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Soil Magnesium and the Growth and Chemical Composition of Plants

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FOREWORD

WM. A. ALBRECHT

Studies, in 1942 and earlier, suggest that some soils in Missouri are so deficient in magnesium that both the crop quantity and the crop quality are disturbed. Because this nutrient element makes up less of the legume plants than calcium, it has not been emphasized in the liming program. Bioassays of forages had not yet connected shortages of magnesium in the soil with poor animal health and reproduction. This neglect may have been more serious than appreciated, since in the ash of the soybean crop and of some of the non-leguminous forages the concentration of the magnesium is the equal of the calcium.

As the only soil-borne inorganic constituent of chlorophyl, which is the tool for converting carbon dioxide and water into carbohydrates, magnesium emphasizes its importance in the plants' biochemical processes rather than in the tissue structure. Numerous other enzymes include magnesium as the central inorganic core around which the protein-like and the vitamin-like parts are arranged in the particular chemical structure. Though the amount found by chemical analysis may be small, its importance as a biochemical tool may be great.

Among the exchangeable cations adsorbed on the clay of the soil, like calcium, potassium, ammonium and others, the magnesium found in differing ratios to each of these suggests differing physiological effects within the crop plants. Concern about the specificity of these cationic ratios in relation to plant functions that modify crop quantity and crop quality was part of the postulate guiding the study reported here. Such ratios are establishing themselves as significant guides in making fertilizer treatments according to soil tests.

The postulate included attention only to the inorganic cationic ratios. It aimed to exclude the disturbing effects on these ratios by variation of the inorganic anions, or by the organic compounds of the soil. When previous research at this station revealed decided effects by an organic cation on the efficiency with which any degree of inorganic cation saturation nourished the crop, these variable anions and specific organic compounds were taken as nearly constant as the plan would permit.

The studies of magnesium are adding clarity to our concept of the chemodynamics by which soil fertility serves in plant nutrition. Through the testing of more soils and the chemical analyses of more crops, these studies are suggesting that the idea of a "balanced diet" is more than fancy, in terms of both the inorganic and the organic nutrients as determiners of crop yields and their nutritional values in feeds. Only more research of this type will give better control of the crop quality via fertility treatments of the soil.

Soil Magnesium and the Growth and Chemical Composition of Plants

E. R. GRAHAM, S. POWELL AND M. CARTER

Magnesium has long been considered an essential element for plant growth. That the level of exchangeable magnesium in the soil is related to the quality and growth of crops, has been recognized for some time. But magnesium associated with organic compounds in what is known as "chelation", and that in the crystal lattice of the clay minerals have received little study. On soils of low organic matter content, of low amounts of exchangeable magnesium, or those of which improper management practices have reduced the supply and availability of magnesium, high yields have not been obtained unless magnesium has been added.

It was the purpose of this study to investigate; (a) the possibility of chelated magnesium serving as a source of this element for plant nutrition; (b) the effects of additions of magnesium on the yield and chemical composition of soybeans, ladino clover, and wheat grown on soils of different types and different magnesium levels; and (c) the possible correlation of such results with the amounts of magnesium measured by different extracting solutions as a possible soil test for this element.

PREVIOUS WORK

McMurtrey (6), in reviewing the early literature on magnesium as an essential plant nutrient noted: that in the middle nineteenth century Salm-Horstmar conducted experiments which proved that magnesia is one of the necessary ash constituents of plants; that Dempwolf showed that magnesium tends to follow protein distribution in plant tissues and accumulates particularly in the seeds; and that Willstatters epoch-making researches proved that magnesium was a constituent of the chlorophyll molecule.

Zimmerman (10) reported in his review of literature: that Javillier and associates found that the magnesium in chlorophyll represented only a fraction of the total magnesium in the plant, which would suggest other functions for magnesium; that Loew showed magnesium closely related to phospholipid formation and to the synthesis of nucleoproteins in plant cells; and that Raumer concluded that magnesium was involved in the transfer of carbohydrates in plants.

According to Bear and Prince (2), the Atlantic and Gulf Coastal Plains regions of the United States are most likely to be deficient in magnesium. This is because of the low amount originally present and the depressive effect on magnesium uptake by potassium, which is being used liberally on these soils. They wrote that large areas of land in New Jersey, especially in the Coastal plains, are known to be low in magnesium. It has also been suggested by Prince *et al* (7) that there is no correlation between the total amount of magnesium in a soil and its crop-producing power. They say that the most important single factor influencing the magnesium uptake by plants is the quantity of potassium that is available.

Increases in yield ranging from 10 to 38 percent were reported by Bear and Prince (2), when 80 pounds of magnesium oxide per acre was added.

