degree of Saturation			Tomato				Tobacco		Corn	
Ca	Mg	Ca:Mg	Ht.	Vine	Fruit	Yield	Ht.	Yield	Ht.	Yield
%	%		Cm				Cm		Cm	
			60	36	15	51	57	17	150	44
100	10	10:1	65	42	18.5	60.5	60	20	174	48
	25	4:1	73	42	20.5	62.5	63	29	145	49.5
	50	2:1	75	50	23.0	73.0	50	49	140	50.5
	75	1.3:1	65	40	12.0	52.0	28	16	125	39
	100	1:1	60	28	12.0	40.0	27	9	120	37
150	10	15:1	70	50	6.0	56.0	24	10	125	35
	25	6:1	68	40	19.0	59.0	27	15	113	38
	50	3:1	68	40	10.0	50.0	20	6	108	35
	75	2:1	50	35	9.0	44.0	18	4	108	32
	100	1.5:1	48	32	7.0	39.0	14	4	106	24

* Figures represent averages of three replicated pots. Weights are dry weights in grams.

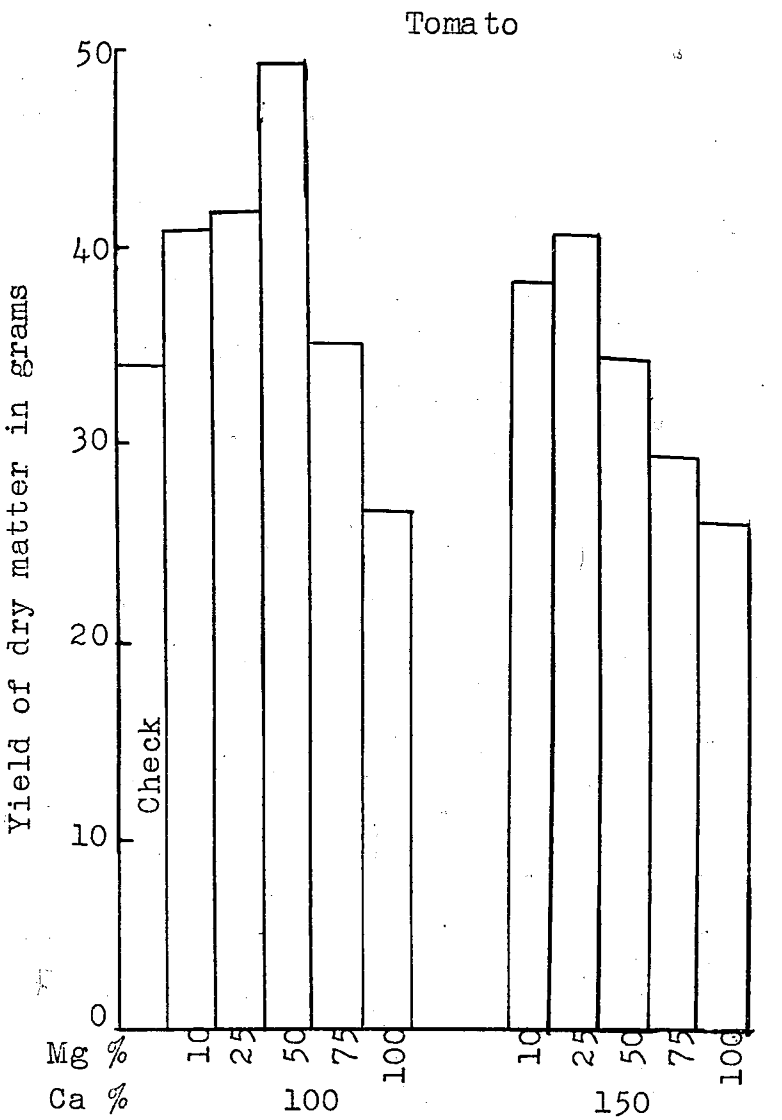

Fig.22. Effect of degree of Ca and Mg saturation on the yield of tomato crop in Wisner soil.

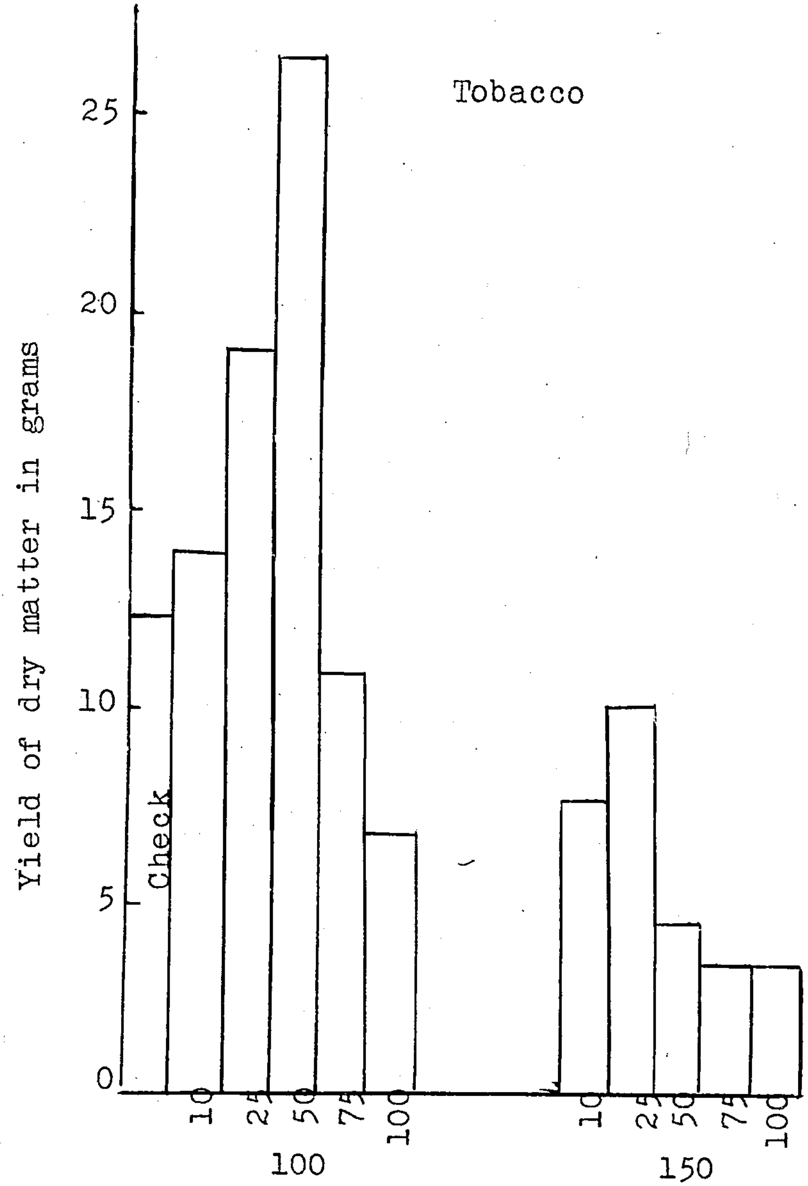

Fig. 23. Effect of degree of Ca and Mg saturation on the yield of Tobacco crop in Wisner soil.

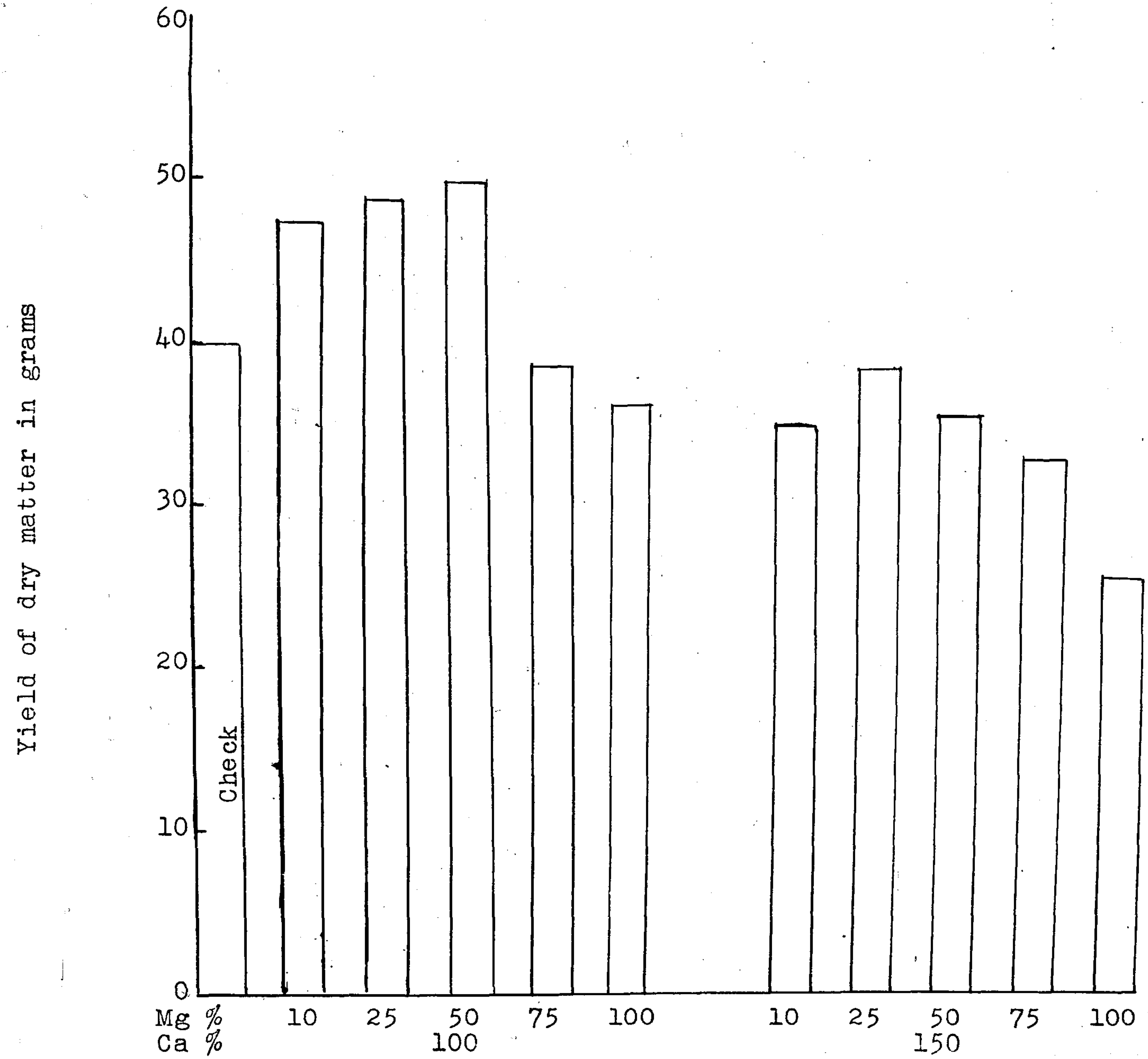

Fig. 24. The effect of degree of Ca and Mg saturation on the yield of corn in Wisner soil.

higher with increased rates of magnesium. A relatively narrow $\frac{Ca + Mg}{K}$ ratio of 2 to 3 favored growth and yield while a ratio of 4 or more caused potassium deficiency and thereby lowered the yield. This is in line with results reported by Stanford et al (56). High calcium carbonate concentration of calcareous soil exerts a repressive effect on the availability of potassium and the response of crops to magnesium is, therefore, low.

<u>Plainfield and Fox Sand</u>. As shown in Figs. 25 through 28, growth and yield of tomato, tobacco and corn in these two soils follow the same pattern. The four levels of calcium and magnesium saturation, which represent a variation in both the supply of exchangeable bases and H ion concentration, indicate that the response of crops to magnesium is greater with increased calcium concentration. Of the 17 treatments shown in Tables XVI and XVII for Plainfield and Fox sand, respectively, there were five equal levels of total bases contained in each soil, viz. 3.95, 4.84, 5.73 and 6.20 m.e. per 100 gms. of Plainfield sand and 3.75, 4.64, 5.48 and 6.33 m.e. per 100 gm. Fox sand. Each level was made up by varying the degree of Ca and Mg saturation. For instance, 4.84 m.e. per 100 gm. Plainfield sand in Table XVI was obtained by 50 per cent Ca saturation and 75 of Mg saturation, 75 per cent Ca saturation and 50 per cent Mg saturation or 100 per cent Ca and 25 per cent Mg saturation. The soil had an exchange capacity of 3.56 m.e. for 100 gm. soil. The total

TABLE XVI

Effect of Different Levels of Calcium and Magnesium on the Yield of Tomato, Tobacco and Corn Crop in Plainfield Sand*

Degree of Saturation			Tomato				Tobacco		Corn	
Ca %	Mg %	Ca:Mg	Ht. Cm	Vine	Fruit	Yield	Ht. Cm	Yield	Ht. Cm	Yield
			50	15	8	23	40	23	160	30
50	25	2:1	52	18	10	28	51	26	165	55
	50	1:1	58	25	11	36	46	28	170	68
	75	.66:1	55	20	10	30	41	23	153	58
	100	.5:1	50	18	7	25	32	20	143	50
75	25	3:1	57	25	11	36	48	27	155	60
	50	1.5:1	60	25	12	37	46	32	165	80
	75	1:1	60	23	8	31	41	26	150	68
	100	.66:1	55	23	8	31	33	19	140	52
100	25	4:1	60	27	10	42	56	40	140	65
	50	2:1	65	29	20	49	56	49	155	68
	75	1.3:1	65	25	14	39	48	28	140	55
	100	1:1	60	20	12	32	48	28	125	50
150	25	6:1	65	29	8	37	50	29	125	52
	50	3:1	64	30	12	42	56	35	150	50
	75	2:1	62	25	13	38	56	25	162	65
	100	1.5:1	54	22	13	35	47	25	150	50

*Figures represent averages of three replicated pots. Weights are dry weights in grams.

TABLE XVII

Effect of Different Levels of Calcium and Magnesium on the Yield of Tomato, Tobacco and Corn Crop in Fox Sand*

Degree of Saturation Ca	Mg	Ca:Mg	Tomato Ht.	Vine	Fruit	Total	Tobacco Ht.	Yield	Corn Ht.	Yield
%	%									
			44	12	2	14	40	12	140	40
50	25	2:1	50	16	5	21	44	15	154	76
	50	1:1	53	16	6.5	22.5	38	18	161	84
	75	.66:1	44	14	6	20	30	12	138	72
	100	5:1	35	14	3	17	25	10	124	42
75	25	3:1	55	16	7	23	38	16	162	110
	50	1.25:1	52	18	9	27	34	19	124	82
	75	1:1	46	15	6	21	30	14	112	70
	100	.66:1	45	11	3	14	22	10	106	54
100	25	4:1	59	16	12	28	39	20.5	136	90
	50	2:1	59	18	10	28	38	17	116	80
	75	1.3:1	53	16	9	25	28	12	116	65
	100	1:1	53	12	8	20	24	12	100	50
150	25	6:1	50	19	10	29	32	18	110	50
	50	3:1	57	25	15	40	36	24	88	60
	75	2:1	57	25	12	37	32	19	90	68
	100	1.5:1	53	20	10	30	29	17	85	50

*Figures represent averages of three replicated pots. Weights are dry weights in grams.

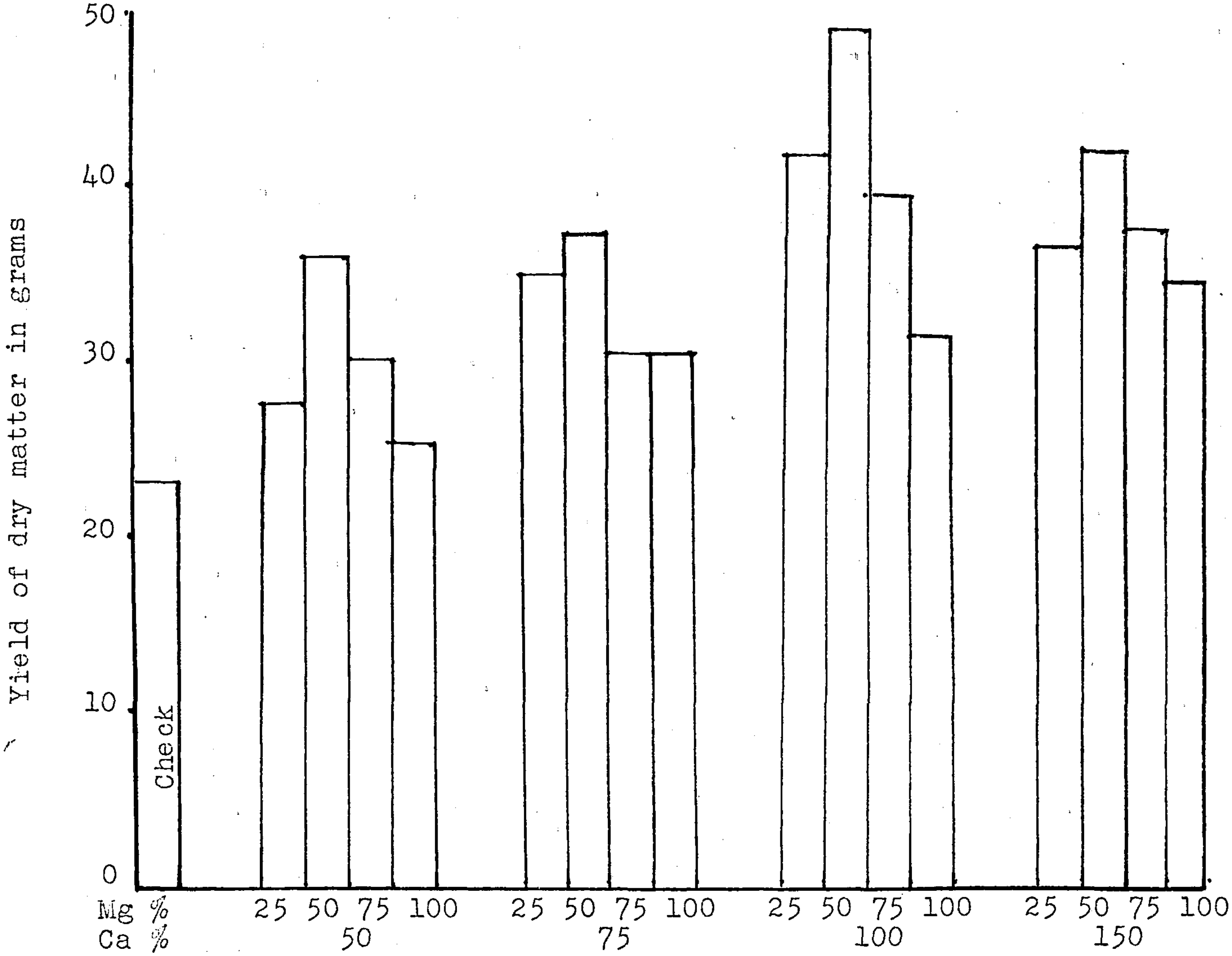

Fig. 25. Effect of degree of Ca and Mg saturation on the yield of tomato in Plainfield soil.

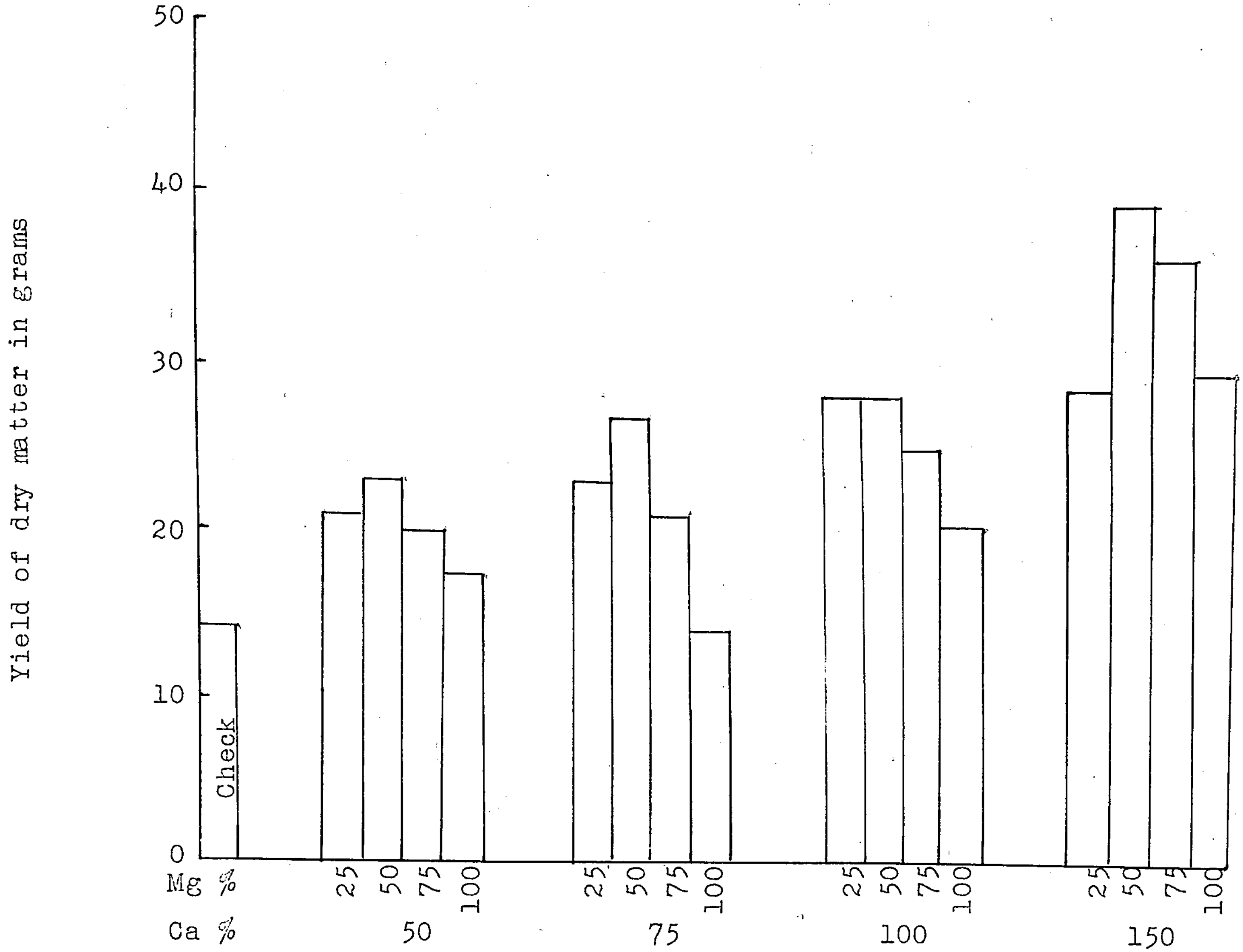

Fig. 26. The effect of degree of Ca and Mg saturation on the yield of tomato in Fox soil.

