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F. B. MUMFORD, *Director*

RELATION OF THE DEGREE OF BASE SATURATION OF A COLLOIDAL CLAY BY CALCIUM TO THE GROWTH, NODULATION AND COMPOSITION OF SOYBEANS

GLENN M. HORNER

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Summary

1. A study was made of the relation of the total calcium supply and of the degree of saturation of a colloidal clay by calcium to the growth, nodulation and chemical composition of soybeans.

2. Clay cultures prepared by titrating electrodialyzed colloidal clay with calcium hydroxide to the desired degree of calcium saturation permitted good growth. Other series of clays with a neutral reaction were prepared by replacing the remaining hydrogen ions with magnesium, barium, potassium or methylene blue. The saturation by calcium varied from 40 to 97 per cent.

3. Growth, nodulation, nitrogen-fixation and calcium absorption increased with higher calcium levels at a constant calcium saturation, and likewise with an increase in the degree of saturation by calcium at a constant calcium level.

4. The same general tendency was shown regardless of whether either hydrogen, magnesium, barium or potassium was used as a supplementary ion.

5. The substitution of the strongly adsorbed methylene blue cation eliminated almost completely the effect of a variation in the calcium saturation. This suggests that the hydrogen ions excreted by the roots of the plant, were not able to exchange with the methylene blue cation to any appreciable extent. Thus, the entire displacing power of the plant's excreted hydrogen ions was directed toward the replacement of calcium ions, resulting in nearly equal absorption of calcium from the different cultures of variable degrees of calcium saturation but ample total calcium supply. With a readily replaceable supplementary ion, the energy of replacement was divided between the two and less calcium was adsorbed.

6. The growth and nitrogen-fixing activities of legumes were closely related to the calcium present in the plant. The amount of calcium absorbed by the plants depended upon the calcium level and the degree of saturation of the clay by calcium.

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ACKNOWLEDGMENT

The author expresses his sincere appreciation for the kindly criticisms and advice of Dr. Wm. A. Albrecht, under whose direction this work was carried out.

Relation of the Degree of Base Saturation of a Colloidal Clay by Calcium to the Growth, Nodulation and Composition of Soybeans*

GLENN M. HORNER†

Introduction

The importance of sufficient calcium for successful legume growth and inoculation has been recognized. It has been more recently observed that there is an intimate relationship between the calcium and nitrogen contents of plants. In the case of legumes, the liming of an acid soil will usually enhance their nitrogen-fixing powers. The beneficial effects of liming an acid soil are commonly attributed to a decrease in the hydrogen-ion concentration, while the conditions under which plants secure an adequate supply of calcium have not been studied as thoroughly. Since the presence of a sufficient amount of calcium within the tissues of legume plants is necessary for their proper growth and nodulation, and since the adsorptive properties and exchange behavior of the colloidal clay fraction of the soil play a significant role in providing the plant with such, a study was undertaken to determine the influence of a variation in the degree of saturation of the clay adsorptive complex by calcium upon the growth, nodulation and chemical composition of soybeans.

Historical

A variation in the calcium saturation of an acid soil is intimately related to its reciprocal, namely, the acidity or hydrogen-ion concentration of the soil. An application of lime to an acid soil will increase the amount of replaceable calcium and will also lower the degree of acidity. Which of these two variables is the principal factor and how it operates in influencing legume growth has not been clearly demonstrated by the numerous studies made on this problem.

Lipman and Blair[13]‡, Scanlan[20], Albrecht and Davis[4] and others have reported the beneficial effects of lime on the growth and inoculation of legumes on acid soils. Holtz[10] found that the calcium content of red clover was largely influenced by the

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†Formerly research scholar in soils, College of Agriculture, University of Missouri, now associate soil conservationist, United States Department of Agriculture, Pullman, Washington.