Longstaff and Graham (5) reported that the magnesium held in magnesite, dolomite, and olivine increased the growth of soybeans by 57 to 130 percent. The magnesium held in hornblende and talc had little effect on the growth or composition of the plants. Their study was carried out on sand and clay cultures in which the clay content was 2.5 percent of the total.

Magnesium, which is usually taken up by plants in the ionic form, may occur in soils (a) as a water soluble ion, (b) as part of the exchange atmosphere of the colloid, (c) as a constituent of the crystal lattice of clay minerals, (d) as part of the primary minerals of the sand and silt separates, and (e) as a chelated ion in organic combination with some constituents of the soil organic matter.

PLAN OF INVESTIGATION

The purpose of this study was to determine the values of chelated magnesium, of exchangeable magnesium, and of crystal-held magnesium for nutrient service in plant growth and in modification of its chemical composition.

Chelated Magnesium

Sand-colloidal clay cultures were used to study the possible value of chelated magnesium. The Putnam clay was prepared and electrodialyzed according to the methods as outlined by Albrecht (1). This clay is made up predominantly of the beidellite mineral. It furnished per pot only 7.1 mgm. of magnesium for soybeans grown on a 2.5 percent sand-clay culture, which was insufficient for the normal growth of soybeans according to experimental trials by Longstaff and Graham (5). The exchange capacity of the clay was determined by titrating its hydrogen system to a pH of 7.0 with standard sodium hydroxide in the presence of 0.01 M. potassium chloride. The exchange capacity of the clay was 90 M.E./100 grams of clay.

A volume of the clay suspension containing 50 grams of clay was placed in each of several containers. To each culture were added the amounts of calcium carbonate and potassium hydroxide calculated to give the degrees of saturation given in Table 1. Magnesium carbonate was added to some of the suspensions in amounts required to give the magnesium saturations listed as Series A of Table 1. To others were added the amounts of Mg-EDTA* which would be equivalent to the saturations listed in Series B, Table 1. The Mg-EDTA does not react with the clay colloid. The amount added per culture was calculated on the basis of metallic magnesium equivalent to the amount of ionic magnesium required to produce the saturation levels listed.

TABLE 1 -- VARIABLE DEGREES OF SATURATION OF THE COLLOIDAL CLAY BY MAGNESIUM IN RELATION TO THE DEGREES OF SATURATION OF CALCIUM AND POTASSIUM.

		Percentage Saturation		
No.	Treatment	Ca	K	Mg
	Series A			
1	Mg added as Mg CO_3	75	3	10.0
2	Mg added as Mg CO_3	75	3	5.0
3	No Mg added	75	3	0.0
	Series B			
4	Mg added as Mg-EDTA	75	3	5.0
5	Mg added as Mg-EDTA	75	3	2.5
6	Mg added as Mg-EDTA	75	3	1.0
7	Mg added as Mg-EDTA	75	3	.5

Three millimoles of phosphoric acid and 0.35 millimoles of ammonium nitrate were added to each of the cultures. Each clay suspension was then mixed with 2000 grams of acid-washed sand and allowed to evaporate to a desirable moisture content.

Soybeans of the Clark variety were germinated on moist cloth until the radicle was about 1 inch long. Fifty of the germinated seedlings were transplanted into each pan.

The cultures were watered with distilled water as often as needed to maintain optimum moisture conditions. After three weeks of growth an additional 0.36 millimole of ammonium nitrate was added to maintain the nitrogen level. At the end of a six-week growth period the plants

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*Mg-EDTA is an abbreviation of sodium magnesium ethylenediamine tetra-acetic acid. This organic metallic combination is interesting in that the magnesium is held as a stable complex which is water soluble and yet the magnesium is non-dissociated. This form of magnesium is usually designated as being "chelated" magnesium. The sodium-magnesium complex contains 5.5% magnesium as metallic magnesium.

were harvested, dried (60° C.), weighed, ground and placed in sample jars for future analysis.

Samples of 2.0 grams each were weighed into dishes and ashed in the muffle furnace. These ashed samples were treated with 2ml. of 72 percent percloric acid and digested slowly on the hot plate for one hour. They were then heated more strongly and evaporated to near dryness. Next they were taken up in distilled water and filtered into 500 ml. volumetric flasks.

The potassium and sodium were determined with the flame photometer; after phosphates had been removed, the calcium was determined with the flame photometer. Magnesium was determined by the Versene method; phosphorus was determined colorimetrically; and the total nitrogen was determined by the standard Kjeldahl method.

The seeds of the soybeans were analyzed with the same methods used for the plant material.

Exchangeable and Readily Soluble Magnesium

The following experiments were carried out on the plant to investigate the value of exchangeable and crystal-held magnesium as nutrients available to plants.