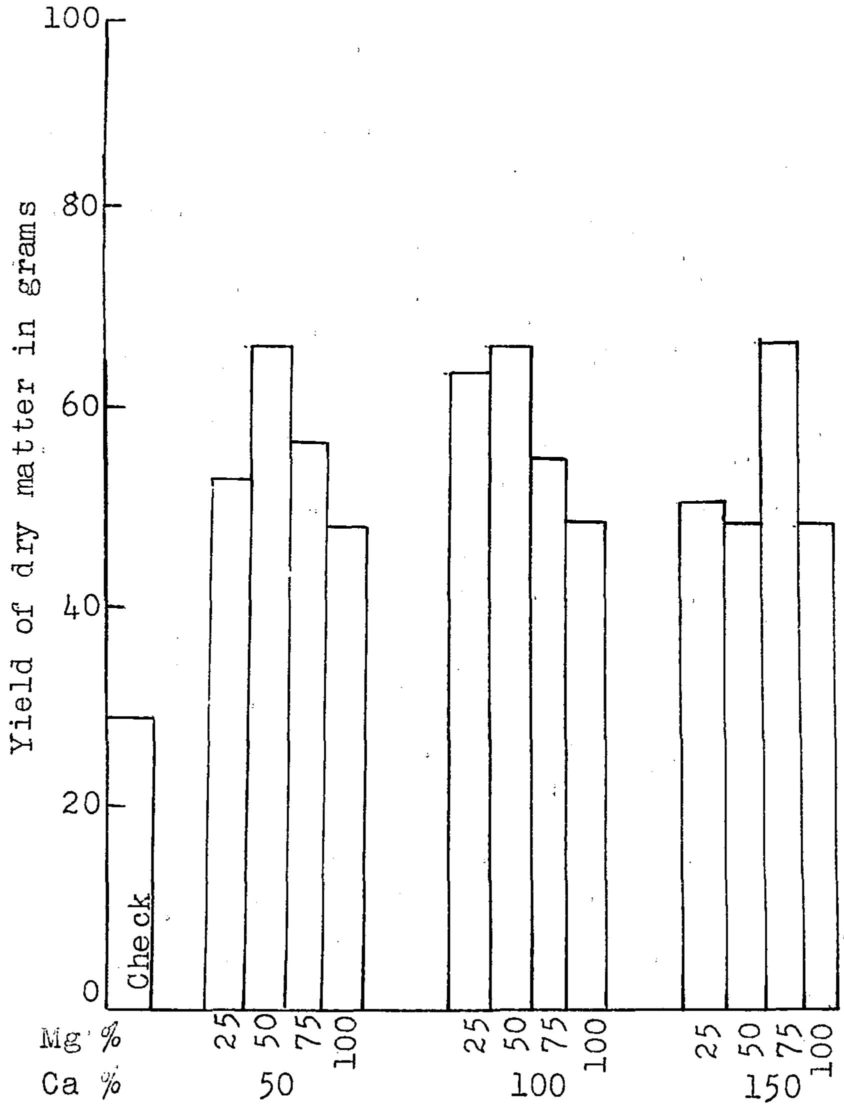

Fig.27. Effect of degree of Ca and Mg saturation on the yield of corn in Plainfield soil.

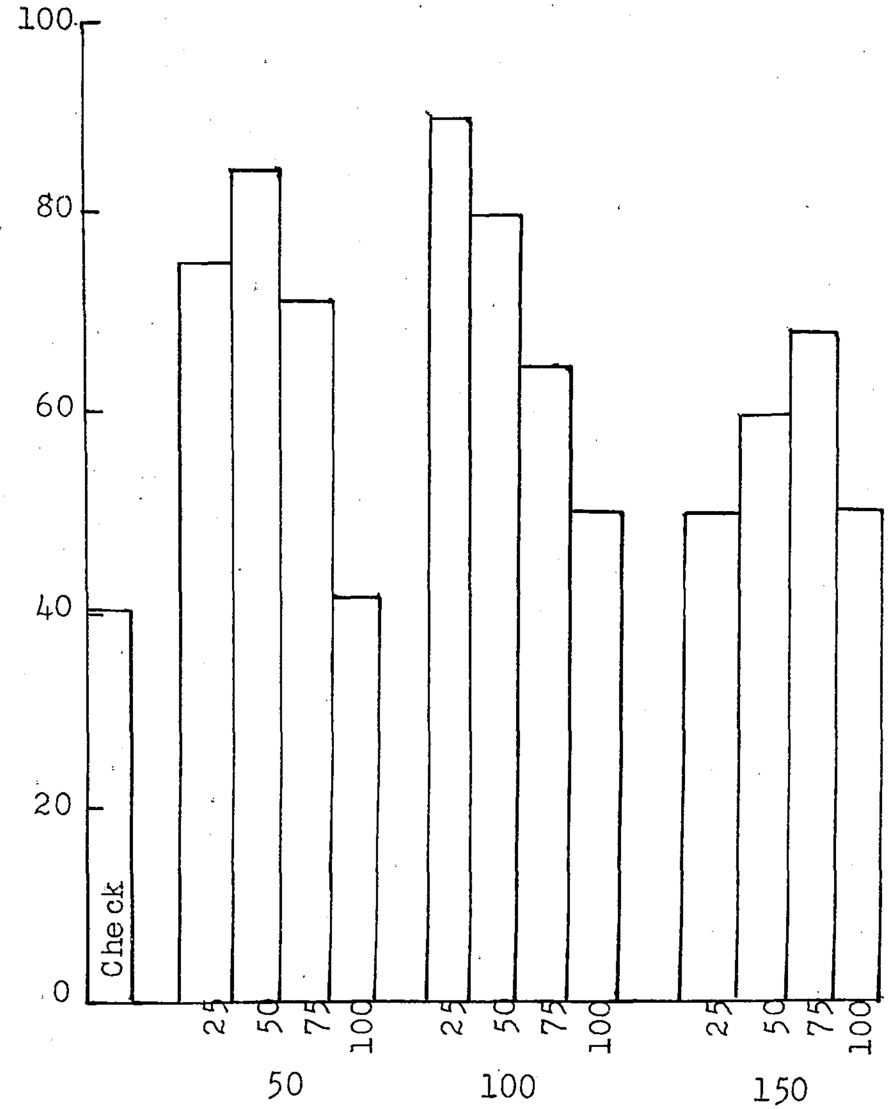

Fig.28. Effect of degree of Ca and Mg saturation on the yield of corn in Fox soil.

cation concentration in each of the treatments was the same while the ratio of Ca:Mg was 0.66:1, 1.5:1 and 4:1, respectively. The pH of the soil receiving such treatments was 4.9, 5.4 and 5.8, respectively. Reduction of acidity was influenced more by Ca than by Mg. The yields of the tomato crop with these treatments were 30, 37 and 40 gms, respectively. Yields of tobacco follow the same pattern. The same relative yields were obtained with Fox sand. Thus, in acid soils, low calcium and high magnesium depressed the yield while high calcium and low magnesium increased the yield. The ratio of Ca:Mg giving highest yield was 4:1, but beyond this ratio, as will be seen from Table XVI and XVII, yields fell sharply, indicating that high calcium saturation overshadowed the effect of magnesium application.

Yields of corn, as presented in Tables XVI and XVII, showed a different trend from that of tomato and tobacco. Higher yields were obtained with higher concentration of magnesium at a constant level of calcium saturation. Bender and Eisenmenger (9) have shown that the effect of one cation on the absorption of another cation was dependant upon plant species provided the soil conditions remain constant. Growth and yield of corn, tomato and tobacco at the increasing level of magnesium saturation at a constant level of calcium saturation emphasize that point.

<u>Hillsdale Subsoil</u>. Yields of tomato and tobacco are given in Table XVIII and are shown in Figs. 29 and 30.

Compared with the yield obtained from no application of Ca or Mg, the response of crops to Mg application was very little when the percentage of calcium saturation was increased to 150. Overliming interfered with the availability of other nutritive elements and the response to magnesium fertilization was not well marked. A comparison of the height of tomato plants as affected by various treatments gives an indication of the influence of magnesium on the vegetative growth of tomato, but there was practically no difference in the yield of fruits, indicating a disturbed carbohydrate hitrogen metabolism so essential for satisfactory reproductive phase of the plant.

TABLE XVIII

Effect of Different Levels of Lime and Magnesium Fertilizer on the Yield of Tomato and Tobacco in Hillsdale Subsoil*

Degree of Saturation			Tomato				Tobacco	
Ca	Mg	Ca:Mg	Ht.	Vine	Fruit	Total	Ht.	Yield
%	%		cm				cm	
69.6	22.7	3.1:1	35	11.8	2.3	14.1	77	15
75	50	1.5:1	42	12.6	3.3	15.9	75	18
	75	1:1	46	17.5	2.0	19.5	75	20
	100	0.75:1	38	12.2	3.9	16.1	82	22
100	50	2:1	40	14.2	2.0	16.2	67	19
	75	1.33:1	42	15.1	2.2	17.3	64	23
	100	1:1	39	16.6	1.9	18.5	68	25
150	50	3:1	40	11.5	1.0	12.5	44	14
	75	2:1	37	12.1	2.0	14.1	48	14
	100	1.5:1	39	11.1	2.5	13.6	50	15

* Figures represent average of the three replications. Weights are dry weights in grams.

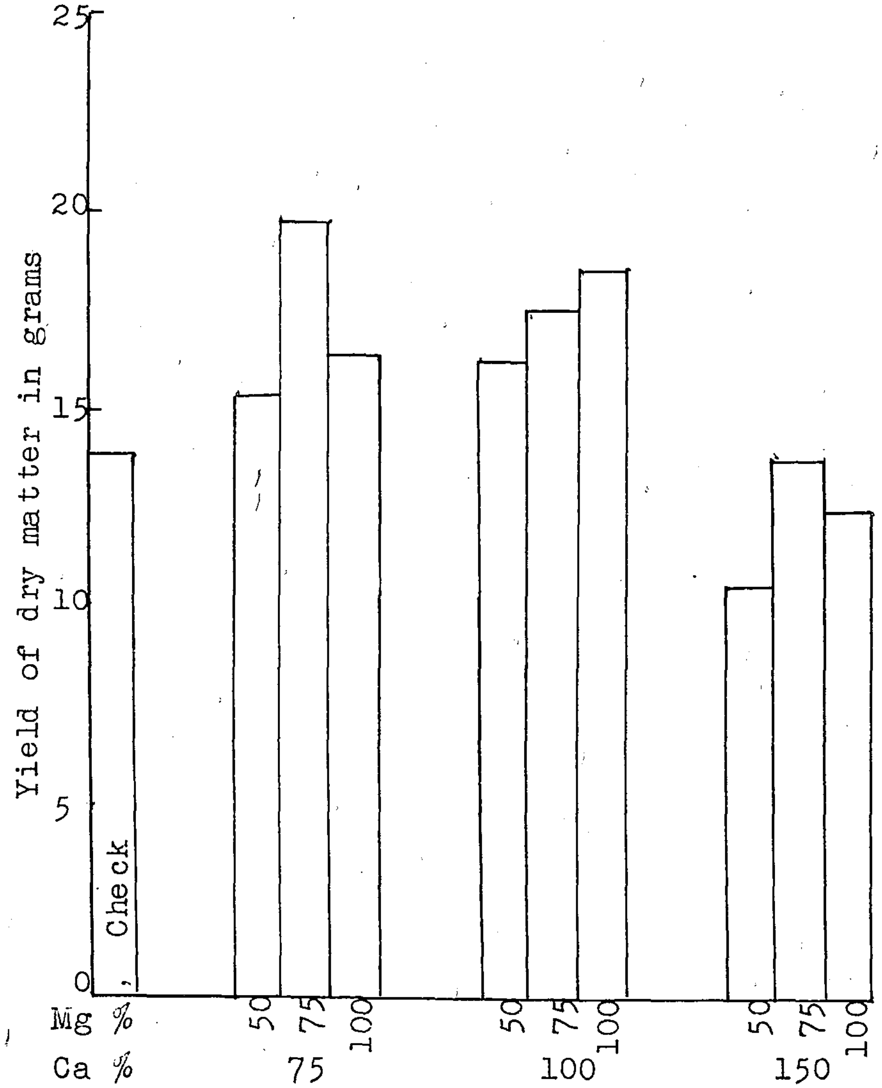

Fig.29. Effect of degree of Ca and Mg saturation on the yields of tomato in Hillsdale subsoil.

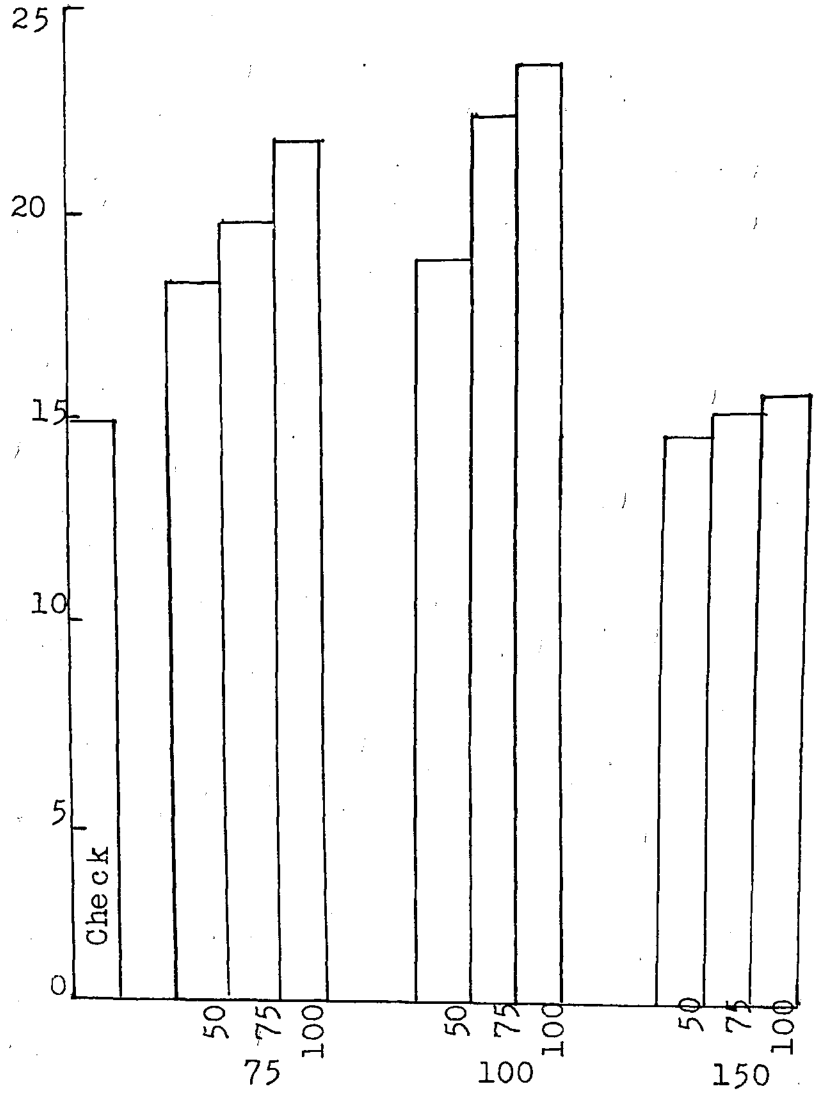

Fig.30. Effect of degree of Ca and Mg saturation on the yields of tobacco in Hillsdale subsoil.

Plant Composition

Data presented in Tables XIX through XXIII show the amount and proportion of calcium, magnesium and potassium in tomato, tobacco and corn crops in relation to the concentration of these ions in soil.

Calcium. From Figs. 31 through 40, it is seen that the concentration of magnesium in the soil influenced the absorption of calcium by the plant. When the concentration of magnesium was low the calcium content of the crop increased fairly consistently with increased application of calcium to the soil, although this increase in no way was proportional to the increased amounts that were added in excess of the original amount present in the soil. As the degree of magnesium saturation increased from 25 per cent to 100 per cent of the total exchange capacity of the soil, the calcium content of the crop significantly decreased. Even the treatments with equimolecular concentration of calcium and magnesium resulted in a lower content of calcium and a higher content of magnesium in the plants. Mobilization of calcium in the plant was, therefore, greatly influenced by the concentration of magnesium in the soil. In all of the soils and with all three crops studied it was evident that magnesium acted as a retarding ion to calcium uptake and the retarding influence increased with increased concentration of the magnesium ion.

TABLE XIX

Effect of Calcium and Magnesium on the Mineral Composition of Tomato, Tobacco and Corn Crops in Quartz Sand. (In Milli-equivalents per 100 gm. dry matter).

M.E. of cations applied			Tomato				Tobacco				Corn			
Ca	Mg	Ca:Mg	Ca	Mg	K	Total	Ca	Mg	K	Total	Ca	Mg	K	Total
0.75	0.06	12.5:1	90	27	61	178	84	32	58	174	38	17	64	119
	0.12	6.25:1	74	57	60	191	78	40	60	178	33	30	72	135
	0.24	3.1:1	61	81	69	211	55	50	69	174	24	36	64	124
	0.60	1.25:1	48	101	51	200	43	60	71	174	22	40	59	121
1.60	0.06	25:1	92	27	61	180	87	30	84	201	36	19	69	134
	0.12	12.5:1	85	47	57	189	75	51	87	213	27	21	74	122
	0.24	6.25:1	75	54	60	189	67	61	92	220	21	33	82	136
	0.60	2.5:1	58	90	47	195	60	65	97	222	18	52	70	140
3.00	0.06	50:1	101	26	64	185	105	25	66	196	41	25	64	130
	0.12	25:1	85	42	54	182	100	25	69	194	30	30	64	124
	0.24	12:1	85	49	48	183	87	37	89	213	27	35	70	132
	0.60	5:1	70	94	47	211	68	37	79	184	23	40	65	128

TABLE XX

Effect of Different Levels of Calcium and Magnesium on the Composition of Tomato, Tobacco and Corn Crops in Wisner Soil. (M.E. per 100 gms dry matter).

M.E. of cations added			Tomato				Tobacco				Corn			
Ca	Mg	Ca:Mg	Ca	Mg	K	Total	Ca	Mg	K	Total	Ca	Mg	K	Total
16.75	0.98	17:1	86	70	16	172	138	38	27	203	61	38	43	142
18.32	2.29	10:1	101	77	11	189	101	61	43	205	61	42	27	130
	4.58	4:1	98	95	13	206	101	81	31	213	52	62	28	142
	9.16	2:1	82	110	14	206	76	88	41	205	58	68	34	160
	13.74	1.3:1	69	129	14	212	66	144	45	255	52	72	28	152
	18.32	1:1	58	145	10	213	48	156	35	239	51	83	20	154
27.48	2.29	15:1	109	87	11	207	138	68	64	270	72	50	20	142
	4.58	6:1	92	110	15	217	120	90	73	283	66	56	27	149
	9.16	3:1	74	124	19	217	106	129	81	316	58	53	29	140
	13.74	2:1	60	140	20	220	106	141	82	323	56	66	30	152
	18.32	1.5:1	59	145	14	228	85	169	69	323	54	66	27	147

TABLE XXI

Effect of Different Levels of Calcium and Magnesium on the Composition of Tomato, Tobacco and Corn Crops in Plainfield Soil. (M.E. per 100 gms dry matter).

M.E. of cations added			Tomato				Tobacco				Corn			
Ca	Mg	Ca:Mg	Ca	Mg	K	Total	Ca	Mg	K	Total	Ca	Mg	K	Total
1.10	0.63		72	29	11	112	101	35	45	181	29	18	36	83
1.78	0.89	2:1	73	46	8	127	107	49	45	201	48	22	21	91
	1.78	1:1	54	80	12	146	59	80	49	188	36	21	29	86
	2.67	0.66:1	46	95	14	155	56	108	51	215	28	50	34	112
	3.56	0.5:1	43	100	10	153	49	114	84	247	22	55	48	122
2.56	0.89	3:1	82	42	10	134	78	51	47	176	56	28	49	133
	1.78	1.5:1	72	84	12	168	84	78	47	209	23	47	51	121
	2.67	1:1	56	93	14	163	57	98	57	212	23	50	51	124
	3.56	0.75:1	52	97	9	158	55	112	72	239	22	55	42	119
3.56	0.89	4:1	88	42	9	139	87	44	33	164	60	40	31	131
	1.78	2:1	72	77	10	159	54	71	43	168	32	50	42	124
	2.67	1.25:1	61	85	12	158	52	93	47	192	23	53	46	122
	3.56	1:1	58	88	8	154	40	113	40	193	26	53	47	126
5.34	0.89	6:1	98	33	8	139	95	53	37	185	46	33	38	117
	1.78	3:1	86	66	10	162	72	68	34	174	41	33	31	105
	2.67	2:1	75	100	10	185	42	65	34	141	32	59	47	138
	3.56	1.5:1	65	100	6	171	46	100	24	170	29	62	55	146

TABLE XXII

Effect of Different Levels of Calcium and Magnesium on the Composition of Tomato, Tobacco and Corn Crops in Fox Sand. (M.E. for 100 gms soil).