‡Numbers refer to items in References, page 36.

amount of calcium in the soil. Bryan[6] observed that the inoculation and power of plants to obtain calcium increased with a decrease in the acidity of the medium. Albrecht[1, 2] prepared clay cultures of varying degrees of acidity at different calcium levels and noted that the nodulation of soybeans was correlated with both the degree of acidity and the available calcium supply in the soil. At pH 5.0, or lower, nodulation was inhibited by the excessive degree of acidity, while at pH values higher than this, the nodulation failure was related more closely to the available calcium in the soil. Albrecht and Davis[3] concluded that the beneficial effect of calcium was the result of its presence within the plant. They observed that both the addition of lime to an acid soil already inoculated and the absorption of calcium by the plant in its early growth increased the nodulation of soybeans.

Pierre[19] found a good correlation between the percentage base saturation of acid soils and defective growth, and suggested that this is one of the most important factors in determining the growth of plants on acid soils. He also suggested that the relative proportion of the various bases present in the exchange complex and in the soil solution may be contributing factors to poor plant growth obtained on acid soils.

The question then arises as to what effect the various bases on the exchange complex have on each other so far as plant growth is concerned. Ginsburg and Shive[8] found a correlation between the calcium in the soil solution and in soybean plants. Fonder[7] and Lipman, Blair and Prince[14] found a physiological balance in alfalfa plants between calcium and potassium. A high calcium content was usually accompanied by a low potassium content and vice versa. Similar observations were made by Loewhing[15] for certain crop plants. He pointed out that additions of potassium may cause calcium starvation on soils low in calcium, and additions of calcium to soils low in potassium may cause potassium starvation. Hoagland and Martin[9] found that the potassium content of the crop consistently depends upon the exchangeable potassium in the soil, and that a striking interrelationship exists between the calcium, magnesium and potassium in the soil. Pfeiffer and Rippel[18] and Moser[17] suggested that the beneficial effect of liming was not due to an alteration of the calcium-magnesium ratio, but to an increase in replaceable calcium.

The various studies reported to date suggest that the capacity of the plants to absorb the different bases from colloidal clay complex may be related to the degree to which each occupies the adsorptive capacity of it, and to the extent to which different bases influence each others exchange activities. A critical study of these questions by varying one exchangeable base at a time in its degree of saturation of the complex and noting its influence on the plant behavior should indicate the role played by these factors so commonly and highly variable in the soil. The work reported herewith represents an attempt to understand more fully the calcium nutrition of legumes manifested in their growth, nodulation and composition as related to the degree to which the colloidal clay complex of the soil is saturated by the nutrient element calcium.

Plan of Experiment

The study was designed to test the effect of the variation in degree of saturation on the plant growth by using quartz sand with different amounts of specially prepared colloidal clay carrying different amounts of adsorbed calcium, as a growth medium for soybeans.

The Virginia variety of soybean was selected for this work as its behavior under such conditions was known from previous studies at this Station. The plants were grown under greenhouse conditions in cultures of pure quartz sand to each of which had been added the specific amount of a particular colloidal clay. The quantity of the special colloidal clay added was designed to supply the desired amount of calcium at definite degrees of saturation of the adsorption complex.

PREPARATION OF THE COLLOIDAL CLAYS

The colloidal clay had been purified by electrodialysis[5] and was used in the preparation of these clay systems by titrating, with a calcium hydroxide solution, to the desired degree of saturation in calcium. he titration curve for this clay is shown in Figure 1. The exchange capacity of the clay was approximately 62 M.E.* of base per 100 grams of clay.

In the first study here reported, the amounts of calcium per plant were the following, 0.05, 0.10, 0.20 and 0.30 M.E. A single clay system was used. The electrodialyzed acid clay was saturated by calcium to 97 per cent of its adsorptive capacity to give a pH of 6.9 and only different amounts of the same clay were taken to sup-

*M.E. is an abbreviation for milligram equivalents per 100 grams of soil and will be used in the following pages.