Eleven Missouri soils (Table 2) of somewhat different physical and chemical properties were collected and taken to the greenhouse. Fourteen of the soil samples were treated with four different extracting solutions of which analyses were made for calcium and magnesium. This was done in an effort to learn something about the level of exchangeable and crystal-held magnesium. The magnesium replaced by the neutral salts, sodium nitrate and ammonium acetate, will be considered "exchangeable" magnesium. The magnesium replaced by HCl will be considered "exchangeable plus crystal-held" magnesium.

The soils were tested for their general contents by a method of Graham (4). Their initial fertility levels are shown in Table 3. In order to eliminate as many variables as possible and to provide a soil of otherwise reasonably high fertility, each soil was considered as follows:

Wherever the exchangeable calcium was less than 65 percent of the total exchange capacity, additional calcium as calcium carbonate was added so as to retain one-fourth of the total exchangeable hydrogen according to the soil test.

Wherever the phosphorus level was less than 100 pounds P_2O_5 per acre (Bray's No. 2 strong reagent), 200 pounds P_2O_5 per acre was added. For a level between 100 and 200, 100 pounds was added, and if the level was above the 200 pound value according to the soil test, no additional phosphate was added. The phosphorus was added as potassium di-hydro-

TABLE 2 -- MISSOURI SOILS STUDIED FOR MAGNESIUM RESPONSE

Sample Number	Soil Series	Surface Color	Surface Texture	Profile Development	Topography	Soil-Forming Material
1	Clarksville	Light gray	Silt loam	Moderate	Hilly	Cherty lime
2	Craig	Dark brown	Silt loam	Moderate	Rolling	Cherty lime
3	Huntington	Brown	Silt loam	Slight	Level	Limestone
5	Baxter	Light brown	Silt loam	Moderate	Hilly	Cherty lime
6	Eldon	Dark brown	Stony loam	Slight	Rolling	Cherty lime
7	Sneed	Black	Silt loam	Slight	Hilly	Limestone
10	River wash	Light brown	Sand	None	Level	Sand
11	Sharon	Brown	Silt loam	Slight	Level	Limestone
14	Lintonia	Light brown	Sandy loam	Slight	Level	Sand
16	Dogwood	Dark gray	Sandy loam	Slight	Level	Sand
17	Putnam	Dark gray	Silt loam	V. strong	Level	Loess

TABLE 3 -- GENERAL FERTILITY LEVELS OF SELECTED MISSOURI SOILS

Sample Number	pH	Exc. H M.E.*	O.M. %	P_2O_5 lb.**	K lb.**	Ca lb.**	Mg lb.**	Ex. Capacity M.E./100 gm.†
1	4.8	3.75	1.8	37	91	1420	170	8.4
2	5.4	4.25	2.8	134	280+	3380	490	14.8
3	6.9	0.50	1.8	224+	280+	4480	190	12.9
5	6.7	0.50	2.9	131	142	5340	155	14.7
6	6.6	1.50	2.6	68	93	5500	220	16.3
7	6.7	1.50	3.7	181	280+	7280	185	20.8
8	5.4	5.00	3.3	84	260	6050	255	21.5
10	7.6	None	0.5	110	139	6750	120	17.5
11	6.8	0.50	2.6	40	125	4990	105	13.6
12	5.7	3.25	1.4	70	170	3790	390	14.3
14	6.2	1.00	1.5	217	280+	2800	100	8.8
15	4.9	3.00	1.1	120	244	560	20	4.8
16	4.2	6.00	2.6	209	92	224	Trace	6.7
17	5.1	6.00	2.4	17	240	2678	400	14.5
18	5.7	2.00	0.6	80	184	448	20	3.4

*Milligram equivalents per 100 grams of soil.

**Pounds per 2 million.

†E. R. Graham, "Testing Missouri Soils," University of Missouri, Agricultural Experiment Station Circular 345, 1950.

gen ortho-phosphate.

The potassium levels of all soils were brought up to the test level of 300 pounds per acre. If the added KH_2PO_4 did not bring the potassium level high enough, then the balance was added as potassium chloride.

In addition to the above treatment, each soil received nitrogen and a minor elements treatment. The materials used and the rates of application were as follows:

Ammonium Nitrate	60 lb./Acre
Manganous Sulfate	20 lb./Acre
Cupric Sulfate	20 lb./Acre
Sodium Tetraborate	10 lb./Acre
Ferrous Tartrate	10 lb./Acre
Sodium Molybdate	2 lb./Acre

After the above treatments, each soil was divided into equal parts. One M.E.** of magnesium as magnesium oxide per 100 grams of soil was added to one part. No additional treatment was made to the other part. Hereafter in this report, the first part will be referred to as the plus, (+) magnesium and the second part will be referred to as minus, (-) magnesium treatment.