M.E. of cations added			Tomato				Tobacco				Corn			
Ca	Mg	Ca:Mg	Ca	Mg	K	Total	Ca	Mg	K	Total	Ca	Mg	K	Total
1.24	0.31	4:1	64	52	30	146	40	13	37	90	24	30	41	95
1.70	0.85	2:1	68	61	21	150	46	77	49	172	49	48	57	154
	1.70	1:1	60	84	27	171	45	92	77	214	40	51	52	143
	2.55	0.75:1	42	112	30	174	27	102	80	209	40	58	53	151
	3.40	3:1	42	127	27	196	33	105	60	195	32	64	62	158
2.55	0.85	3:1	78	94	16	188	55	49	50	154	51	37	34	122
	1.70	1.5:1	69	99	18	186	43	73	66	182	35	53	48	136
	2.55	1:1	58	119	24	191	35	81	70	186	34	56	68	158
	3.40	.75:1	54	132	20	206	34	102	52	188	30	71	56	157
3.40	0.85	4:1	90	68	14	172	60	44	52	156	58	39	49	136
	1.70	2:1	85	92	17	194	48	55	58	161	52	48	60	160
	2.55	1.33:1	80	109	19	208	35	71	70	176	44	62	65	171
	3.40	1:1	69	121	20	210	26	90	65	181	34	83	57	174
5.10	0.85	6:1	104	56	14	174	77	32	55	164	70	36	52	158
	1.70	3:1	88	89	16	193	66	49	65	180	52	51	48	151
	2.55	2:1	74	103	29	206	39	66	68	173	46	44	52	142
	3.40	1.5:1	65	124	20	209	35	68	62	165	46	59	41	146

TABLE XXIII

Effect of Different Levels of Calcium and Magnesium on the Composition of Tomato and Tobacco in Hillsdale Subsoil.
(M.E. per 100 gms dry matter)

M.E. of Cations added			Tomato				Tobacco			
Ca	Mg	Ca:Mg	Ca	Mg	K	Total	Ca	Mg	K	Total
0.92	0.30	3:1	100	59	13	172	87	35	71	193
0.99	0.66	1.5:1	63	78	16	157	81	61	71	213
	0.99	1:1	57	80	11	148	85	79	79	243
	1.32	0.75:1	41	87	10	138	82	61	71	214
1.32	0.66	2:1	60	40	15	115	82	30	71	183
	0.99	1.3:1	58	80	17	155	67	60	70	197
	1.32	1:1	47	85	15	147	54	75	71	200
1.98	0.66	3:1	107	63	15	185	104	30	82	216
	0.99	2:1	68	59	15	142	95	44	78	217
	1.32	1.5:1	48	62	14	124	77	64	78	219

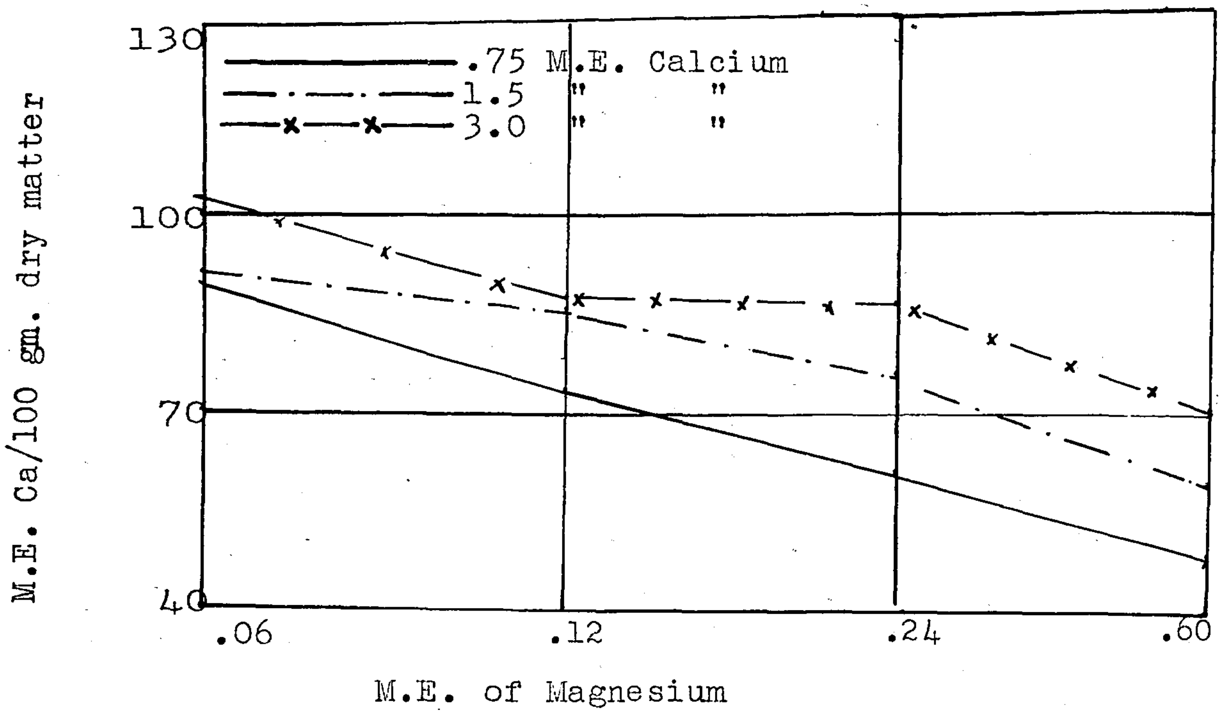

Fig. 31. The effect of interaction of Ca and Mg saturation on the Ca content of tomato plants in Quartz sand culture.

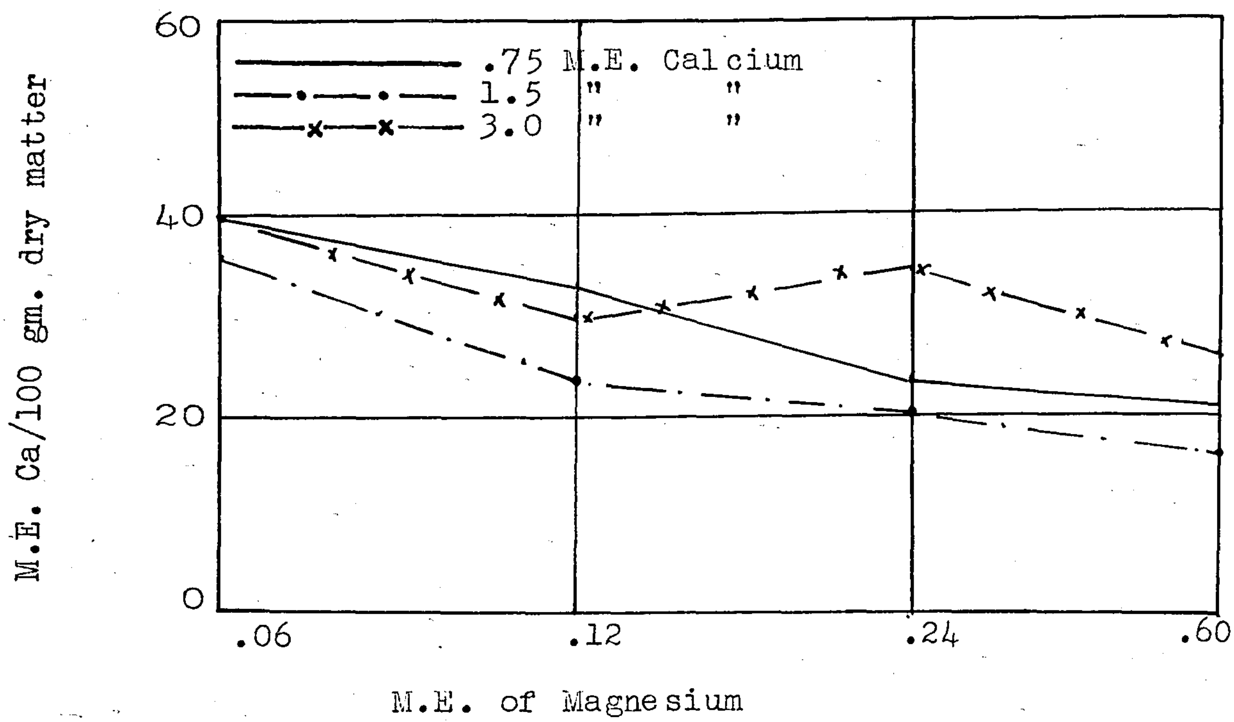

Fig. 32. The effect of interaction of Ca and Mg saturation on the Ca content of corn plants in Quartz sand culture.

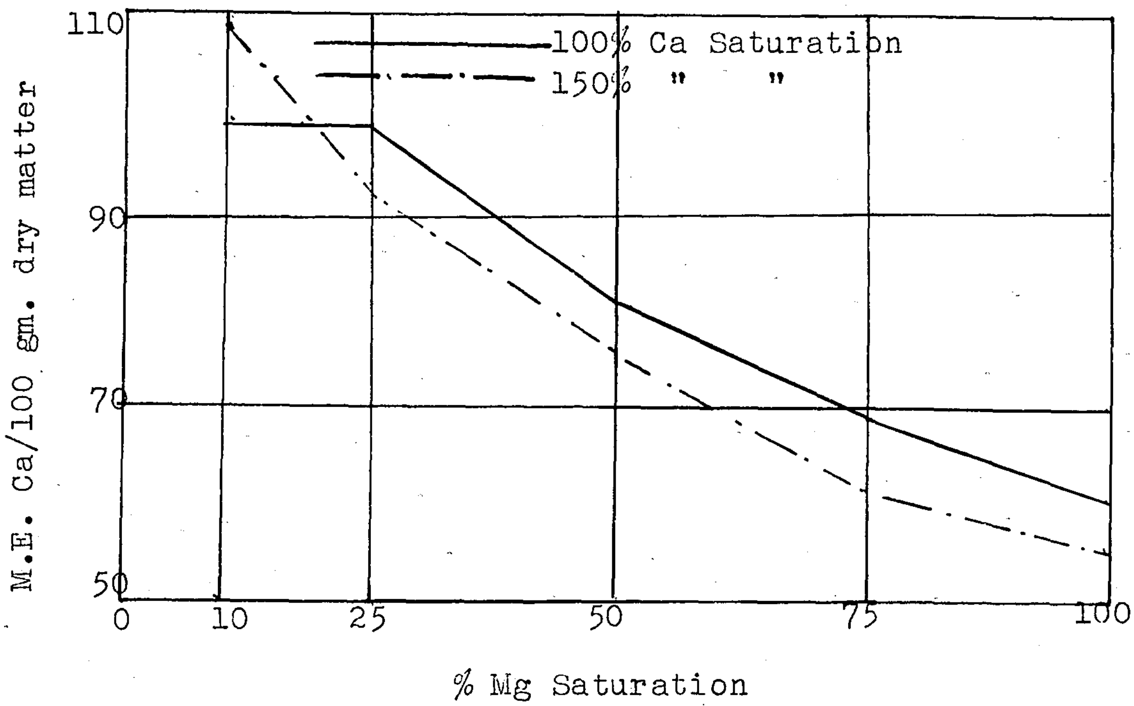

Fig. 33. The effect of degree of Ca and Mg saturation on the Ca content of tomato plants in Wisner soil.

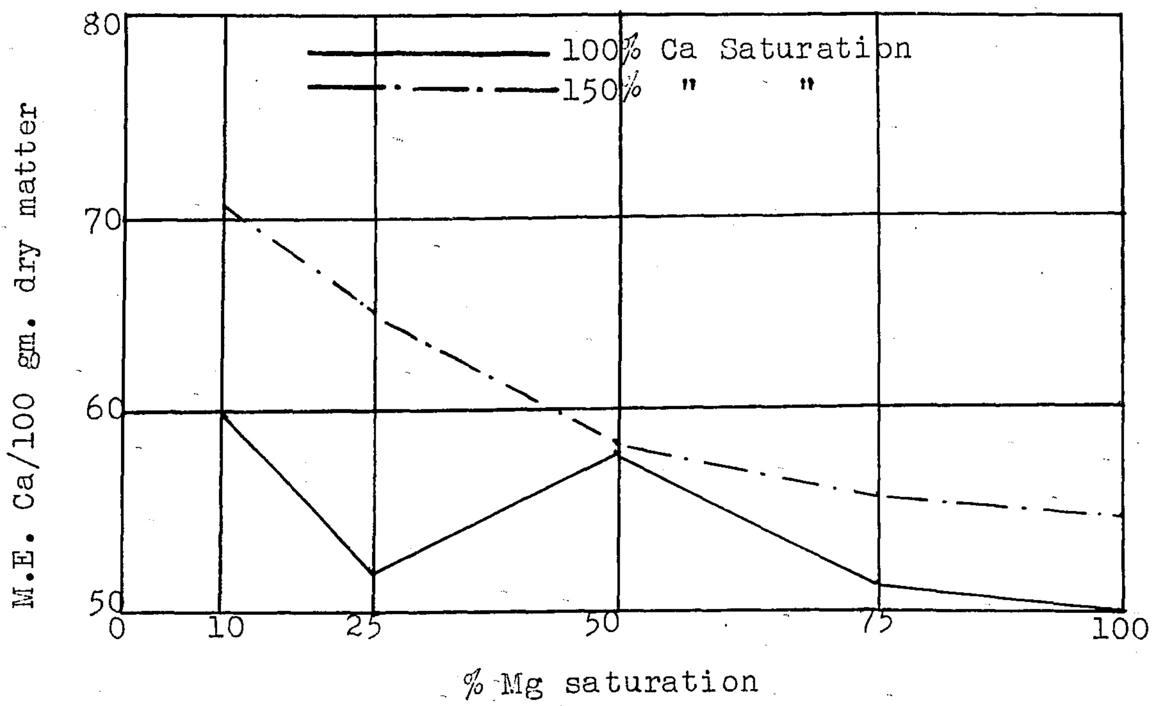

Fig. 34. The effect of degree of Ca and Mg saturation on the Ca content of corn plants in Wisner soil.

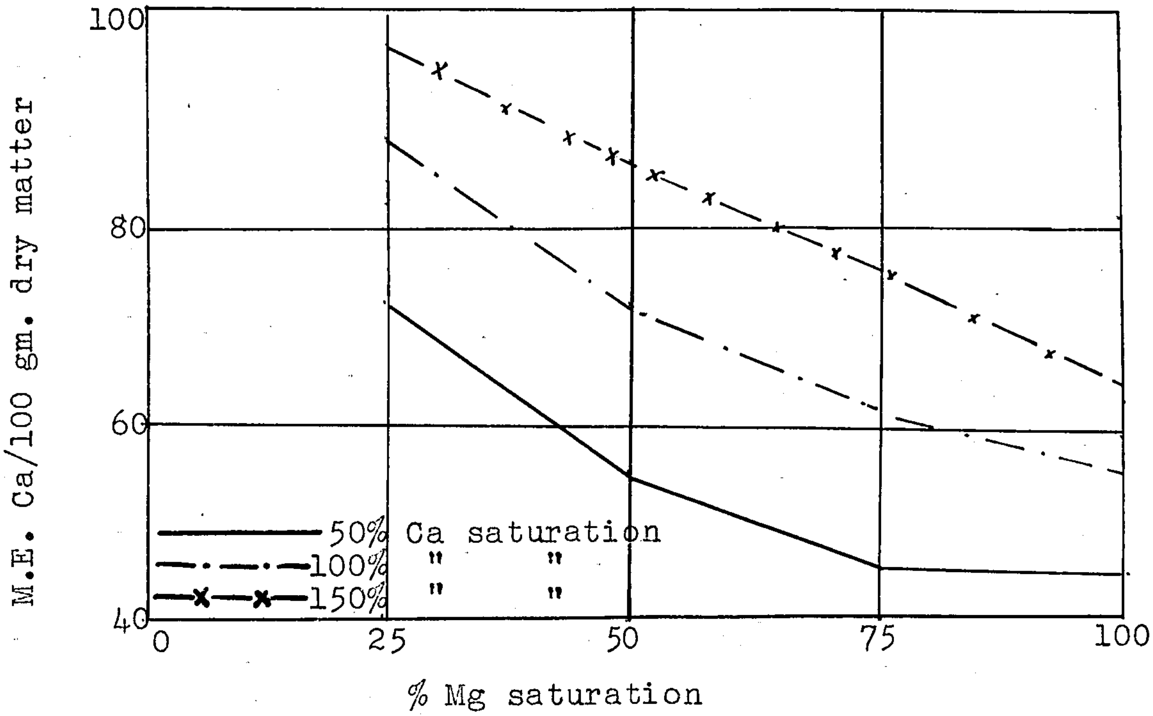

Fig. 35. The effect of degree of Ca and Mg saturation on the Ca content of tomato plants in Plainfield soil.

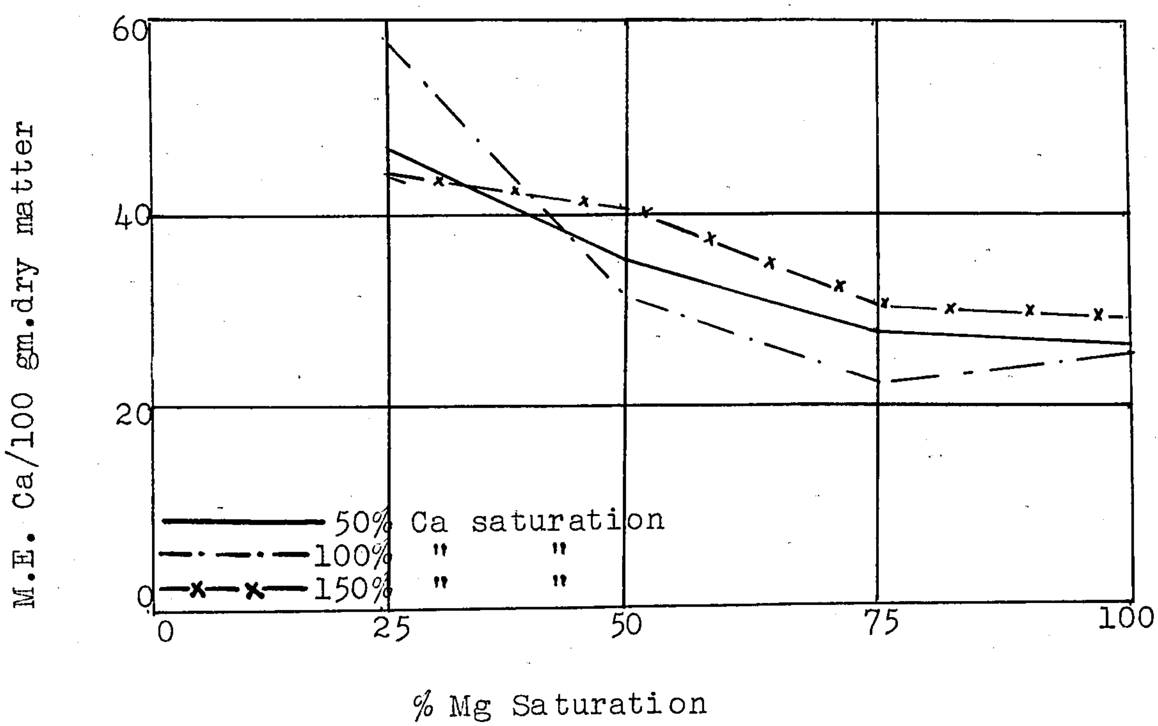

Fig. 36. The effect of degree of Ca and Mg saturation on the Ca content of corn plants in Plainfield soil.