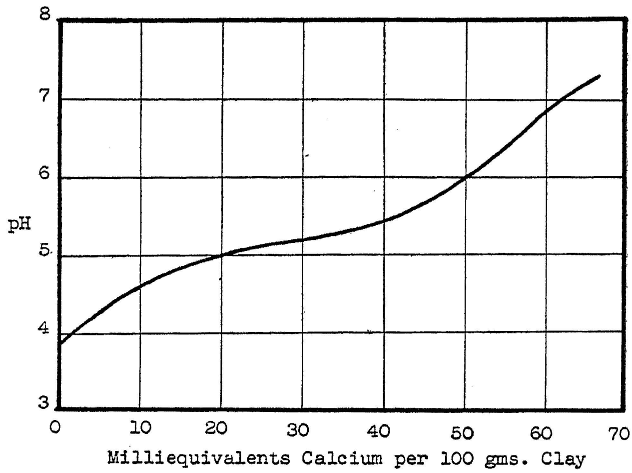

Fig. 1.—Titration curve of hydrogen clay and calcium hydroxide.

ply these different amounts of calcium per plant. Thus there was given to the plants varying amounts of calcium at a constant degree of calcium saturation in order to determine first the amount of calcium most effective under the conditions of the experiment. Previous studies[2] had pointed to 0.20 M.E. of calcium as sufficient calcium and this trial was inserted here for verification of this figure. For the remaining studies, different clay systems were prepared so as to make possible several series of cultures in which the degree of base saturation in calcium was varied in each series, while the total amount of replaceable calcium per plant was kept constant at 0.20 M.E., an amount sufficient according to previous studies. Each series of cultures included the following percentages of calcium saturation: 40, 60, 75, 87.5 and 97. The balance of the saturation capacity was met by hydrogen or another positively charged ion. In order to provide a constant amount of calcium per plant in each culture, it was necessary to increase the amount of clay with decreasing saturation in calcium. This variation in amount of clay in the quartz sand was not significant enough to disturb physical conditions of the medium.

In order to produce one series of the clay systems carrying varying amounts of calcium supplemented by reciprocally varying amounts of other cations, only calcium was added to the hydrogen clay. This resulted in a calcium-hydrogen series with a pH range of 5.1 to 6.9. The other series of clay systems were prepared with the same variation in the degree of saturation in calcium, but cations other than hydrogen were added until the colloidal complex was 97 per cent saturated by bases. In each series the hydrogen ion was replaced by another ion fully enough to give approximately a neutral clay with a pH 6.85 to 6.90. Magnesium, barium, potassium and methylene blue were the cations used for this purpose. Each series consisted of four cultures with the degree of saturation in calcium as 40, 60, 75 and 87.5 per cent and the corresponding percentages of the supplementary ion as 57, 37, 22 and 9.5. The total quantities of the supplementary ions added to the cultures were 1.06, 2.90, 6.13 and 14.19 M.E., respectively. The fifth culture of the calcium-hydrogen series, with the clay 97 per cent saturated by calcium, was considered as common to each of the other series. On this plan, each series consisted of five cultures with calcium saturation ranging from 40 to 97 per cent, and with the corresponding saturation of the supplementary ion ranging conversely from 57 to 0 per cent.

In the preparation of the different clays, the supplementary ion* was the first to be added to the electrodialyzed clay in the desired amount. After equilibrium conditions were reached between the clay and the supplementary ion, the calcium was added as the hydroxide. Magnesium was added as the oxide and the barium and potassium as the hydroxides. A different procedure was followed in preparing the calcium-methylene blue-clay, since it was necessary to remove from the system the chlorine carried by the methylene blue molecule. A calcium saturated clay was treated with a solution of methylene blue until the calcium was completely replaced by the methylene blue cation. This was continued until a slight excess of methylene blue remained as a free electrolyte. The calcium chloride produced by the reaction between the Ca-clay and methylene blue, and also the free methylene blue were washed out by repeated centrifugings with alcohol. This was continued until the washings were free from chlorides. This methylene blue clay was then mixed with pure Ca-clay in the proper amounts and proportions to give the desired calcium-methylene blue-clays. This method was adopted on the assumption that calcium and methylene blue cations would interchange in accordance with their differences in concentration and would reach equilibrium in accordance with such. It has been pointed out, however, by Mattson[16] that the methylene blue cation is very strongly adsorbed and does not appear to be dissociated from the colloidal

*With the exception of the first methylene blue clay series.

complex. It might be expected then, that the mere mechanical mixing of Ca-clay with methylene blue-clay would result in very little or no chemical reaction between the two systems. That is, those individual colloidal particles originally saturated with calcium would remain as such, instead of having adsorbed a definite proportion of both calcium and methylene blue ions, as is probably true in the case of the other systems used in this investigation. If such is true, then the four calcium-methylene blue systems would be identical so far as the calcium is concerned, since each had the same amount of completely saturated Ca-clay mechanically mixed with different quantities of the relatively inactive methylene blue-clay.