Two-gallon earthenware pots, each containing 7000 grams of soil, were set up in triplicate from each of the plus and each of the minus magnesium portions of the 15 soils. Each culture was seeded with 50 seeds of Wabash soybeans. Another series was set up in a like manner and each culture was seeded with 100 seeds of Ladino clover. The two series were seeded in June, 1951. Each culture was kept at optimum moisture condition by adding distilled water as needed. The soybeans and the Ladino clover were harvested in August, 1951, at which time both crops were in full bloom. The harvested material was oven dried at 60° C., weighed, ground and placed in sample jars for chemical analysis. Immediately following the harvesting of the soybean crop, this series was planted to wheat without further soil treatment. Fifty seeds of Vigo wheat were planted to each culture. Two more harvests of the Ladino clover were made (October, 1951, and January, 1952). The second and third harvests were dried and weighed. The wheat crop was harvested four times, the harvest being dried and weighed.

Duplicate 2.0 gram samples of the oven-dried, ground material were dry-ashed in a muffle furnace at 500-550° C. for 24 hours. After cooling, further ashing treatment was given by the addition of 2 ml. of 70-72 per-

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**The abbreviation M.E. will be used to express milliequivalents throughout this text. The cation exchange chemistry of soils is expressed in M.E. per 100 grams of soil, which would be 20 mgm. Ca per M.E., 12 mgm. Mg per M.E., and 39 mgm. K per M.E.

cent perchloric acid and heating until near dry. The ashings were then taken up in solution and made to a known volume.

Suitable aliquots were removed for the determinations of phosphorus, potassium, calcium, and magnesium. Phosphorus was determined by the colorimetric molybdate method (4). Potassium was determined on another aliquot by the internal standard method using the flame photometer (9). The interferring elements, iron, aluminum, and manganese were removed, using the method of Cheng and Bray (3).

After the removal of these elements, calcium was determined by the direct method using the flame photometer. Magnesium was determined by the versenate titration method of Chen and Bray (3).

Duplicate 10-gram samples of 14 of these soils were extracted separately with 200 ml. of each of the following four extracting solutions:

1. 0.5 N hydrochloric acid
2. 0.05 N hydrochloric acid
3. 1.0 N neutral ammonium acetate
4. 1.0 N sodium nitrate

Each of the extractions was then treated for the removal of iron, aluminum, and manganese, using the method outlined by Cheng and Bray (3). Calcium in the first three extracting solutions was determined by the direct method, using the flame photometer. However, in the case of the sodium nitrate extracting solutions, calcium was determined by its precipitation as oxalate and the subsequent titration with potassium permanganate. Magnesium was determined on all extractions by the versenate titration method of Cheng and Bray (3).

RESULTS AND DISCUSSION

Sand-Colloidal Clay Cultures

The appearance and growth weights of the plants grown in treatments with magnesium carbonate, Nos. 1 and 2, of the sand clay cultures were characteristic of what one might expect from the treatments. The data and chemical compositions are presented in Table 5. They showed more growth than the plants grown on no magnesium treatments and developed only a few abnormalities. Treatment 1 showed a 27 percent increase in dry weight over the no treatment and 19.9 percent increase over treatment 2.

The series of sand-colloidal clay cultures that were supplied with magnesium as Mg-EDTA, produced normal soybean plants without reduction in yield until the magnesium was lowered to 0.5 percent of the saturation. Even in this instance, the yield was 19 percent above that of the no magnesium treatment. The plants grown at this low magnesium

TABLE 4 -- EXCHANGE CAPACITIES AND PERCENTS SATURATION OF ORIGINAL SOILS

Sample Number	Hydrogen		Magnesium		Calcium		Potassium		Exc. Cap.	Cation Saturation
	M.E.	%	M.E.	%	M.E.	%	M.E.	%	M.E.	%
1	4.00	48.0	0.70	8.3	3.55	42.4	0.12	1.4	8.37	52.0
2	4.00	27.0	2.00	13.5	8.45	57.0	0.35	0.3	14.80	73.0
3	0.50	3.9	0.80	6.2	11.20	87.2	0.35	2.7	12.85	96.1
5	0.50	3.5	0.64	4.3	13.35	91.0	0.18	1.2	14.67	96.5
6	1.50	9.2	0.91	5.5	13.75	84.4	0.12	0.7	16.28	90.8
7	1.50	7.2	0.77	3.7	18.20	87.4	0.35	1.7	20.82	92.8
8	5.00	23.3	1.06	4.9	15.12	70.7	0.33	1.5	21.51	76.7
11	0.50	3.6	0.43	3.1	12.47	91.9	0.16	1.1	13.56	96.3
12	3.00	21.0	1.60	11.2	9.47	66.3	0.21	1.4	14.28	79.7
14	1.00	11.4	0.41	4.6	7.00	80.0	0.35	4.0	8.76	88.5
15	3.00	62.7	0.08	1.6	1.40	29.2	0.31	6.4	4.79	37.3
16	6.00	90.0	Trace	Trace	0.56	8.4	0.11	1.6	6.67	10.0
17	6.00	41.3	1.60	11.0	6.64	45.6	0.30	2.0	14.54	58.7
18	2.00	58.3	0.08	2.3	1.12	32.6	0.23	6.7	3.43	41.7