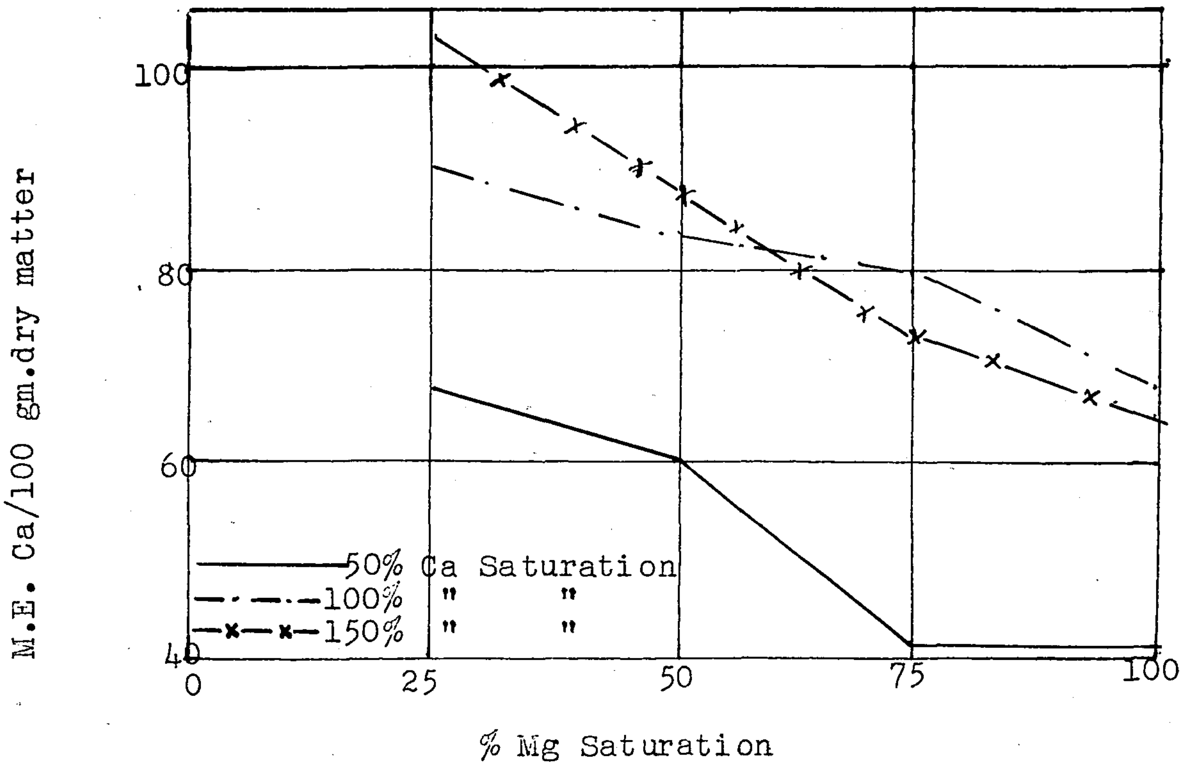

Fig. 37. The effect of degree of Ca and Mg saturation on the Ca content of tomato plants in Fox soil.

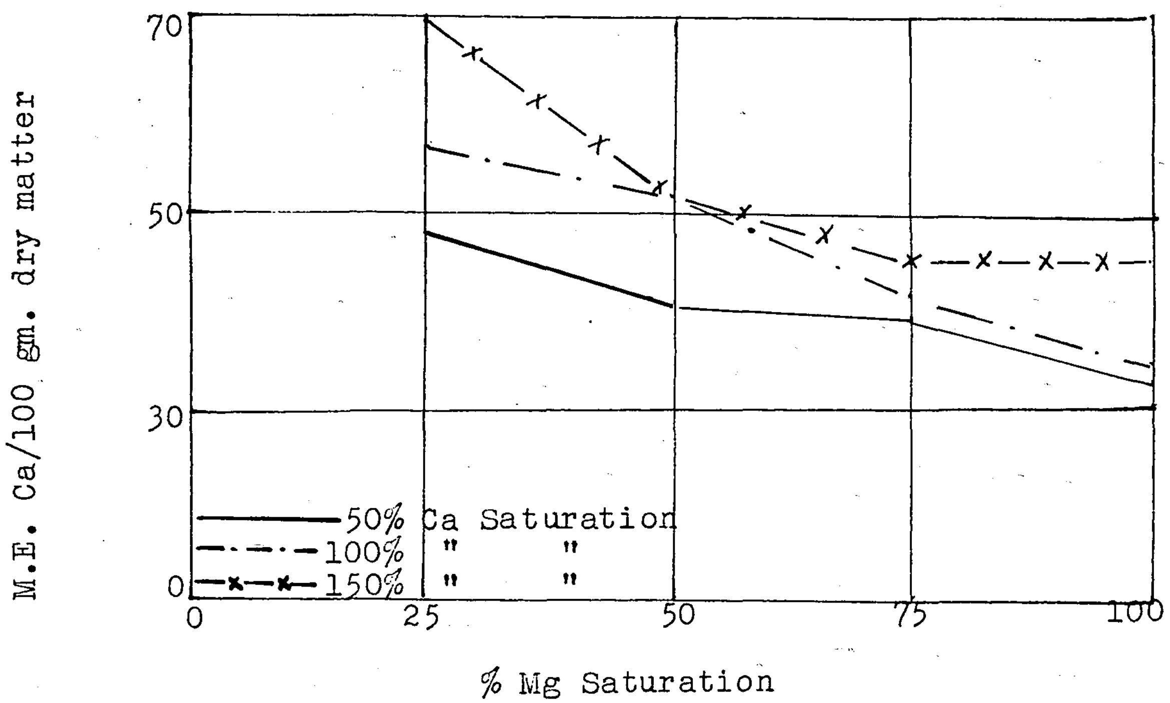

Fig. 38. The effect of degree of Ca and Mg saturation on the Ca content of corn plants in Fox soil.

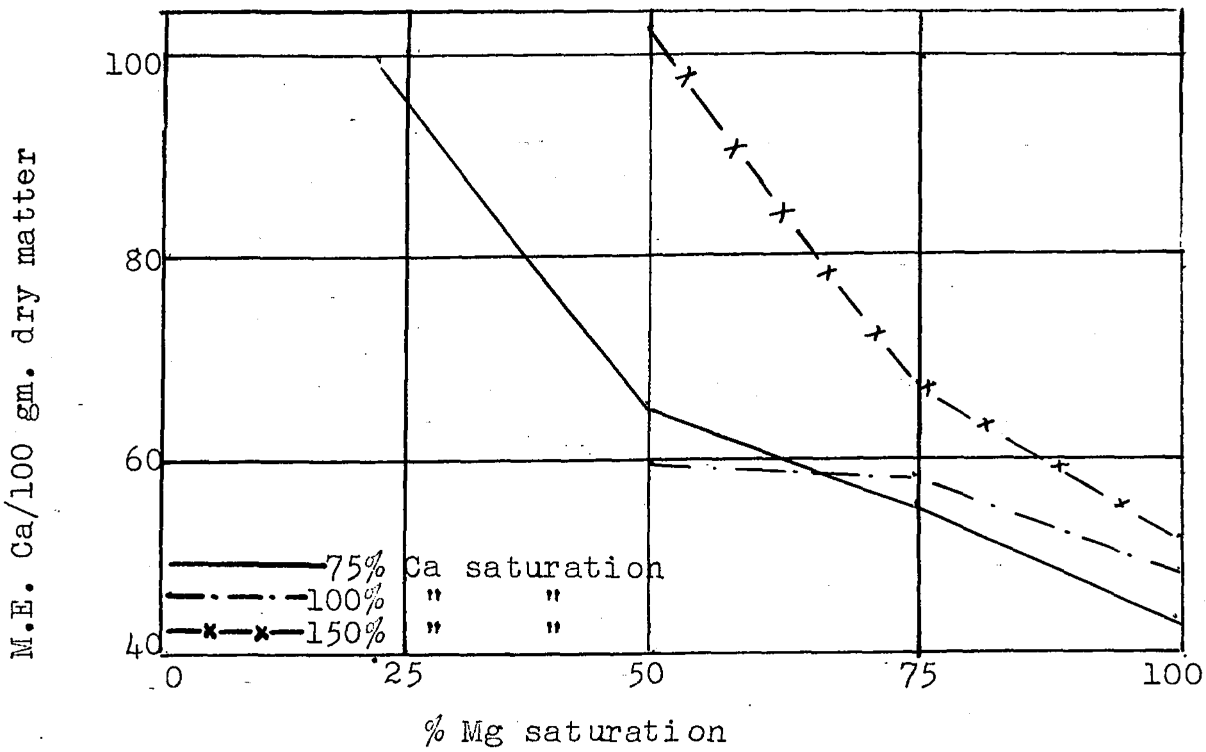

Fig. 39. The effect of degree of Ca and Mg saturation on the Ca content of tomato plants in Hillsdale subsoil.

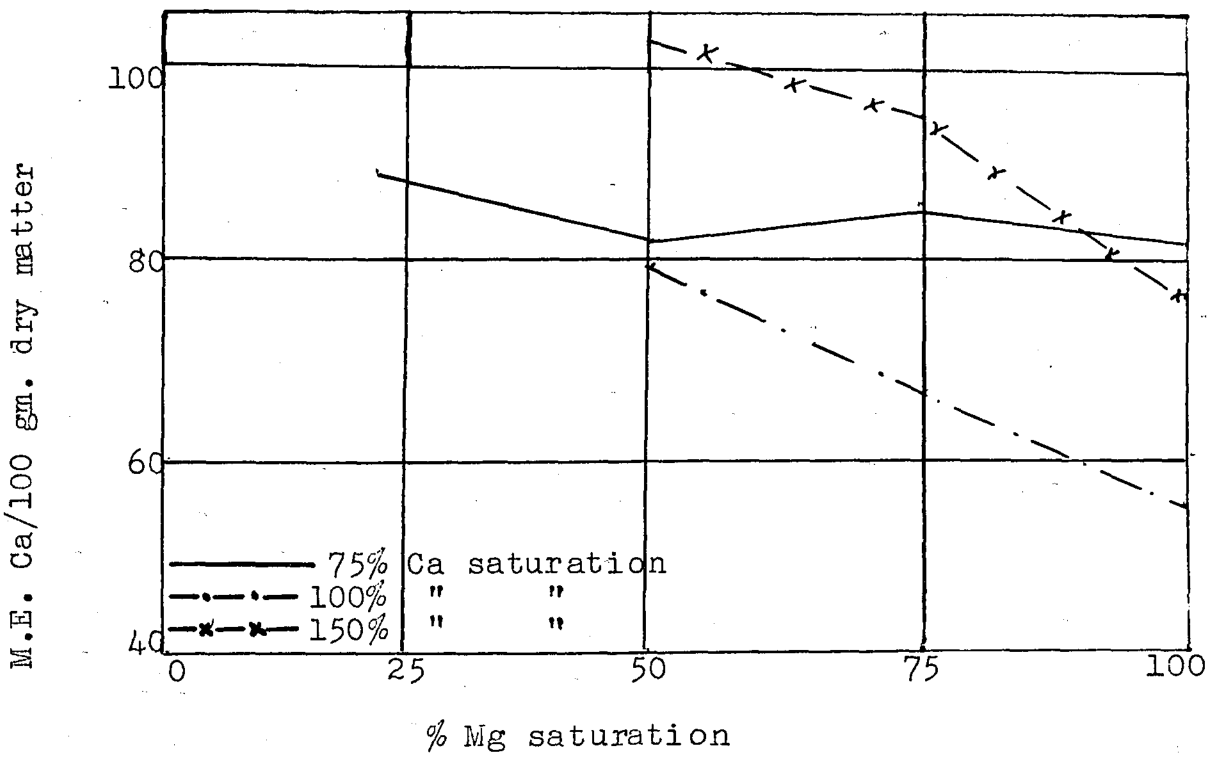

Fig. 40. The effect of degree of Ca and Mg saturation on the Ca content of tobacco plants in Hillsdale subsoil.

<u>Magnesium</u>. The graphs (Figs. 41 through 50), showing the magnesium content of tomato, tobacco and corn grown in quartz sand culture and in the four different soil types, are almost straight lines indicating thereby that by increasing the degree of magnesium concentration at each level of calcium concentration increased amounts of magnesium was delivered to the crop. From an equimolecular concentration of calcium and magnesium, e.g. 18.32 m.e. of Ca and 18.32 m.e. of Mg (Table XX); 1.78, 2.67, 3.56 m.e. of Ca and Mg (Table XXI); and 1.70, 2.55 and 3.54 m.e. of Ca and Mg (Table XXII) more magnesium than calcium has been taken up by the plant. At low concentrations of magnesium, either at 10 per cent saturation in Wisner soil or 25 per cent saturation in Plainfield and Fox sand, increasing concentration of calcium in the soil resulted in greater uptake of calcium by plants. At higher magnesium concentrations the uptake of calcium was suppressed. Thus, when the Ca:Mg ratio in the solution was narrow, magnesium had a suppressive effect on the uptake of calcium and to certain extent on the uptake of potassium.

The absorption of increased increments of magnesium neither induced good growth nor produced any increase in yield. Such an absorption of magnesium is considered a luxury consumption. At the lower range of concentrations of the element in the soil there seemed to be economical utilization of nutrients and hence better growth and yield of the crops.

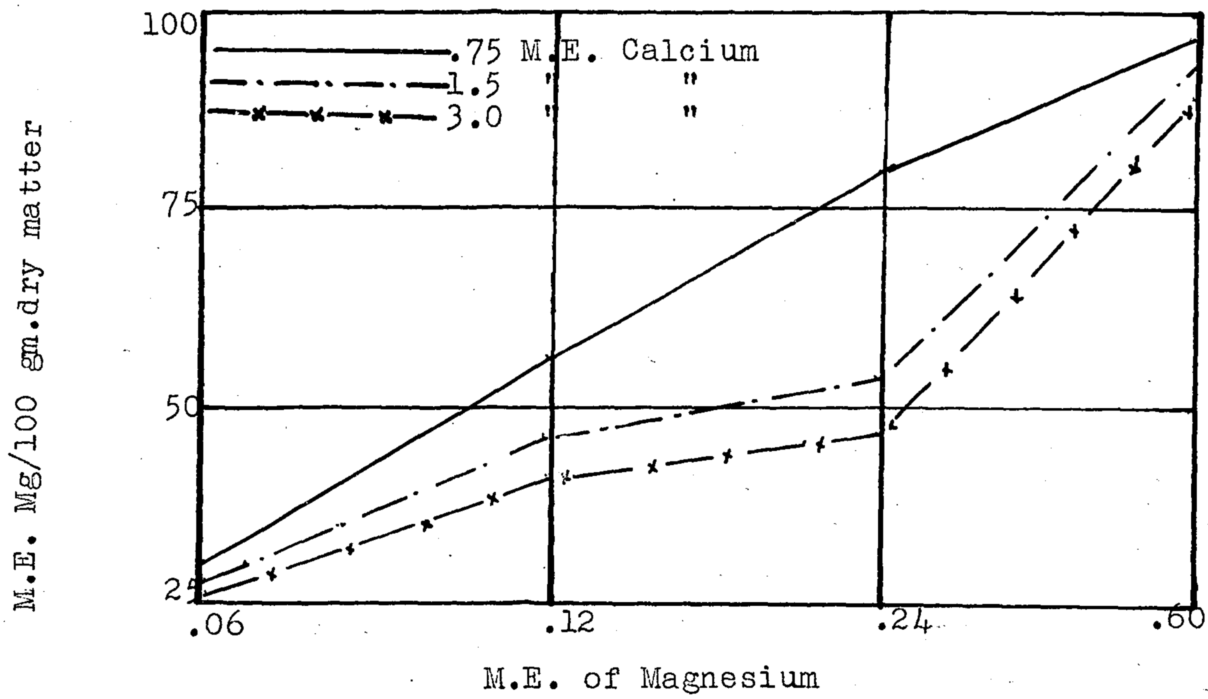

Fig. 41. The effect of interaction of Ca and Mg saturation on the Mg content of tomato plants in Quartz sand culture.

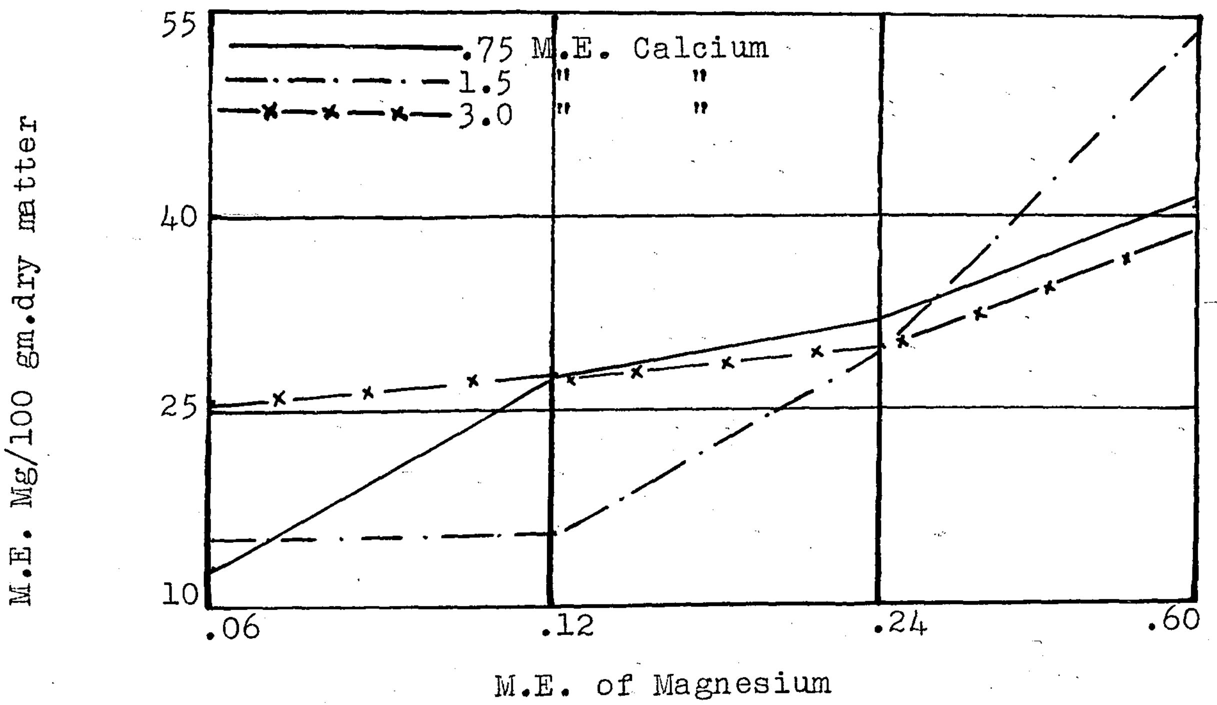

Fig. 42. The effect of interaction of Ca and Mg saturation on the Mg content of corn plants in Quartz sand culture.

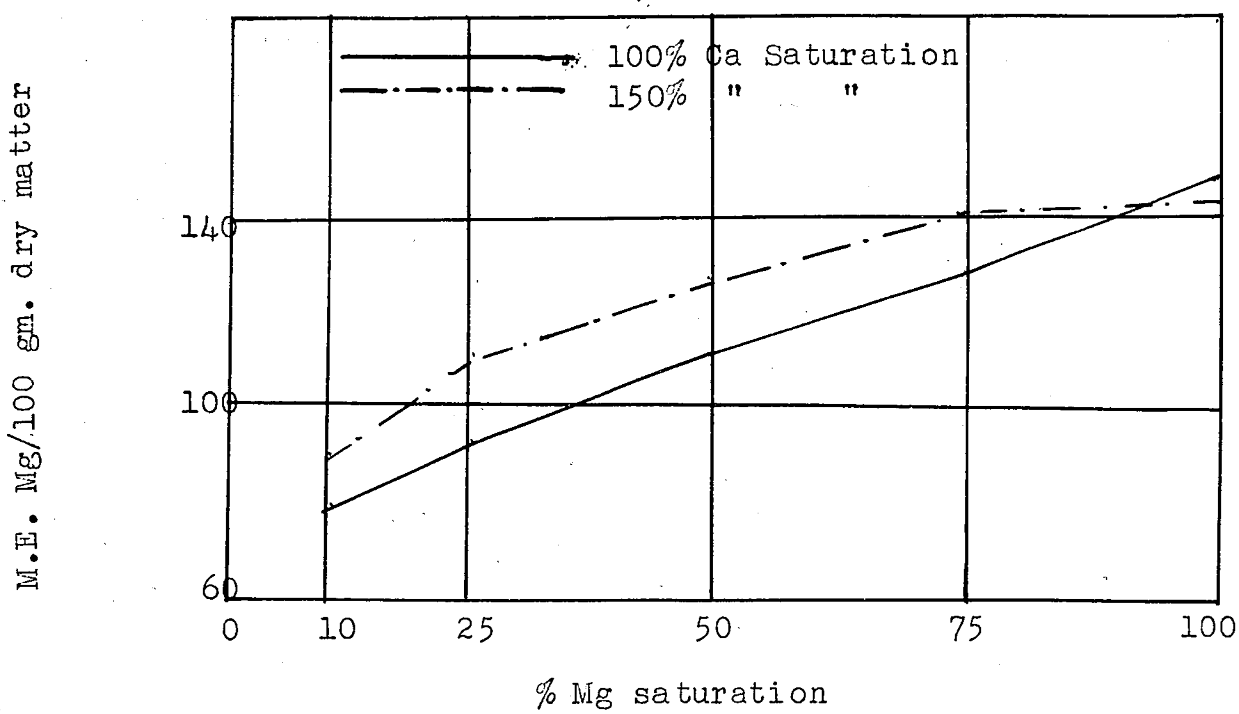

Fig. 43. The effect of degree of Ca and Mg saturation on the Mg content of tomato plants in Wisner soil.

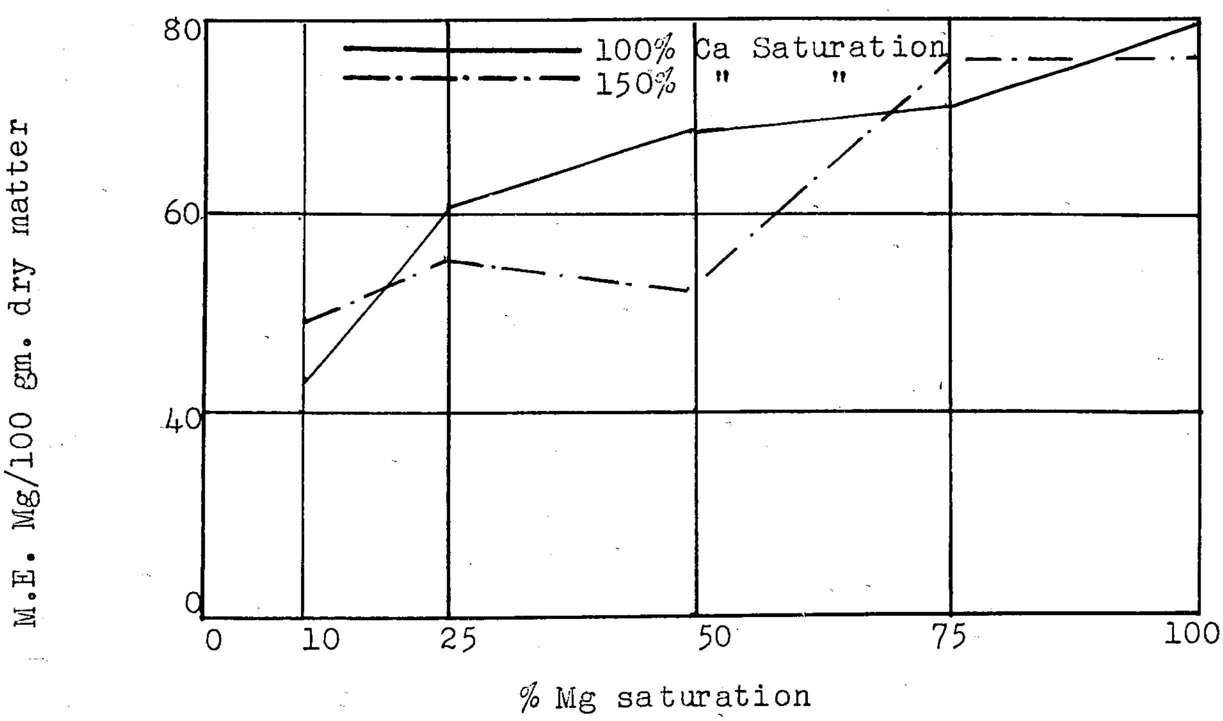

Fig. 44. The effect of degree of Ca and Mg saturation on the Mg content of corn plants in Wisner soil.

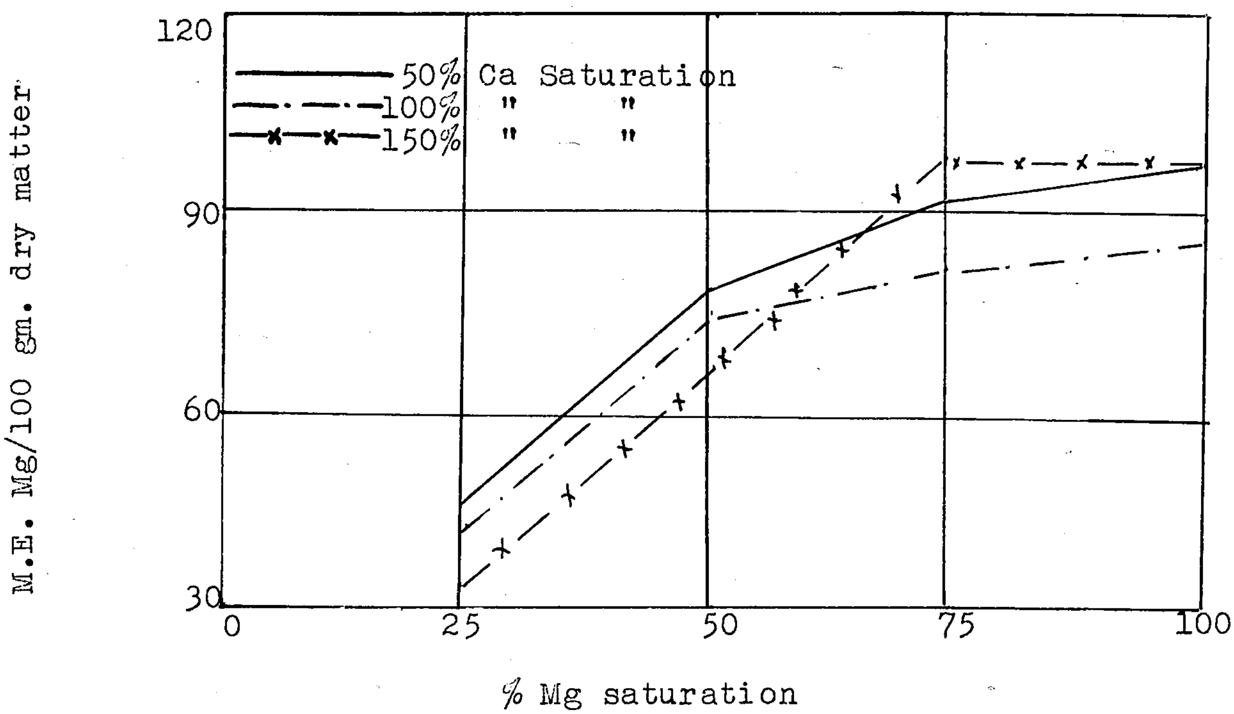

Fig. 45. The effect of degree of Ca and Mg saturation on the Mg content of tomato plants in Plainfield soil.

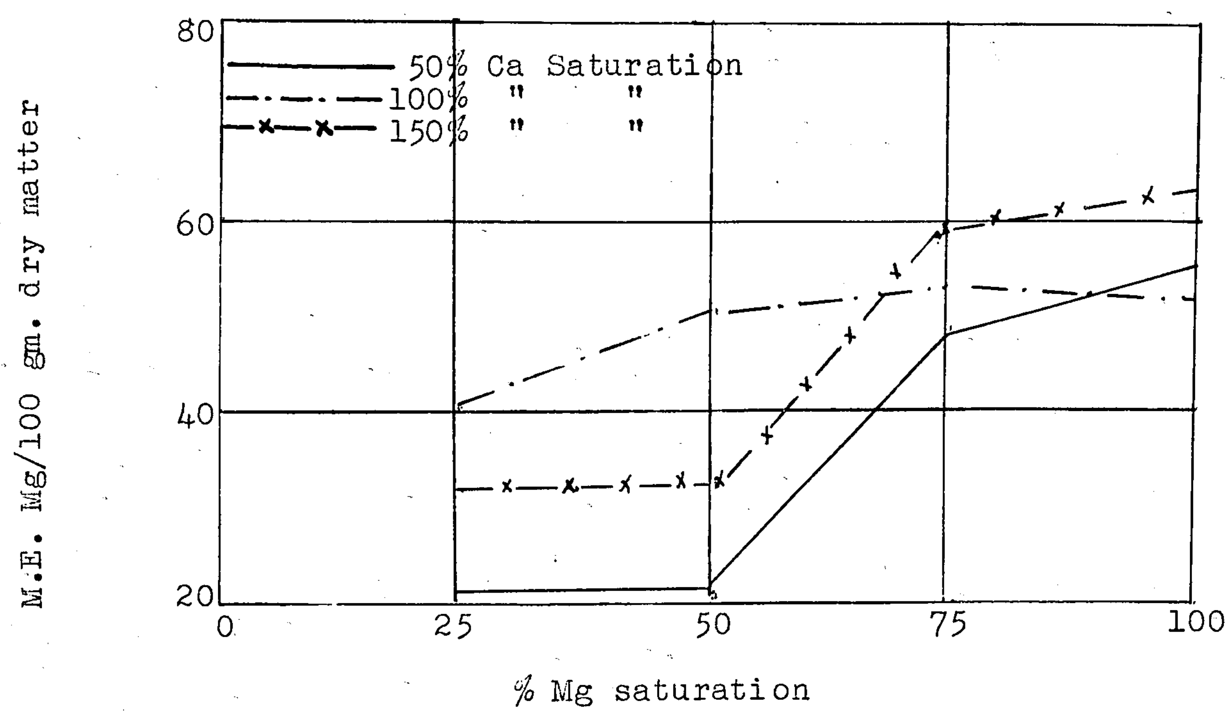

Fig. 46. The effect of degree of Ca and Mg saturation on the Mg content of corn plants in Plainfield soil.

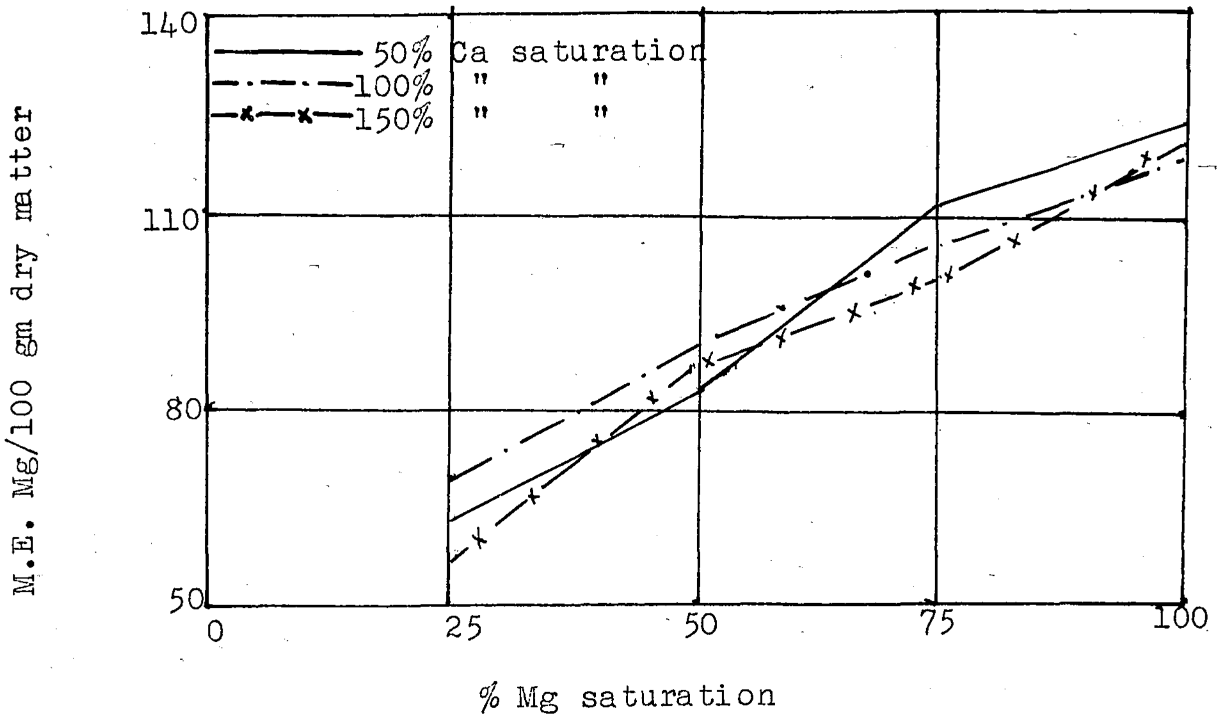

Fig. 47. The effect of degree of Ca and Mg saturation on the Mg content of tomato plant in Fox soil.

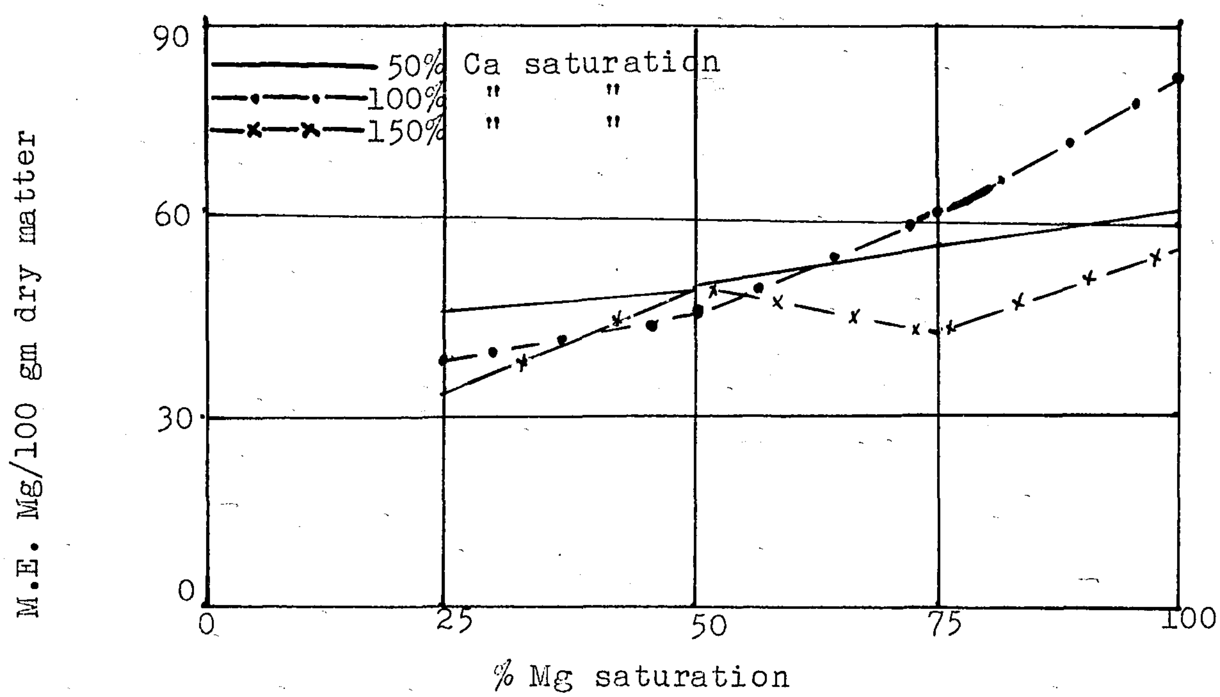

Fig. 48. The effect of degree of Ca and Mg saturation on the Mg content of corn plants in Fox soil.

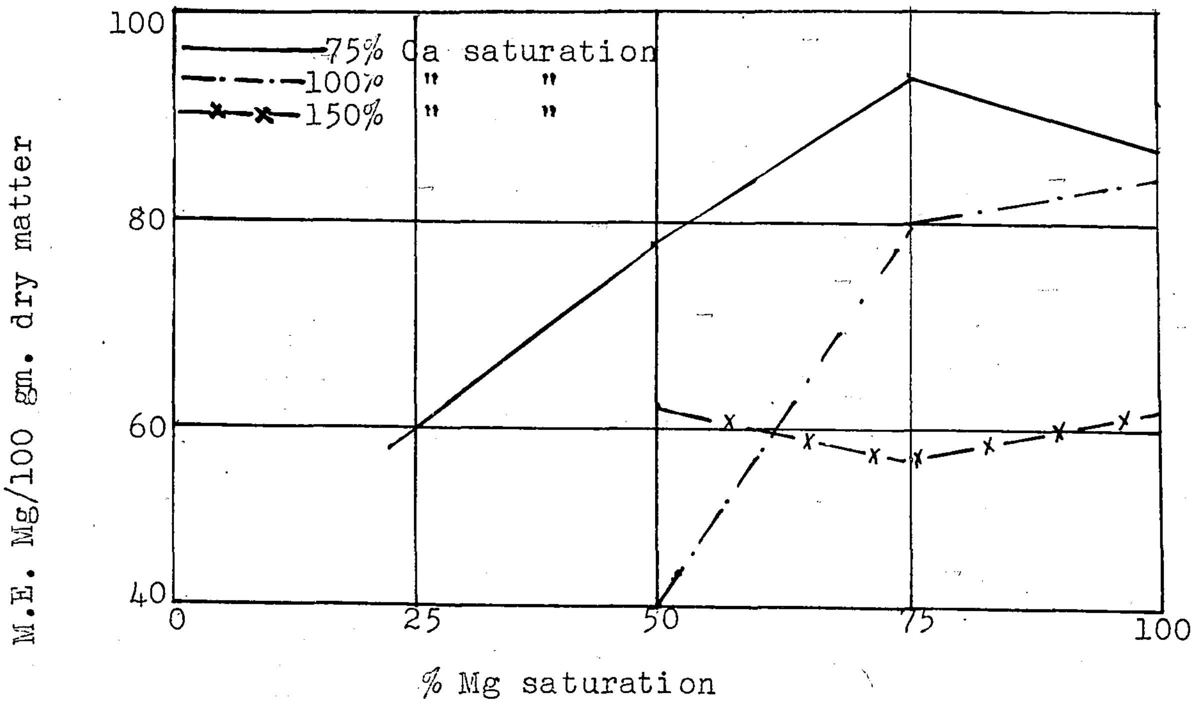

Fig. 49. The effect of degree of Ca and Mg saturation on the Mg content of tomato plants in Hillsdale subsoil.

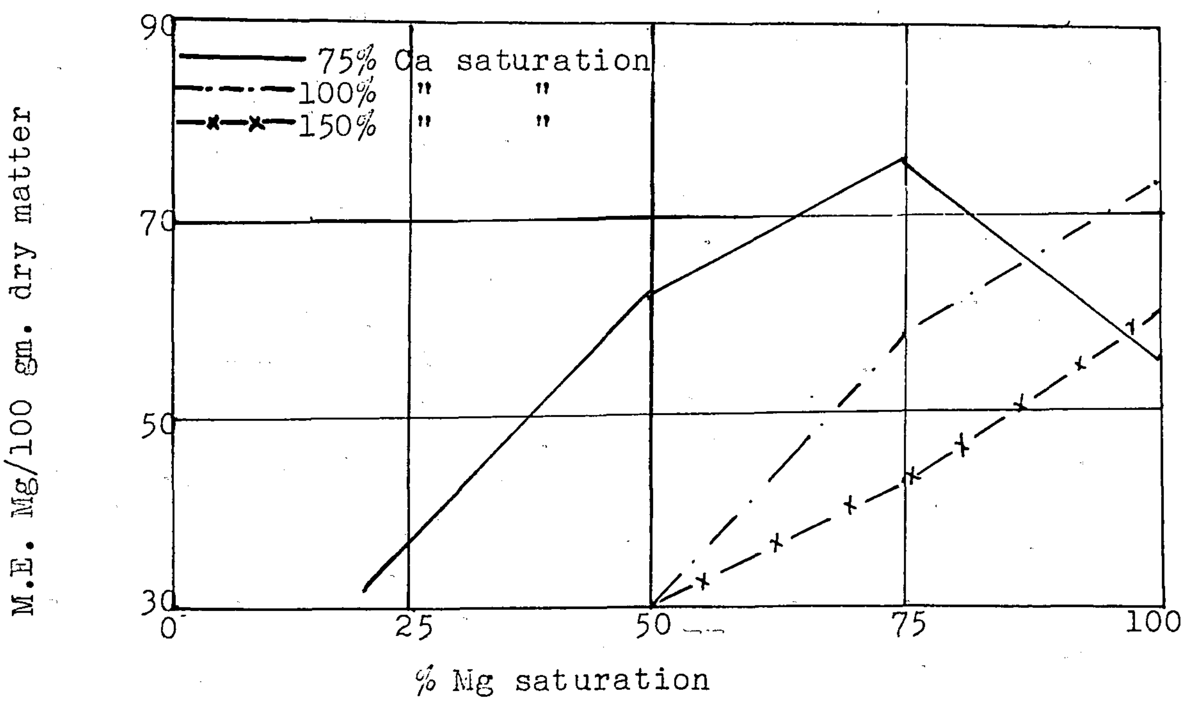

Fig. 50. The effect of degree of Ca and Mg saturation on the Mg content of tobacco plants in Hillsdale subsoil.

In terms of magnesium concentrations and total magnesium content of the crops, they were greater in the acid soils than in the calcareous soils. Thus, the absorption of both calcium and magnesium decreased at the higher pH values. When acid soils, such as Plainfield and Fox sand, were limed to a neutral condition the base status of the soils and the mobility of the calcium as well as magnesium was increased.

Potassium. As indicated in Figs. 51 through 60, the potassium content of tomato, tobacco and corn appeared to be influenced more by the magnesium than the calcium content of the soil. Increasing concentrations of calcium in the soil had but little influence on the uptake of potassium by the plants. With a constant amount of potassium in the soil, the percentage as well as the total amount of potassium absorbed by tomato, tobacco and corn increased with increasing magnesium concentrations, when the content of calcium remained constant. Thus, there is apparently a "synergistic effect" of magnesium on potassium inasmuch as the former is associated with the movement of the potassium into the plant. But this synergistic effect seemed to be related to a definite concentration of magnesium with respect to the saturation capacity of the exchange complex. In the present studies this concentration level appeared to be 75 per cent of the saturation of the original exchange capacity of the soil. Beyond this level a competitive effect arises, the uptake of magnesium increases while

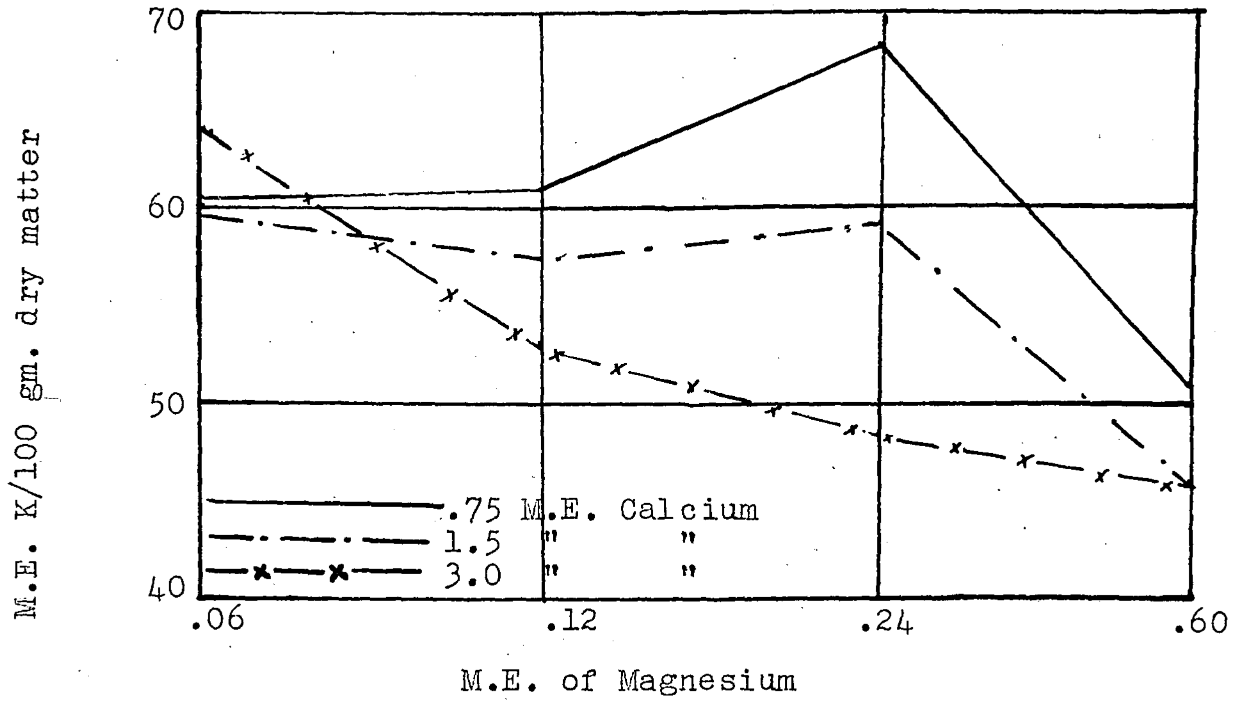

Fig. 51. The effect of interaction of Ca and Mg saturation on the K content of tomato plants in Quartz sand culture.