TABLE 5 -- WEIGHTS AND COMPOSITION OF SOYBEAN PLANTS AS INFLUENCED BY DIFFERENT MAGNESIUM TREATMENTS

No.	Treatment	Dry Weight	Potassium		Calcium		Magnesium		Phosphorus		Nitrogen		Sodium	
		gm.	mgm.	%	mgm.	%	mgm.	%	mgm.	%	mgm.	%	mgm.	%
	Series A													
1	Mg added as Mg CO_3	13.4	92.5	.71	110.7	.83	25.6	.19	42.3	.42	359	2.70	4.4	.033
2	Mg added as Mg CO_3	12.7	86.1	.68	105.6	.84	28.5	.23	46.5	.42	380	3.04	4.7	.038
3	No Mg added	10.5	101.9	.97	64.9	.62	15.9	.15	39.4	.38	429	4.06	3.9	.038
	Series B													
4	Mg added as Mg-EDTA	12.3	112.7	.92	96.7	.76	25.3	.21	46.1	.38	385	3.14	5.5	.045
5	Mg added as Mg-EDTA	13.3	101.8	.76	100.5	.75	23.1	.17	38.8	.29	390	2.93	5.4	.040
6	Mg added as Mg-EDTA	13.4	113.1	.85	107.2	.80	23.3	.17	42.1	.32	392	2.93	4.7	.035
7	Mg added as Mg-EDTA	12.4	119.6	.97	72.5	.59	18.6	.15	40.3	.32	399	3.23	4.3	.035

50 seeds contained: K - 134 mgm.; Ca - 15 mgm.; Mg - 17 mgm.; P - 33 mgm.; N - 442 mgm.; Na - 1.8 mgm.

level were low in both magnesium and calcium. They were also chlorotic in appearance.

The plants with no magnesium treatment began showing magnesium deficiency syptoms during the third week and many leaves showed severe chlorosis by the sixth week.

The chemical analysis of the plant material revealed interesting and significant relationships. It should be noted that only the tops of the plants were analyzed. The data for the chemical analyses of the plant material and for the dry weights harvested per culture are reported in Table 5. These are the mean values of the composition of the duplicate samples from each culture.

The highest amount of magnesium was taken up from the 5 percent saturation with the treatment of magnesium carbonate (Table 1). The magnesium taken up in this treatment was 78.1 percent greater than the amount taken up by the no magnesium treatment. This represents 66.3 percent of the available magnesium that was supplied by the seed and the treatment, less that amount which would have been in the roots.

In the case of the Mg-EDTA treatment at the 5 percent level, the increase in magnesium taken up was 58.8 percent more than the no magnesium treatment and represents 57.7 percent of the available magnesium

The treatment with 2.5 percent magnesium as Mg-EDTA showed an increase in magnesium of 45.1 percent with 75.8 percent of the available magnesium being taken.

The culture with 1.0 percent magnesium as Mg-EDTA showed a 49.2 percent increase. This represents more magnesium than was supplied by the treatment and the seeds and does not include the magnesium of the roots. Therefore the crystal-held magnesium of the clay must have become available for the soybean plants.

The plant tops of the treatment receiving only 0.5 percent magnesium as Mg-EDTA contained 94.6 percent of the magnesium supplied and showed a 17.1 percent increase over the check treatment. The plants on this treatment developed magnesium deficiency symptoms in the late weeks of growth.

These data indicate that the release of magnesium from the clay lattice is insufficient to prevent magnesium deficiency. However, the clay content of the sand-clay culture was only 2.5 percent.

The uptake of calcium was favored by available magnesium. In Treatments 1 and 2, the calcium content increased 62.8 and 70. 6 percent over that of the no magnesium treatment, as the available magnesium was increased. Treatments 4, 5 and 6, where magnesium was supplied as Mg-EDTA, revealed increases in calcium content of 50 to 60 percent. For Treatment 7, where the magnesium supplied was so small that it ap-

TABLE 6 -- YIELDS OF SOYBEANS, LADINO CLOVER, AND WHEAT

(Dry Wt. Gm.; % Increase)