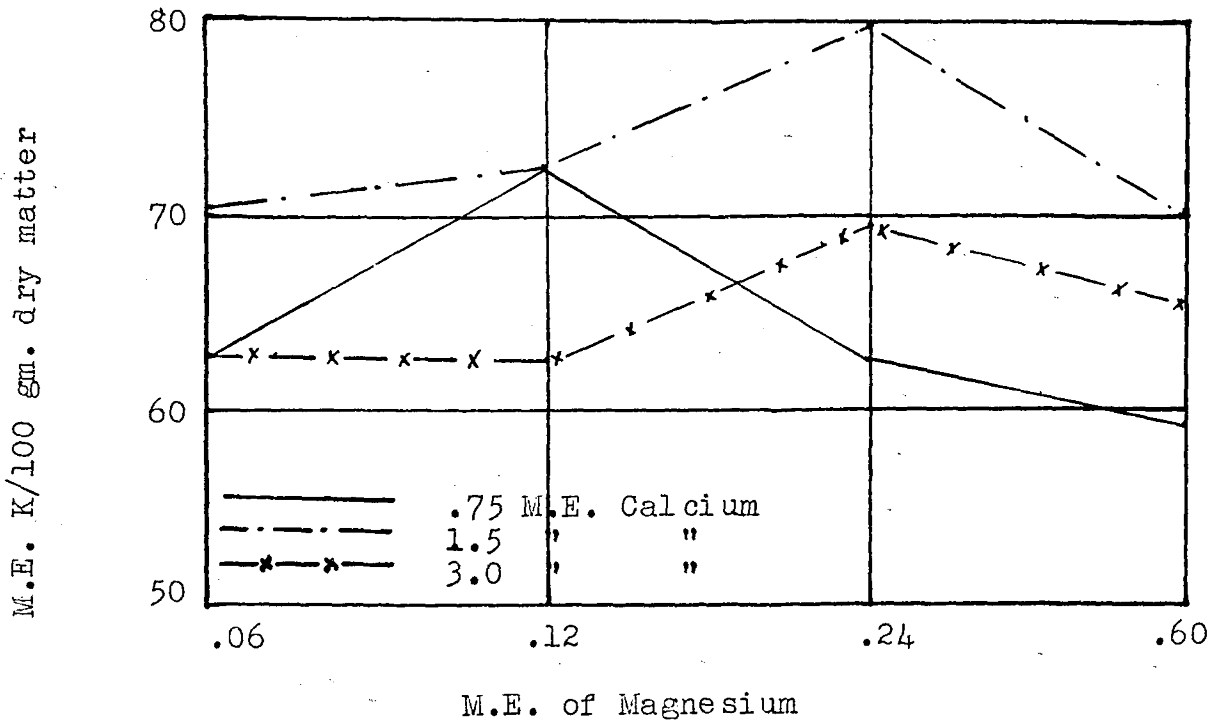

Fig. 52. The effect of interaction of Ca and Mg saturation on the K content of corn plants in Quartz sand culture.

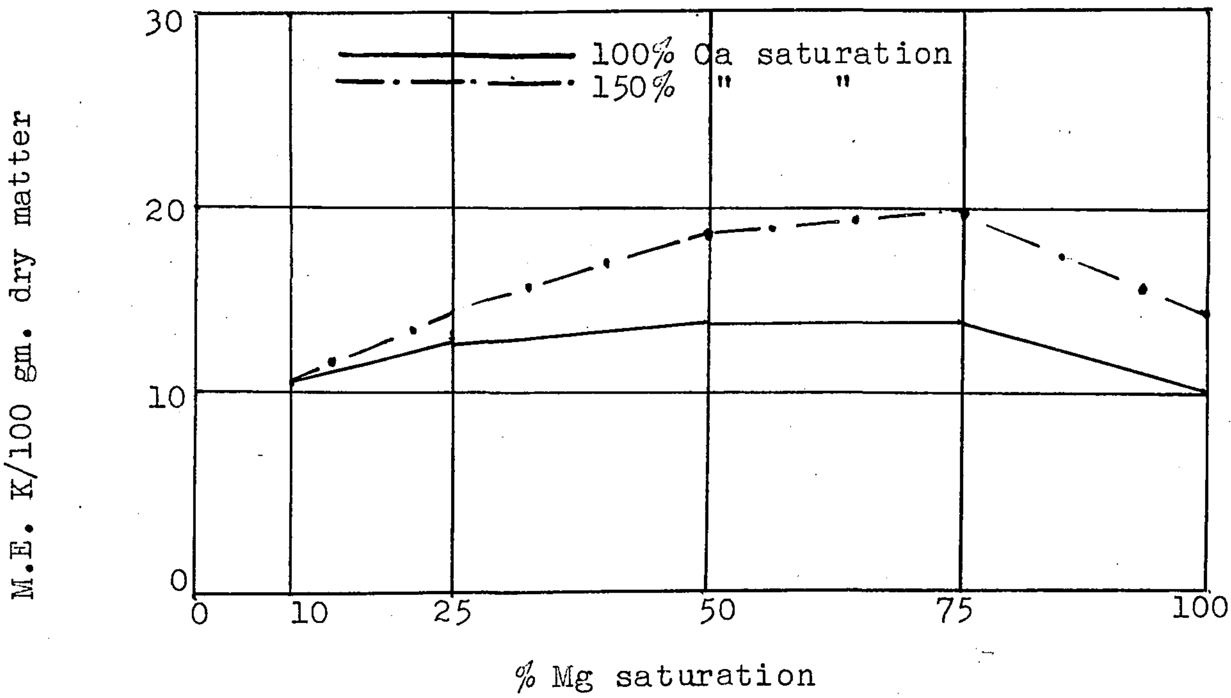

Fig. 53. The effect of degree of Ca and Mg saturation on the K content of tomato plants in Wisner soil.

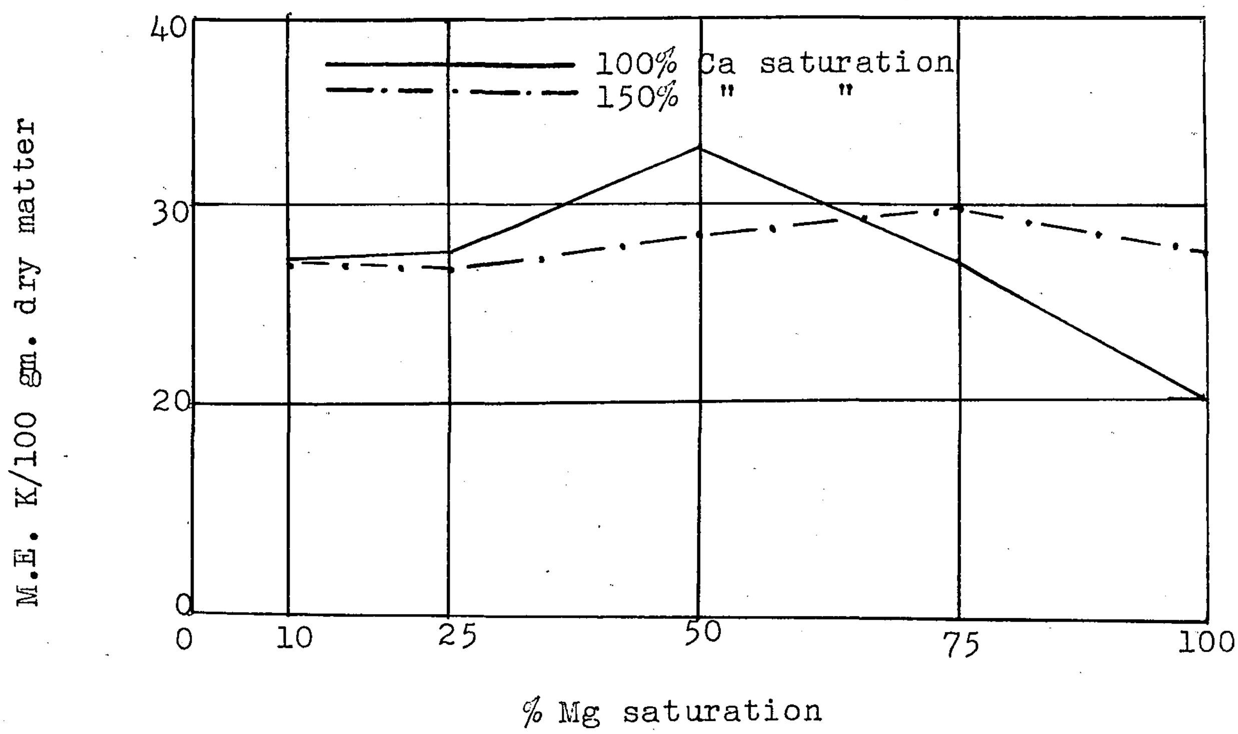

Fig. 54. The effect of degree of Ca and Mg saturation on the K content of corn plants in Wisner soil.

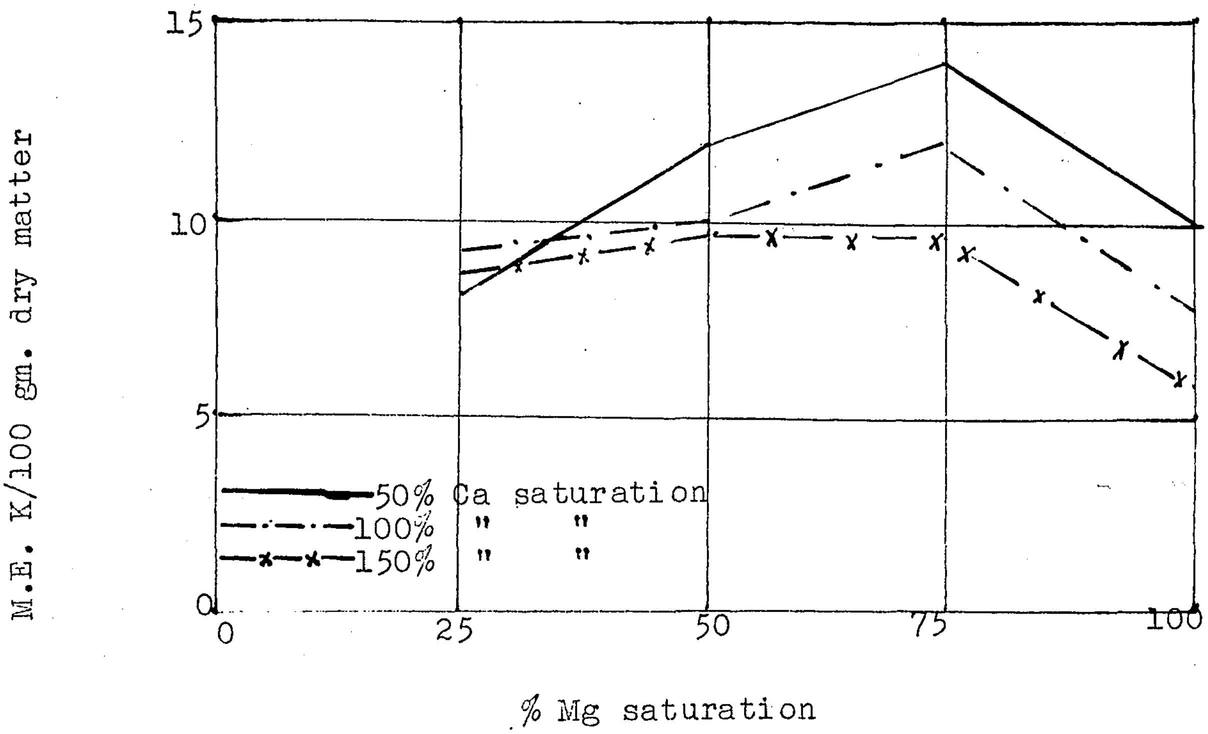

Fig. 55. The effect of degree of Ca and Mg saturation on the K content of tomato plants in Plainfield soil.

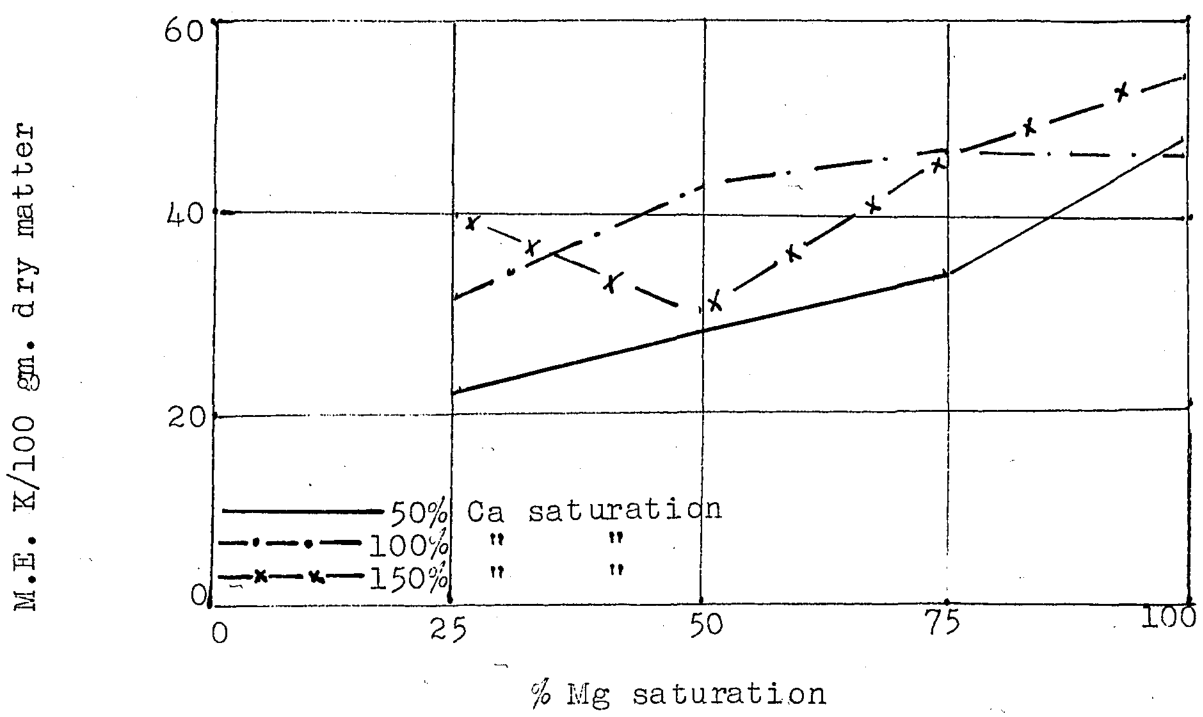

Fig. 56. The effect of degree of Ca and Mg saturation on the K content of corn plants in Plainfield soil.

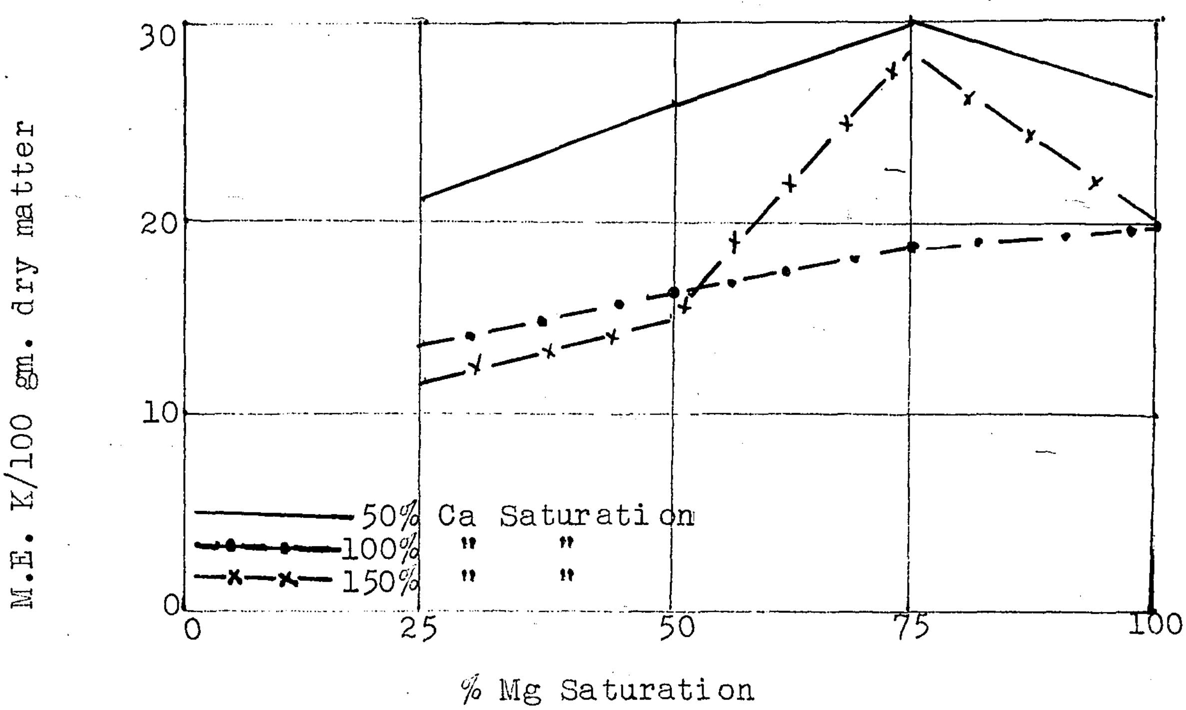

Fig. 57. The effect of degree of Ca and Mg saturation on the K content of tomato plants in Fox soil.

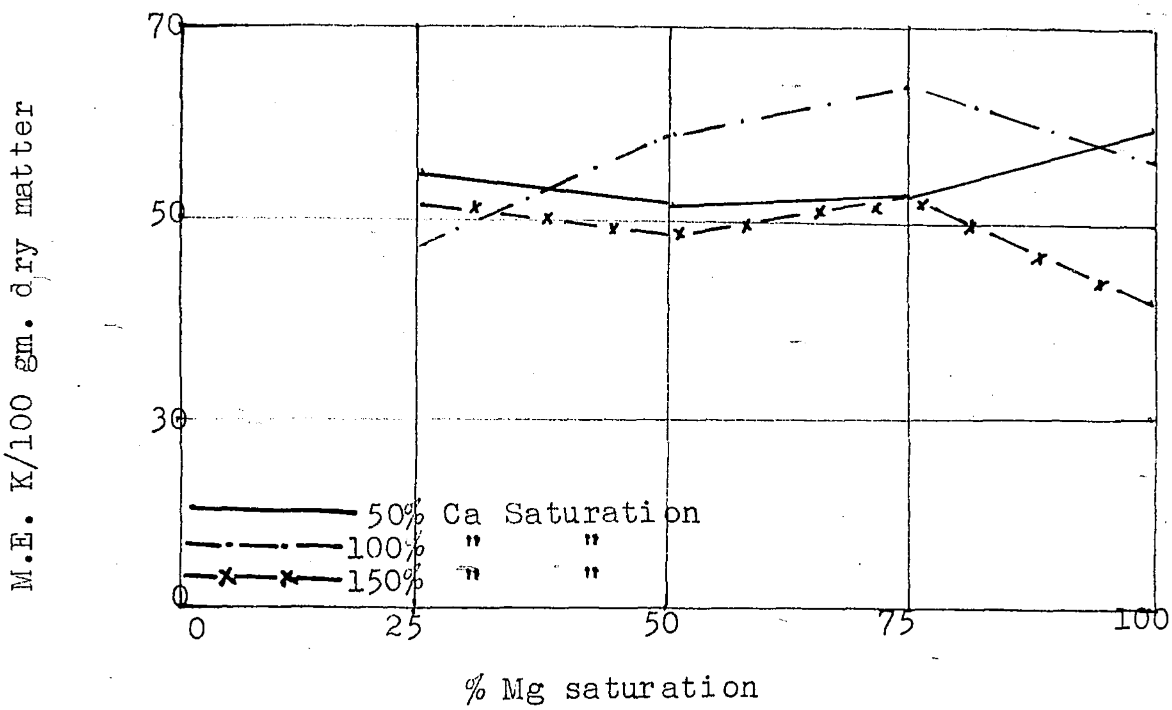

Fig. 58. The effect of degree of Ca and Mg saturation on the K content of corn plants in Fox soil.

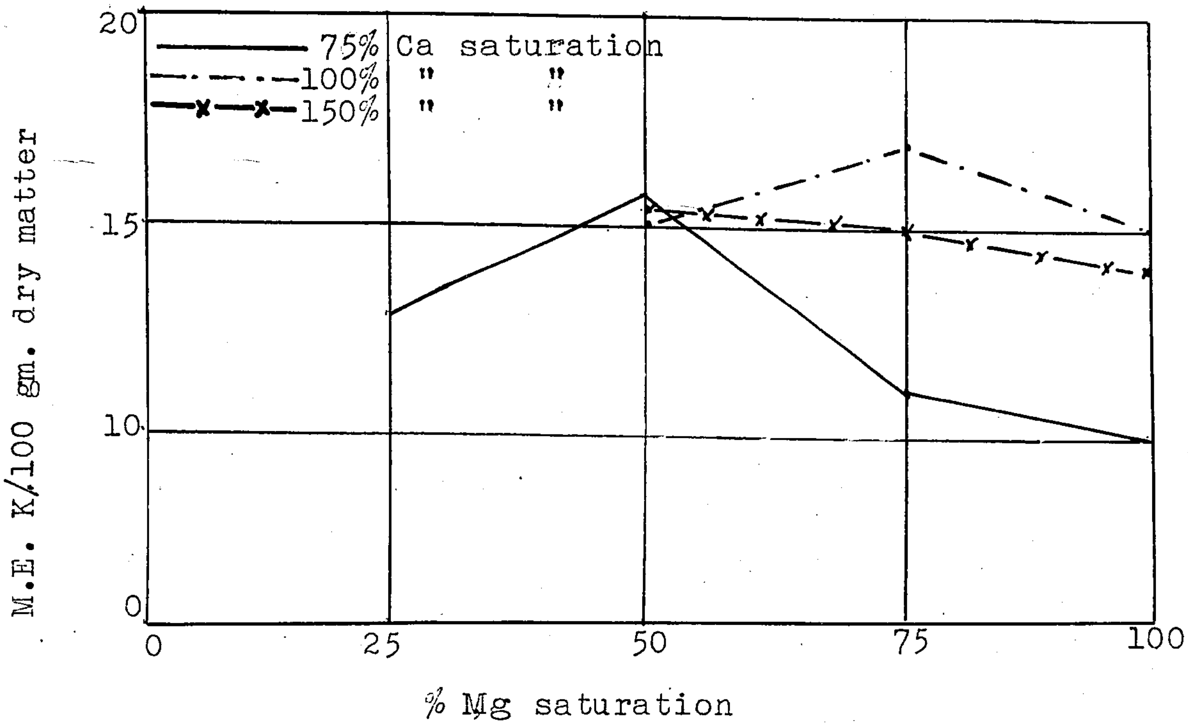

Fig. 59. The effect of degree of Ca and Mg saturation on the K content of tomato plants in Hillsdale subsoil.

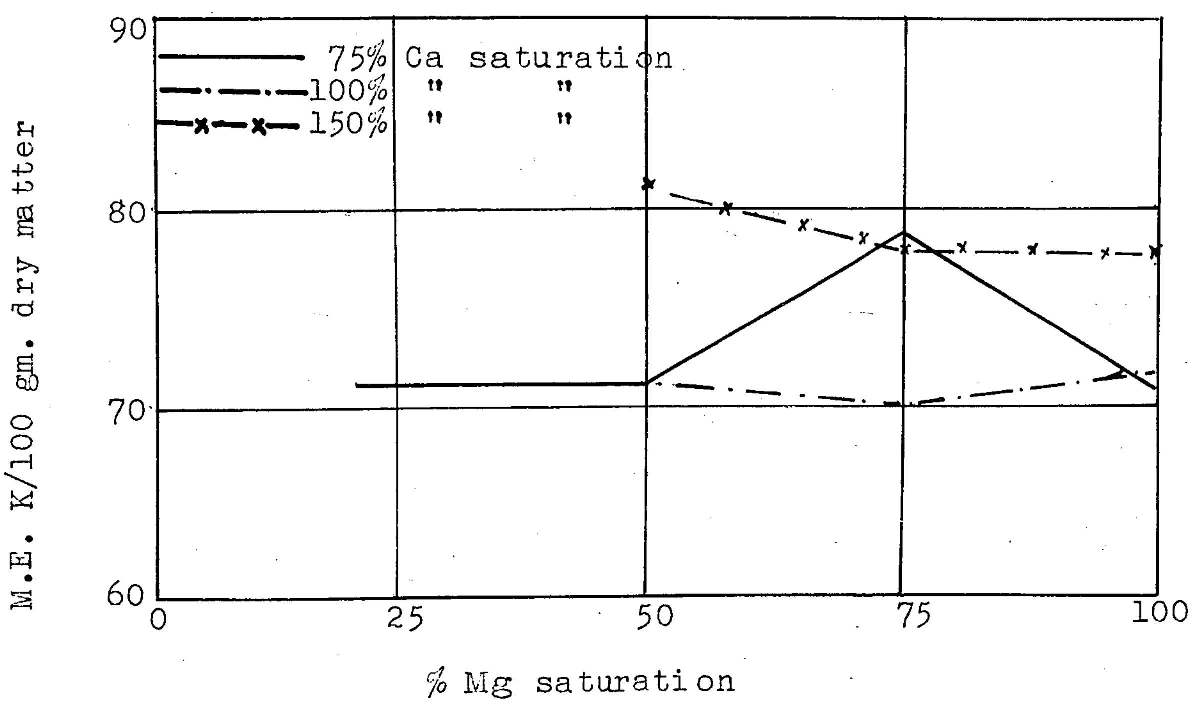

Fig. 60. The effect of degree of Ca and Mg saturation on the K content of tobacco plants in Hillsdale subsoil.

the uptake of potassium decreases. It may be mentioned here that, as was shown in Tables XI, XII and XIII, there was increased accumulation of nitrogen when the concentration of magnesium went beyond 75 per cent saturation level of the exchange capacity of the soil. Bartholomew and Jannesen(6), working with tomato plants, have found that nitrogen and potassium bear an inverse relationship; a high percentage of one is associated with low percentage of the other in the plant. Under the present experimental conditions, the suppressive effect of Mg is probably towards the maintenance of a physiological balance, although this adjustment results in injury to plants by retarding growth and depressing yields.

In comparing the K content of the tomato, tobacco and corn crops grown in the high-lime Wisner and Hillsdale subsoil with the base unsaturated Plainfield and Fox sand, it becomes apparent that calcareous soils fixed much larger amounts of potassium into nonexchangeable form than did acid soils. Magnesium had a beneficial effect on the absorption of K; although this beneficial effect was noticed more with corn and tobacco than with tomato.

Ca:Mg Relationship in Phosphorus Nutrition

Beeson et al (8) have shown that magnesium content of tomato leaflets was associated with a Mg-Ca interaction while P content of the leaflets was associated with Mg-P interaction. Truog et al (60) have shown that increasing supplies of available Mg increased the P content of the peas much more than did increasing supplies of available P. They concluded that available Mg in soils promotes efficient use of P. Kellog (31) has stated that in calcareous soil, Mg deficiency limits the P fertilization and P nutrition could be improved by applying Mg fertilizer. But Sturgis and Reed (57) could not find any correlation between the Mg and P content of rice straw and grains. Willis et al (63) could not find any difference in the influence of Ca and Mg on P absorption. Bartholomew (5) from his study of utilization of phosphatic fertilizers did not find any pronounced relationship between Mg and P utilization. So the correlation between Mg and P utilization is questionable.

The percentage composition of phosphorus is presented in Tables XXIV and XXV and shown in Fig. 61. The results show that there was very little influence of exchangeable Mg in the soil at any given level of Ca saturation on the uptake of P by plants. Decreasing the Ca:Mg ratio to 0.75:1 0.5:1 did not appreciably increase the P content. Thus, there appeared to be no close correlation between the Mg content of soil and uptake of P by the plant.

Seifritz (53) arranges the anions according to the rates of penetration as follows:

$$NO_3 > HPO_4 > H_2PO_4 > SO_4$$

Table XXIV

Phosphorus Content of Tomato, Tobacco and Corn grown on Soils with Different Degrees of Ca and Mg saturation. % of Dry Matter.

Degree of Saturation			Tomato		Tobacco		Corn
Ca	Mg	Ca:Mg	Wisner	Hillsdale subsoil	Wisner	Hillsdale subsoil	Wisner
Check			0.12	0.10	0.09	0.08	0.12
100	10	10:1	0.11	--	0.08	--	0.14
	25	4:1	0.12	--	0.08	--	0.15
	50	2:1	0.12	0.11	0.09	0.10	0.15
	75	1.3:1	0.11	0.10	0.08	0.10	0.13
	100	1:1	0.10	0.10	0.09	0.09	0.13
150	10	15:1	0.09	--	0.08	--	0.12
	25	6:1	0.11	--	0.09	--	0.12
	50	3:1	0.11	0.09	0.10	0.09	0.12
	75	2:1	0.10	0.10	0.08	0.09	0.13
	100	1.5:1	0.09	0.10	0.08	0.08	0.13

TABLE XXV

Phosphorus Content of Tomato, Tobacco and Corn grown on Soils with Different Degree of Ca and Mg Saturation. % on dry matter.

Degree of Saturation			Tomato		Tobacco		Corn	
Ca	Mg	Ca:Mg	Plain-field	Fox	Plain-field	Fox	Plain-field	Fox
Check			0.06	0.08	0.09	0.10	0.11	0.12
50	25	2:1	0.08	0.08	0.08	0.10	0.10	0.10
	50	1:1	0.09	0.08	0.10	0.12	0.11	0.12
	75	0.75:1	0.09	0.10	0.10	0.11	0.11	0.11
	100	.5:1	0.08	0.09	0.11	0.10	0.10	0.11
75	25	3:1	0.11	0.13	0.09	0.08	0.09	0.10
	50	1.5:1	0.10	0.12	0.10	0.12	0.12	0.11
	75	1:1	0.11	0.09	0.08	0.09	0.10	0.12
	100	0.75:1	0.10	0.10	0.09	0.10	0.09	0.10
100	25	6:1	0.12	0.14	0.12	0.10	0.12	0.12
	50	2:1	0.13	0.13	0.12	0.12	0.12	0.13
	75	1.3:1	0.13	0.14	0.11	0.12	0.11	0.13
	100	1:1	0.12	0.12	0.10	0.10	0.11	0.11
150	25	6:1	0.13	0.14	0.13	0.12	0.12	0.10
	50	3:1	0.14	0.14	0.13	0.11	0.12	0.12
	75	2:1	0.13	0.13	0.12	0.12	0.11	0.12
	100	1.5:1	0.12	0.13	0.12	0.11	0.10	0.10

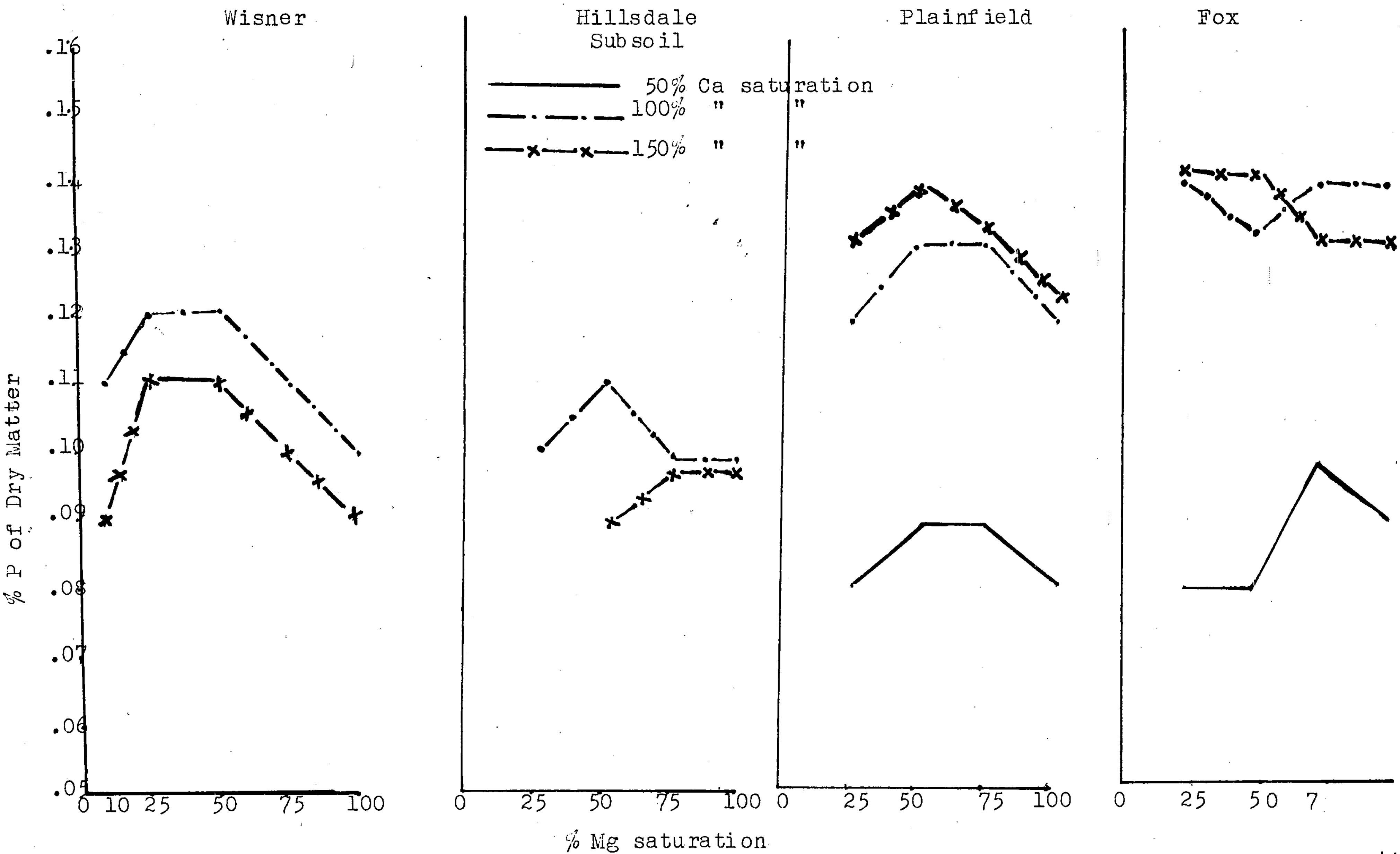

Fig. 61. Phosphorus content of tomato plant as influenced by the varying level of Ca and Mg saturation in soil.

Hoagland et al (22) postulate that there exists a definite competition between anions, the more active anion repressing the accumulation of the less active ion. They also suggest that similarity of electrical charge brings about competitive effect on the accumulation of anions. Data presented in Tables XI, XII and XIII show that there is a direct relationship between the accumulation of N with increasing concentration of magnesium at a given calcium saturation. The accumulation of nitrate anion depresses the accumulation of $H_2PO_4^-$ to balance the total negative charge. Like cation equivalency, anion equivalency may prevail. This inverse relationship between NO_3^- and $H_2PO_4^-$ can explain the negative correlation between magnesium and phosphorus uptake.

Cation Equivalent Constancy

The quality and quantity of plant growth is greatly influenced by the physiological balance of the three basic cations Ca, Mg and K. Although each cation has a specific function in the plant, there are some physiological functions that are performed in common by these cations. Variation in these three cations within a certain range may not affect the growth and quality of the crop, but any extreme variation that results from luxury consumption of one cation will be reflected in the growth and composition of the crop, because Lucas et al (37,38), Van Itallie (61), Bear and Prince (7) and Hunter (24) have shown that when the individual cation content of plants are expressed on an equivalent basis, the sum of the equivalents tends to be constant.

The sum of the milliequivalents of Ca, Mg and K in tomato, tobacco and corn crops are presented in Tables XIX through XXIII. The data show that there is a considerable variation in the Ca, Mg and K contents of plants with increasing Mg saturation at each level of calcium saturation of the exchange complex in soil. The content of individual cation of each crop varies with the soil type. Notwithstanding such variation of the individual cation, the sum of the three cations per unit of plant material tends to be constant. The range of variation in the sum for a given crop is between 20 and 30, depending upon the soil type considered. This variation was smaller than for each of the individual Ca and Mg ions, with increasing Mg saturation at a constant level of Ca saturation in the soil. The mutual replacement of both the ions is great but the total cation equivalency remains constant. Such a constancy in equivalence does not result in high yield due to luxury consumption of magnesium.

This brings out the importance of balanced concentrations of these three cations in the soil. If the content of any one is high the reserve of the other two should be brought up to such a level as to maintain a physiological balance of the three cations. This also emphasizes the importance of lime content of soil for the maintenance of a physiological balance in the Mg nutrition of crops.

Ca and Mg Content of Soils at the End of Crop Harvest

The Ca and Mg content of each soil at the start and at the harvest of the tomato crop is presented in Tables XXVI and XXVII. The total exchange capacity of soils seems to be increased and this may probably be due to incorporation of organic matter through the plant roots during the growth of the crop. However, the data show that in a soil with definite exchange capacity, any change in the amount of one exchangeable cation is accompanied by a reciprocal change of the other cation and also a definite amount of each is present in the adsorbed state, while the rest remains as free salt or reacts with other soil constituents to form insoluble compounds.

From Tables XXVI and XXVII, it is seen that in acid soils like Plainfield and Fox adsorption of magnesium have increased with increasing levels of Ca saturation. This may be due to adsorption of magnesium in replacement of adsorbed calcium as represented below.

$$\begin{matrix} H \\ Ca \end{matrix}(\text{Clay}) + \begin{matrix} Ca(OH)_2 \\ MgSO_4 \end{matrix} = \begin{matrix} CaSO_4 \\ H_2SO_4 \end{matrix} + \begin{matrix} C \\ H \\ Mg \end{matrix}(\text{Clay})$$

Lime readily replaces hydrogen of the clay and the adsorbed calcium content is thereby increased. This adsorbed calcium in turn is replaced by magnesium. Thus, increase in lime content of an acid soil helps the retention of magnesium of the added fertilizer in the adsorbed state. This result is in line with the observations of Peech (45).

Wisner and Hillsdale subsoil show very little increase in exchangeable magnesium. The high alkaline condition of the soils have favored fixation of magnesium as insoluble magnesium silicate.

TABLE XXVI

Exchangeable Calcium and Magnesium at the Start and at Harvest of Tomato Crop.
M.E. per 100 gm. Soil [illegible].

Wisher				Hillsdale Subsoil			
At start		At end		At start		At end	
Ca	Mg	Ca	Mg	Ca	Mg	Ca	Mg
16.75	0.98	13.1	0.20	0.92	0.30	0.78	0.92
18.32	1.83	12.2	0.09	0.99	0.66	0.78	0.12
"	4.58	15.2	2.5	"	0.99	1.28	0.21
"	9.16	16.0	5.7	"	1.32	1.17	0.33
"	13.74	15.0	6.4	1.32	0.66	0.81	0.24
"	18.32	14.0	9.2	"	0.99	1.30	0.48
27.48	1.83	12.8	1.0	"	1.32	1.29	0.84
"	4.58	12.7	2.3	1.98	0.66	0.41	0.24
"	9.16	19.3	5.9	"	0.99	0.75	0.48
"	13.74	18.3	8.0	"	1.32	0.49	0.63
"	18.32	21.3	8.1				

TABLE XXVII

Exchangeable Calcium and Magnesium at Start and at Harvest of Tomato Crop. M.E. for 100 gm. Soil

Plainfield				Fox			
At Start		At Harvest		At Start		At Harvest	
Ca	Mg	Ca	Mg	Ca	Mg	Ca	Mg
	0.63	0.93	0.14	1.24	0.31	0.91	0.19
1.78	0.89	1.16	0.73	1.70	0.85	1.02	0.60
2.67	0.89	1.74	0.75	2.55	0.85	2.00	0.69
3.56	0.89	2.92	0.77	3.40	0.85	2.90	0.71
5.34	0.89	4.10	0.78	5.10	0.85	3.00	0.75
1.78	1.78	1.17	0.90	1.70	1.70	1.01	1.20
2.67	1.78	1.92	1.10	2.55	1.70	2.05	1.30
3.56	1.78	2.58	1.20	3.40	1.70	2.76	1.33
5.34	1.78	3.90	1.40	5.10	1.70	2.96	1.35
1.78	2.67	1.60	1.07	1.70	2.55	1.30	2.00
2.67	2.67	1.98	1.90	2.55	2.55	2.08	1.90
3.56	2.67	3.00	2.07	3.40	2.55	2.90	1.93
5.34	2.67	3.90	2.10	5.10	2.55	2.98	1.92
1.78	3.56	1.45	2.38	1.70	3.40	1.05	2.20
2.67	3.56	2.78	2.40	2.55	3.40	2.02	2.25
3.56	3.56	2.00	2.43	3.40	3.40	2.92	2.18
5.34	3.56	3.00	2.45	5.10	3.40	3.01	2.27

DISCUSSION

The results in this study show the importance of lime content of soil in relation to crop response to magnesium. Although the amount of magnesium used in this investigation was far in excess of that used in ordinary agronomic practice, yet the results demonstrate the harmful effects of magnesium when it exceeds the saturation capacity of the exchange complex beyond a certain limit. This limit of saturation depends upon the nature of colloid and also the initial saturation of bases as was illustrated by the Plainfield and Fox sand which are acid in reaction. At a low level of base saturation, magnesium increases the efficiency of the plant and thereby the elements supplied through N-P-K fertilizers are more economically used and crop production is increased. At high magnesium levels the uptake of magnesium is increased but the crop suffers from the excess magnesium. Above 75 per cent saturation of the exchange capacity with magnesium in the case of Wisner and Hillsdale subsoil the crop growth was increased but the nutrient balance was such that the supply of the other nutritive elements and organic foods were inadequate for production of fruits and for maintaining a healthy plant condition.