	Soil 1			Soil 2			Soil 3			Soil 5			Soil 6			Soil 7			Soil 8		
Crop	+ Mg	- Mg	Increase	+ Mg	- Mg	Increase	+ Mg	- Mg	Increase	+ Mg	- Mg	Increase	+ Mg	- Mg	Increase	+ Mg	- Mg	Increase	+ Mg	- Mg	Increase
Soybeans	81.1	66.5		158.9	100.8		133.5	79.0		82.2	92.8		107.3	73.1		77.5	90.3		88.4	78.6	
L. Clover																					
1st. Cut	11.4	14.7		16.6	17.4		13.6	16.7		12.1	12.9		12.9	14.0		16.6	15.3		17.7	15.7	
2nd. Cut	2.4	2.3		2.8	3.0		2.7	2.4		2.1	2.1		4.1	3.7		5.3	3.7		6.1	6.9	
3rd. Cut	8.4	6.6		7.9	7.4		9.1	9.1		7.2	8.1		6.7	7.0		8.3	7.6		9.1	8.8	
Wheat																					
1st. Cut	4.6	4.6		7.4	7.9		4.8	3.1		4.9	6.2		4.5	2.7		4.1	4.5		4.8	5.5	
2nd. Cut	2.4	2.3		2.8	3.0		2.7	2.4		2.1	2.1		2.2	1.2		1.4	3.0		2.5	2.5	
3rd. Cut	1.9	1.7		1.5	1.4		1.8	1.7		0.9	1.0		1.4	1.0		1.2	1.5		1.1	1.1	
4th. Cut	2.3	1.1		3.9	3.1		4.6	4.1		3.5	3.4		3.1	3.6		4.3	4.3		3.0	3.7	
Average of all forage harvests:	14.31	12.47	+14.6	25.22	18.00	+40.0	20.35	14.81	+37.4	14.37	16.07	-10.5	17.77	13.28	+33.8	14.83	16.27	- 8.8	16.58	15.35	+ 8.0

TABLE 6 -- CONTINUED

	Soil 11			Soil 12			Soil 14			Soil 15			Soil 16			Soil 17			Soil 18		
Crop	+ Mg	- Mg	Increase	+ Mg	- Mg	Increase	+ Mg	- Mg	Increase	+ Mg	- Mg	Increase	+ Mg	- Mg	Increase	+ Mg	- Mg	Increase	+ Mg	- Mg	Increase
Soybeans	92.7	82.2		Sample burned			87.8	64.8		92.0	79.9		43.9	33.5		137.6	129.6		144.0	92.2	
L. Clover																					
1st. Cut	9.4	8.6		9.0	8.4		6.3	7.3		9.6	9.5		2.1	0.6		16.6	13.4		7.4	5.8	
2nd. Cut	Died	2.7		Died	4.6		1.1	4.6		1.0	1.2		Died	Died		7.3	4.0		1.1	0.7	
3rd. Cut	Died	6.8		5.0	5.8		7.9	8.0		7.3	7.2		3.8	1.8		8.1	6.4		7.1	6.4	
Wheat																					
1st. Cut	2.2	3.5		1.3	0.7		3.3	3.5		3.4	3.0		2.0	1.6		3.0	3.4		2.9	2.8	
2nd. Cut	1.5	1.8		0.9	0.8		1.8	1.6		1.4	1.3		0.8	0.8		1.8	2.2		1.1	1.1	
3rd. Cut	1.6	1.6		0.9	1.0		1.5	1.5		1.1	1.1		1.3	1.3		2.0	1.9		1.7	1.5	
4th. Cut	3.3	2.9		2.6	3.3		2.7	2.9		2.4	2.6		1.7	1.9		4.9	5.1		2.3	1.7	
Average of all forage harvests:	18.45	13.76	+34.0	3.28	3.51	- 6.5	14.06	11.77	+27.9	14.77	13.22	+11.7	7.94	5.93	+33.9	22.66	20.75	+ 9.2	20.95	14.02	+49.4

peared to be limiting the plant growth, there was only a small increase in the calcium adsorbed.

The potassium concentration, or percentage, in the soybean plants reflected the fact that in treatments where magnesium was added as a carbonate, the potassium content of the plants was lower by 28 percent than that of the untreated plants. However, when magnesium was added as Mg-EDTA the average percentage decrease was only 10 percent when compared with the check. These data indicate a possible explanation for some of the differences obtained by plant chemists when they have studied potassium-magnesium ratios in plants grown under different conditions.

The nitrogen concentration of the plant material seemed to decrease with increasing amounts of available magnesium.

The variation of phosphorus content was not significant and could not be related to the supply of magnesium.

Soil Cultures

Eleven of the 15 soils used in this study showed an average increase in yield, for the three crops, ranging from 8.0 to 49.0 percent when magnesium was added. The yield data are given in Table 6. Of the three crops studied —soybeans, Ladino clover, and wheat—the soybeans showed positive yield responses to magnesium treatments on only the 11 soils where the average responses of all the crops were positive.