Soils fairly rich in both mineral and organic colloids become highly dispersed as the magnesium concentration is increased. No such effect was noticed as long as calcium was the predominating ion in the exchange complex and concentration of magnesium was low. According to the hypothesis of Russel (51) the clay particles are held together by oriented molecules of a polar liquid. These polar molecules lie between negative charges on the clay surface and the exchangeable cations that have dissociated from the clay surface and are strongly oriented in the electrostatic field between these charges. Calcium has only one molecule of water of hydration while magnesium takes up nine molecules of water of hydration (19). The water dipole molecules, instead of being oriented between the clay particles, become oriented around magnesium ions and remain as bound water with loss of free energy to act. Thus the particles with the loss of forces for orientation become dispersed. Joffe and Zimmerman (29) also found this same dispersive effect of magnesium on the soil colloids and came to the conclusion that there must be sufficient calcium to counteract this dispersive effect of magnesium. No specific ratio of Ca:Mg can be given as representing most favorable one for all conditions, but in case of a low Ca:Mg ratio it appears to be the low content of Ca rather than the high content of magnesium that is harmful to the plant.

Any application of magnesium above the saturation capacity of a sandy soil is believed to be precipitated as complex silicates. This is indicated from the amount applied at the start and the amount of exchangeable magnesium recovered at the end of the investigation, as presented in Table XXVI. The removal of magnesium by the crops was not very high and, therefore, a large percentage of the added magnesium reacted with silicic acid. This reaction is favored by a high pH of the soil (49). So overliming of an acid soil will precipitate magnesium as insoluble silicate. This possibly accounts for the observation of Bower and Turk (10) that alkaline soils may show a deficiency of available magnesium.

If we assume that the percentage composition of the nutrient elements in a plant reflects the physiological activity of the plant during the growth, then the variation in the uptake of Ca, Mg, and K from a constant concentration of calcium and varying concentration of magnesium must have been influenced by the latter. The difference in mineral composition is not the result of differential plant growth. The total quantities of an ion absorbed by the plant follows the same trend as the concentration of the ion in the plant. Thus, the total amount of an ion absorbed by the plant is dependent upon the respective rate of absorption that occurred during the growth of the plant. The rate and quantity of absorption is modified by the concentration of magnesium in the soil.

If it is assumed that a plant root absorbs the ion from the solid phase of soil by the process of "contact exchange" as advanced by Jenny and Ayres (26), the amount of an ion that can be removed depends upon the oscillation volume of that ion. In the Hofmeister Series H>Ca>Mg>K>Na, calcium is characterized by a higher energy of adsorption which indicates that it has a lesser amplitude of oscillation, while magnesium has a lower absorption energy or larger amplitude of motion. Thus, in a mixture of Ca and Mg ions, the latter will remain at the periphery of the ionic atmosphere, and hence more contact exchange of magnesium with the root hair. If the concentration of magnesium ions is higher than that of Ca, the former will not only be at the periphery of the ionic atmosphere but will penetrate deeper and will be adsorbed on the colloidal surface.[25] This was evidenced from the data in Tables XX through XXIII, where it was shown that, the exchangeable magnesium increased and exchangeable calcium decreased, when the concentration of added magnesium was increased with a constant concentration of calcium. In this instance the uptake of magnesium was greater than that of calcium.

Data presented in the analysis of green leaf tissue (Tables XI, XII and XIII) show that the water soluble magnesium content of the leaf increased as the concentration of magnesium in the soil increased. The excess concentration of magnesium ions enter into the deeper layer of the plant cells. Due to the greater hydration effect of magnesium, it has a greater coagulating effect on the cell protoplasm than either potassium or calcium. This coagulating effect of the protoplasm was reflected by the reduced growth of the plant. At higher calcium concentrations in the substrate, the absorption of calcium was increased and that of magnesium was decreased. Thus, at high calcium concentrations, magnesium had less opportunity to inhibit plant growth. This emphasizes the importance of calcium in the magnesium nutrition of the plant. Calcium must be at a higher concentration than that of magnesium in the soil complex.

If the process of uptake of ions by plants is assumed to be due to ionic or molecular movement in the soil solution, then the rate of entry or interchange of ions will be determined by the position of the ion in the lyotropic series and its concentration in the soil solution. There are no electrostatic attractive forces of the soil particles to restrain the movement of the ions. Such ions moving free in the soil solution, on the other hand, are surrounded by a layer of oriented water molecules. So in an equimolar solution of Ca and Mg ions, the concentration of solution will be higher with respect to Mg than Ca because the water of hydration of Mg is more than that of Ca. As a result, the bombardment of magnesium ions at the root surface will be more frequent than that of the calcium ions. Hence, the chance of entry of magnesium ions from the solution into the root is greater than that for calcium. This is evident from the ion composition of tomato, tobacco and corn crops grown in Quartz sand and presented in Tables XX, XXI, XXII and XXIII. The inert quartz sand has very little electrostatic attractive forces on its surface. The added ions are in the liquid phase and the absorption of the ions is also from this liquid phase. To reduce the uptake of magnesium the concentration of calcium ions should be much greater than that of magnesium ions.

Absorption of ions is conditioned, as postulated by Marshall (39) by two factors, viz. (1) the chemical equilibrium that exists between the inner and outer environment, and (2) the steady state that is maintained between them. The maintenance of the steady state is conditioned by the chemical potential of the solvent outside and the sum of the chemical potentials of the solute inside. The chemical potential of a solution containing a large proportion of calcium ions and lesser amount of magnesium ions will be greater than that of a solution with higher concentration of magnesium and lower concentration of calcium. To maintain equilibrium between such outside solutions and inside solute concentration potentials, more calcium will have to be absorbed from the solution with higher concentration of calcium while more magnesium from the solution containing higher concentrations of magnesium. As such absorption of magnesium results in poor growth, yield and unbalanced composition of plant, the concentration of calcium should always be higher than magnesium to maintain high chemical potential and greater absorption of calcium than magnesium.

It has been suggested that ion absorption may take place either by free diffusion or by chemical interaction with the membrane of the root hairs. Hansteen-Garner (21) suggest that lipoid and pectic materials govern the permeability of the cell wall. Alkalis act as dispersants and calcium as coagulants. Thus, the stability of the calcium pectate that constitutes the major part of the cell wall is maintained when sufficient calcium ions are present. Permeability and diffusion of ions are easy. With magnesium predominating,the permeability of cell wall is disturbed. The walls are highly hydrated and become unstable. This was evident from the examination of the microchemical cross section of the leaf which had received large applications of magnesium. When the stability or permeability of the cell wall is disturbed, the equilibrium of the protoplasm with which it is chemically and biologically associated is disrupted, the normal growth of the plant is inhibited.

In conclusion, it can be said that, from the standpoint of nutrient supply, two factors determine the growth, yield, and composition of plants. These two factors can be designated as "intensity" and "capacity factors." Addition of magnesium invariably increased the productive capacity of the plants. This is evident from the growth and yield of plants which received no added magnesium but depended entirely on soil magnesium for their supply of this element. Low magnesium was associated with low yields. With increased magnesium, plant growth improved but when the quantity of magnesium was increased beyond a certain percentage of saturation of the exchange complex, there was luxury consumption of magnesium and physiological disturbance set in. The other essential elements could not be utilized. The "quality factor" or nutrient balance in the plant was disturbed and the result was low yield. The lime content of the media largely controls this "intensity" and "quality" factor in the magnesium nutrition of plants. Hence, the best growth response and nutrition of plant can be achieved only when the per cent saturation and total concentration of calcium exceeds that of magnesium.

These results indicate that best results from magnesium fertilization can be obtained only when it is accompanied by lime application. The lime application, however, should not be in excess as was demonstrated by the growth and yield of crops grown in Hillsdale subsoil thath contains a high proportion of free calcium carbonate which masks the beneficial effect of magnesium application.

SUMMARY

This investigation was undertaken to study by means of pot culture the lime content of soil in relation to crop response to magnesium.

Four soils were used for the study including two, the Wisner and Hillsdale subsoil, which were alkaline in reaction and contained free carbonates, and two, the Plainfield and Fox sand, which were acid and low in degree of base saturation. Quartz sand cultures were also used for comparative purposes.

Calcium and magnesium applications were made on the basis of per cent saturation of the exchange complex. The treatments were designed to evaluate the effect of increasing amounts of magnesium when calcium was held constant and the changes caused by variations in the proportions of the two cations at constant level of base saturation.

Tomato, tobacco and corn were grown as test crops. Growth, yield and composition of the crops were determined.

In the alkaline Wisner soil, containing a fair amount of organic matter and mineral colloids, high applications of magnesium were found to destroy tilth of the soil. Morphological characteristics of a solonetz soil were noticed. The growth of young seedlings was poor due to the high water tension.

In sandy Hillsdale subsoil very little response to magnesium was noticed. Due to the high pH there was considerable fixation of magnesium as insoluble magnesium silicate. This was indicated by the low recovery of exchangeable magnesium after harvesting the crop.

In the acid soils, Plainfield and Fox, the response to magnesium was best when the base saturation was high and the soil reaction was about neutral.

In all soils, when the concentration of magnesium was higher than calcium, magnesium sickness of the plant was conspicuous. There was sufficient vegetative growth to maintain a good healthy plant but the growth was insufficient to induce fruiting in tomato.

With increasing concentrations of magnesium, at a constant calcium concentration, the calcium content of the plants decreased. The magnesium content increased with a linear relationship and potassium content was increased up to the 75 per cent saturation with respect of magnesium, but beyond this the K content decreased. Growth and yield were directly proportional to Ca and inversely proportional to magnesium at high magnesium levels in the soil.

Although there was great variation in the uptake of individual cations, the sum total of the cations was constant with the different treatments. This indicates that the cations perform some common function in the plant.

No direct correlation between the magnesium and phosphorus uptake was observed with any of the crops studied. The idea that Mg ions act as a carrier of PO_4 ions is questionable.

Factors influencing the differential uptake of calcium and magnesium have been discussed.

The results of this investigation emphasize that it is not the calcium:magnesium ratio but the concentration and degree of saturation of the exchange complex with calcium that determine the response of crops to the application of magnesium.

LITERATURE CITED

1. Allway, W. H. 1945
Availability of replaceable calcium from different types of Colloids as affected by degree of calcium saturation. Soil Sci. 59: 207-217.

2. Albrecht, W. A. and McCalla, T. M. 1938
The colloidal clay fraction of soil as a cultural medium. Amer. Jour. Bot. 25: 403-407.

3. Anderson, M. S. 1929
The influence of substituted cations on the properties of soil colloids. Jour. Agr. Res. 38: 564-584.

4. Arnon, D. I. and Grossenbacher, K. A. 1947
Nutrient culture of crops with the use of synthetic ion-exchange materials. Soil Sci. 63: 159-180.

5. Bartholomew, R. P. 1933
The Availability of Phosphatic Fertilizers. Ark. Agr. Expt. St. Bul. 289.

6. Bartholomew, R. P. and Jannesen, G. 1931
The rate of absorption of potassium by plants and its possible effect upon the amount of potassium remaining in soils from applications of potassium fertilizers. Ark. Agr. Exp. Bul. 265.

7. Bear, F. E. and Prince, A. L. 1945
Cation-equilibria in alfalfa. Jour. Amer. Soc. Agron. 37: 217-222.

8. Beeson, K. C., Lyon, C. B. and Barrantine, M. W. 1944
Ionic absorption by tomato plants as correlated with variations in the composition of the nutrient medium. Plant Physiol. 19: 258-277.

9. Bender, W. H. and Eisenmenger, W. S. 1941
Intake of certain elements by calciphilic and calciphobic plants grown on soils differing in pH. Soil Sci. 52: 297-307.

10. Bower, C. A. and Turk, L. M. 1946
Calcium and magnesium deficiencies in alkali soils. Jour. Amer. Soc. Agron. 38: 723-727.

11. Bradfield, R. 1941
Calcium in Soil. I. Physicochemical relations. Proc. Soil Sci. Soc. Amer. 6: 8-26.

12. Burkhart, L. and Page, N. R. 1941
Mineral nutrient extraction and distribution in the peanut plant. Jour. Amer. Soc. Agron. 33: 743-755.

13. Bouyoucos, G. J. 1936
Directions for making mechanical analysis of soils by hydrometer method. Soil Sci. 42: 225-229.

14. Chapman, H. D. 1928
The precipitation of calcium oxalate in the presence of iron, aluminum, manganese, magnesium and phosphate with special reference to the determination of total calcium. Soil Sci. 26: 479-486.

15. Clark, H. E. 1936
Effect of Ammonium and nitrate nitrogen on composition of tomato plant. Plant Physiol. 11: 5-24.

16. Cooper, P. H., Paden, W. R. and Garman, W. H. 1947
Some factors influencing the availability of magnesium in soil and the magnesium content of certain crop plants. Soil Sci. 63: 27-42.

17. Clevenger, C. B. 1919
Hydrogen ion concentration of plant juices. II. Factors affecting the acidity or hydrogen ion concentration of plant juices. Soil Sci. 3: 227-242.

18. Eaton, F. M. and Horton, C. H. 1940
Effect of exchange sodium on the moisture equivalent and the wilting coefficients of soils. Jour. Amer. Soc. Agron. 32: 401-425.

19. Flint, L. H. 1932
Hydration of solutions of the higher elements. Jour. Wash. Acad. of Sci. 22: 97-

20. Gedroiz, K. K. 1931
Exchangeable cations of the soil and plants. Relations of plant to certain cations fully saturating the soil exchange capacity. Soil Sci. 32: 51-63.

21. Hansteen - Garner, B. 1914
Uber das Verhalten der kultur pflanzen gu den Bodensalzen III - Beitreige zur biochemie and physiologie der zellwand lebender zellen. Jahrle. Wiss. Bot. 53: 536-599.

22. Hoagland, D. R., Davis, A. R. and Hibbard, P. L. 1928
General nature of process of salt accumulation by roots with description of experimental methods. Plant Physiol. 3: 473-486.

23. Hissink, D. J. 1923
Method of estimating absorbed bases in soils and importance of these bases in soil economy. Soil Sci. 15: 269-276.

24. Hunter, Albert S. 1949
Yield and Composition of alfalfa as affected by variations in the calcium-magnesium ratio in the soil. Soil Sci. 67: 53-62.

25. Jarusov, S. S. 1937
On the mobility of exchangeable cations in the soil. Soil Sci. 43: 285-303.

26. Jenny, H. and Ayers, A. D. 1939
The influence of degree of soil colloids on the nutrient intake by roots. Soil Sci. 48: 443-459.

27. Jenny, H. and Cowan, E. W. 1933
Uber die Bedewtung der im boden adsorbierten kationen fur das pflanzen wachstum. Ztschr Pflawzenrnahr. Dungung U. Bodenk (A) 31: 57-67.

28. Joffe, J. S., Kardos, L. T. and Mattson, S. 1935
Laws of soil colloidal behavior XVII Magnesium silicate--its base exchange properties. Soil Sci. 40: 255-268.

29. Joffe, J. S. and Zimmerman, M. 1944
Sodium, calcium and magnesium ratios in the exchange complex. Proc. Soil Sci. Soc. Amer. 9: 51-55.

30. Kardos, L. T. and Joffe, J. S. 1938
The preparation, composition and chemical behavior of the complex silicates of magnesium, calcium, strontium and barium. Soil Sci. 45: 293-307.

31. Kellog, C. E. 1931
Magnesium--a possible key to the phosphorus problem in certain semi-arid soils. Jour. Amer. Soc. Agron. 23: 494-495.

32. King, E. J. 1932
The colorimetric determination of phosphorus. Biochem. Jour. 26. Part I. 292-307.

33. Lawton, K. 1945
The determination of exchangeable potassium in soils using hexanitrodiphenylamine. Proc. Soc. Sci. Amer. 10: 126-128.

34. Lipman, C. B. 1916
A critique of the lime-magnesia hypothesis. Plant World. 19: 83-105 and 119-133.

35. Loew, O. 1892
Uber die physiologischen funktionen der kalium and magnesia saltz in pflanzer organisms. Flora. 75: 368-394.

36. Loew, O. and May, D. W. 1901
The relation of lime and magnesium to plant growth. U.S.D.A. Bur Plant Indus Bul. 1.

37. Lucas, R. E., Scarseth, G. D. and Seiling, D. H. 1942
Soil fertility levels as it influences plant nutrients composition and consumption. Ind. Agr. Expt. St. Bul. 468.

38. Lucas, R. E. and Scarseth, G. D. 1947
Potassium, calcium and magnesium balance and reciprocal relationship in plants. Jour. Amer. Soc. Agron. 39: 887-896.

39. Marshall, C. E. 1944
The exchangeable bases of two Missouri soils in relation to composition of four pasture species. Mo. Agr. Expt. Sta. Res. Bul. 385.

40. McGeorge, W. T. and Breazeale, J. F. 1938
Studies on soil structure. Effect of puddled soils on plant growth. Ariz. Agr. Expt. Sta. Tech. Bul. 72.

41. Mehlich, A. 1938
Use of Triethanolamine acetate--Barium hydroxide buffer for the determination of base exchange properties and lime requirements of soils. Proc. Soil Sci. Soc. Amer. 3: 162-166.

42. Mehlich, A. and Colwell, W. E. 1946
Absorption of calcium by peanuts from kaolin and bentonite at varying levels of calcium. Soil Sci. 61: 369-374.

43. Mehlich, A. and Reed, J. F. 1946
The influence of degree of saturation, potassium level and calcium additions on removal of calcium, magnesium and potassium. Soil Sci. Soc. Amer. Proc. 10: 87-93.

44. Peech, M. and English, L. 1944
Rapid michrochemical soil tests. Soil Sci. 57: 167-196.

45. Peech, M. 1941
Availability of ions in light sandy soils as affected by soil reaction. Soil Sci. 51: 473-486.

46. Piper, C. S.
Soil and Plant Analysis. InterScience Publishers, Inc., New York, 1944.

47. Puri, A. N. and Uppal, H. L. 1938
Base exchange in soils--A critical examination of the methods of finding base exchange capacity of soils. Soil Sci. 47: 245-253.

48. Ratner, E. I. 1935
The influence of exchangeable sodium in the soil on its properties as a medium for plant growth. Soil Sci. 40: 459-468.

49. Ray, R. C. and Ganguly, P. B. 1930
The optimum conditions for the formation of silica gel from alkali siicate solutions. Jour. Phys. Chem. 34: 352-358.

50. Richards, L. A. 1928
The usefulness of capillary potential to soil moisture and plant investigation. Jour. Agr. Res. 37: 719-742.

51. Russel, E. W. 1935
The binding forces between clay particles in a soil crumb. Trans. Third Int. Cong. Soil Sci. 1: 26-29.

52. Schollenberger, C. J. and Simon, R. H. 1945
Determination of exchange capacity and exchangeable bases in soils--Amonium acetate method. Soil Sci. 59: 13-24.

53. Seifritz, Wm. 1936
Protoplasma. McGraw-Hill Book Co., Inc., New York.

54. Spurway, C. H. 1944
Soil Testing - A practical system of soil fertility diagnosis. Mich. Agr. Expt. Tech. Bul. 132 (revised).

55. Sorokin, Helen and Sommer, Anna L. 1929
Changes in the cells and tissues of root tips induced by the absence of calcium. Amer. Jour. Bot. 16: 23-39.

56. Stanford, G., Kelly, J. B. and Pierre, W. H. 1941
Cation balance in corn grown on high-lime soils in relation to potassium deficiency. Soil Sci. Soc. Amer. Proc. 6: 335-341.

57. Sturgis, M. B. and Reed, J. F. 1937
The relation of organic matter and fertilizer to the growth and composition of rice. Jour. Amer. Soc. Agron. 29: 360-366.

58. Thorne, D. W. 1944
Growth and nutrition of tomato plants as influenced by exchangeable sodium, calcium and potassium. Soil Sci. Soc. Amer. Proc. 9: 185-189.

59. True, R. H. and Bartlet, H. H. 1912
Bureau of Plant Industry.U. S. D. A. Agr. Bul. No. 231: 1-36.

60. Truog, et al 1947
Magnesium-Phosphorus relationships in plant nutrition. Soil Sci. 63: 19-25.

61. Van Itallie, T. B. 1938
Cation equilibria in plants in relation to the soil. Soil Sci. 46: 175-186.

62. Volk, N. J. and Truog, E. A. 1934
Rapid Chemical method for determining the readily available potash in soils. Jour. Amer. Soc. Agron. 26: 537-546.

63. Willis, L. G., Piland, J. R. and Gay, R. L. 1934
The influence of magnesium deficiency on phosphorus absorption by soybeans. Jour. Amer. Soc. Agron. 26: 419-422.