Relative to the effects on crop composition, as shown in Table 7, the addition of magnesium to the soils decreased (1) the percentage of phosphorus in the soybeans, suggesting a dilution effect by increased growth of more carbohydrate, and (2) the percentage of calcium in wheat. It had no significant effect on the percentage of potassium or magnesium in any of the crops. These facts are evident in the Table 7 data.

The extractions of the soils with a normal solution of neutral ammonium acetate, and sodium nitrate, for which the data are shown in Table 8, reveal magnesium levels near those obtained by the rapid test (Table 3). These values were loosely correlated with the dry weight yields. The magnesium values obtained by leaching the soil with hydrochloric acid were 3 to 10 times greater than those obtained by treating the soil with the solutions of neutral salts. The fact that the acids, even though dilute, extracted such large amounts of magnesium, indicates the ease with which crystal-held (or organically combined) magnesium might become available to the plants.

The data, when arranged in order of rank of magnesium by soil tests and given in M.E./100 gm. soil or pounds per acre, showed a correlation with the percentage increases in yield resulting from added magnesium (similarly arranged by rank). The equilibrium extraction with 2.94 (So-

TABLE 7 -- CHEMICAL COMPOSITION OF CROPS GROWN
(Percent of Dry Weights)

Sample	Soybeans				Ladino Clover 1st Cut				Wheat 1st Cut			
Number	P	K	Ca	Mg	P	K	Ca	Mg	P	K	Ca	Mg
1 + Mg	0.53	2.12	0.70	0.24	0.54	1.45	1.07	0.12	0.16	3.17	0.26	0.19
1 - Mg	0.63	2.12	0.71	0.28	0.66	1.40	1.17	0.09	0.22	2.81	0.54	0.18
2 + Mg	0.52	1.25	0.85	0.19	0.52	1.02	0.50	0.09	0.36	2.62	0.20	0.22
2 - Mg	0.64	1.27	0.58	0.41	0.38	1.45	1.05	0.18	0.37	2.81	0.57	0.33
3 + Mg	0.52	2.43	0.75	0.26	0.56	1.70	0.52	0.16	0.22	3.95	0.22	0.10
3 - Mg	0.65	2.07	0.75	0.31	0.47	1.55	0.90	0.08	0.35	4.30	0.68	0.22
5 + Mg	0.50	1.22	0.75	0.44	0.71	1.36	0.42	0.16	0.29	3.00	0.32	0.25
5 - Mg	0.63	1.17	0.90	0.44	0.36	1.00	1.25	0.18	0.23	2.18	0.64	0.40
6 + Mg	0.58	1.47	0.70	0.42	0.38	1.20	0.85	0.09	0.24	3.00	0.40	0.31
6 - Mg	0.63	1.37	0.72	0.42	0.43	1.92	0.90	0.16	0.21	2.20	0.61	0.28
7 + Mg	0.49	1.45	0.65	0.39	9.40	2.30	0.70	0.08	0.29	3.70	0.22	0.07
7 - Mg	0.61	1.50	0.83	0.37	0.71	1.62	0.27	0.19	0.23	3.40	0.55	0.12
8 + Mg	0.49	1.99	0.85	0.31	0.20	2.52	0.77	0.09	0.18	3.80	0.20	0.13
8 - Mg	0.64	1.80	0.77	0.38	0.53	1.30	1.20	0.09	0.28	3.45	0.62	0.23
11 + Mg	0.52	1.71	0.75	0.32	0.64	2.27	0.20	0.11	0.25	3.62	0.20	0.14
11 - Mg	0.63	1.70	0.73	0.28	0.53	2.17	0.85	0.08	0.29	3.67	0.39	0.18
12 + Mg	Sample burned				0.59	2.92	0.20	0.12	Insufficient sample			
12 - Mg	Sample burned				0.53	2.15	0.80	0.07	Insufficient sample			
14 + Mg	0.52	1.45	0.65	0.28	0.52	1.55	0.55	0.08	0.20	3.32	0.21	0.12
14 - Mg	0.64	1.50	0.73	0.29	0.58	1.57	0.65	0.09	0.22	3.70	0.46	0.12
15 + Mg	0.48	1.02	0.65	0.48	0.35	1.12	0.85	0.13	0.20	2.67	0.34	0.22
15 - Mg	0.62	1.20	0.70	0.32	0.61	1.82	0.45	0.13	0.20	2.70	0.59	0.23
16 + Mg	0.42	1.02	0.73	0.24	0.41	1.00	0.85	0.12	0.23	2.60	0.31	0.34
16 - Mg	0.63	0.95	0.83	0.20	Insufficient sample				Insufficient sample			
17 + Mg	0.44	0.96	0.68	0.44	0.45	1.65	0.85	0.08	0.18	2.72	0.14	0.12
17 - Mg	0.54	0.87	0.68	0.31	0.52	1.70	0.95	0.15	0.20	2.26	0.48	0.21
18 + Mg	0.48	1.20	0.80	0.24	0.39	0.82	0.70	0.18	0.24	2.47	0.30	0.46
18 - Mg	0.64	1.25	0.84	0.34	0.47	0.90	0.90	0.14	0.21	2.47	0.76	0.31

TABLE 8 -- MAGNESIUM CONTENTS OF SOILS AS MEASURED BY DIFFERENT EXTRACTING SOLUTIONS**

Soil Number	0.5 N HCl Leaching M.E./100 gm.	0.05 N HCl Leaching M.E./100 gm.	1.0 N NH_4CH_3COO Leaching M.E./100 gm.	1.0 N N_4NO_3 Leaching M.E./100 gm.	Quick* Test M.E./100 gm.
1	2.6	3.9	1.60	.TR	.70
2	7.6	5.8	3.20	1.90	2.00
3	3.5	3.3	1.00	.TR	.80
5	3.8	3.9	.60	.TR	.64
6	5.4	4.8	.24	.30	.81
7	13.1	7.8	1.30	1.30	.77
8	6.2	5.8	1.80	2.20	1.06
11	4.4	4.0	.60	1.00	1.43
12	4.0	3.7	1.82	1.70	1.60
14	2.9	2.6	1.06	1.20	.41
15	1.5	3.8	1.35	.30	.08
16	.3	2.5	.13	.TR	.TR
17	6.2	5.2	2.60	3.20	1.60
18	.8	1.1	1.00	.80	.08

*Extracting Reagent was 2.94 N Na NO_3 - 5 gm. soil 10 ml. solution equilibrated by shaking 15 minutes.

**Correlations between Mg as M.E./100 gm. soil and percentage yield increase were as follows: 0.5N HCl = 0.34, 0.05 N HCl = 0.45, 1.0 N NH_4COOCH_3 = 0.32, 1.0 N Na NO_3 = 0.39, 2.94 N Na NO_3 equilibrated by shaking = 0.23.

dium Nitrate)revealed the lowest correlation of the five methods investigated.

The number of soils responding to magnesium treatments was greater than would have been expected from the data on percent of magnesium saturation or from the calicum-magnesium ratios. A comparison of the percentage increases in yield by order of magnitude and the percentage magnesium saturation by any of the extracting solutions failed to show any correlation. The calcium-magnesium ratios did not correlate in their order of magnitude with the similar arrangement of percentage increases, expressed as yield obtained by treating the soils with magnesium.

This study reveals the importance of organic combinations of magnesium in supplying magnesium for soybeans, as well as the importance of the adsorbed magnesium readily replaceable by dilute (0.05 N) hydrochloric acid. Therefore, these factors should be considered in future studies revolving around levels of magnesium available in soils. The importance of the magnesium in organic combination and that in the crystal lattice as magnesium sources in plant nutrition helps to explain some of the conflicting observations which have been made in the study of the calcium-magnesium ratios.

SUMMARY AND CONCLUSIONS

A study of the chelated, exchangeable, and readily soluble magnesium as factors in the magnesium nutrition of plants revealed the following items of importance.

1. Soybeans utilized magnesium when it was supplied as sodium magnesium ethylenediamine tetra-acetic acid.
2. Low concentrations of magnesium, such as sodium magnesium ethylenediamine tetra-acetic acid, were as effective for increasing plant growth and magnesium uptake as high concentrations of the carbonate of magnesium. Additions of high concentrations of magnesium, when chelated with sodium magnesium ethylenediamine tetra-acetic acid, did not result in significant increases in growth or of magnesium uptake by the plant.
3. The treatments of magnesium resulted in an increase in the uptake of calcium but had little, if any, effect on the uptake of phosphorus or of potassium at the levels used in this experiment.
4. There was no injury to any of the soybean plants from using sodium magnesium ethylenediamine tetra-acetic acid in the culture medium at the concentrations selected.
5. Eleven of the 15 soils used showed increases in plant yields when magnesium was added to the soil.

6. Of the three crops studied —soybeans, Ladino clover, and wheat — the soybeans appeared to be the most responsive indicator crop for magnesium use.

7. The highest correlation between the amount of magnesium shown by soil test and percent increase in crop yield was obtained when the soil was extracted with 0.05 N hydrochloric acid.

8. All of the extracts (their amounts of magnesium expressed at M.E. per 100 grams of soil) were more highly correlated with the percentages of increase in yield from added magnesium than were the calcium-magnesium ratios or percentages of magnesium saturation.

9. In general, the soils with less than 10 percent magnesium saturation of the total exchange capacity of the soil showed yield responses when magnesium was added. This fact reinforces the suggestion that this 10 percent level would be a helpful guide when determining the desirable level of magnesium in the soil.

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