As a test of this point, another calcium-methylene blue clay series was prepared according to the following procedure. Electrodialyzed clay was treated with small successive additions of a methylene blue solution. After each addition, the clay was electrodialyzed for about 8 hours in order to remove most of the free hydrochloric acid resulting from the replacement of the hydrogen ions on the clay by the methylene blue cation. Care was taken to keep the concentration of the acid below 0.001 normal. By noting the total amount of the standardized methylene blue solution added to the clay and also by determining the quantity of replaceable hydrogen remaining adsorbed on the clay, it was possible to saturate the clay to the desired extent with the methylene blue cation. When this point was reached, the clay was thoroughly electrodialyzed until free from the chloride ion. This was accomplished without any appreciable removal of the methylene blue cation, because of its high energy of adsorption. By repeating the above procedure with different portions of H-clay, four hydrogen-methylene blue systems were prepared, each with the desired degree of saturation in the methylene blue cation. The remaining adsorbed hydrogen ions were then replaced with calcium ions to produce approximately neutral calcium-methylene blue-clays in which the amount and degree of saturation in calcium duplicated the other series. This series will hereafter be designated as the "calcium-methylene blue series II" to distinguish it from the first one, which will be termed the "calcium-methylene blue series I".

PLANT GROUPS GROWN

The plants were grown in three different groups designated as A, B and C according to their sequence. Group A, which consisted of the calcium-hydrogen, calcium-magnesium and calcium-barium series, was planted in November. Group B, which consisted of the calcium-potassium, calcium-methylene blue I and calcium-variable level series in addition to a duplicate of the calcium-hydrogen series of group A, was planted in February. Group C, which consisted of the calcium-hydrogen series was planted the following January. The Ca-H series was repeated in each group as a basis for comparison between the three groups and as a check on seasonal differences in growth. After the growth of the first group and the complete removal of the plants, the same cultures were replanted without any change of the system or procedure.

The plan of the treatments arranged in schematic form was as follows:

Group	Combination of cations on the clay	Season of growth	Period of growth-days
A	Calcium-hydrogen Calcium-magnesium Calcium-barium	November	30
B	Calcium-hydrogen Calcium-potassium Calcium-methylene blue I Calcium at variable levels	February	30
C	Calcium-hydrogen Calcium-methylene blue II	January	35

The sand-clay cultures were each planted with 50 soybeans, which had been soaked in distilled water 24 hours and germinated between filter papers until the radicles were about 1 cm. in length. Inoculation of the plants was insured by adding to the cultures a suspension of the proper bacteria in distilled water. An optimum-moisture content was maintained by daily additions of distilled water. The growth period was 30 days for groups A and B and 35 days for group C. In order to eliminate the effects of photoperiodism, resulting from the short winter days, the sunlight was supplemented by sufficient artificial light to produce an approximate 14-hour day.

ANALYTICAL METHODS

The analytical data reported in this paper represent the analyses of both the tops and roots of 50 plants. The analyses of calcium, magnesium and potassium were made according to standard analytical methods on aliquots of a concentrated sulfuric acid digestion of the plants. The nitrogen was determined on separate aliquots.

Experimental Results

GROWTH AND NODULATION

—First Crops, Group A, B and C—

Relation to Total Exchangeable Calcium.—The general growth of the plants as related to the total quantity of calcium available at a constant hydrogen ion concentration is shown by the data in Table 1 and Figures 2 and 3. These results point out that as the supply of calcium per plant was increased from 0.05 to 0.30 M.E., the height, weight and nodulation were increased by 87, 61 and 465 per cent, respectively. The increasing growths for the increasing amounts of calcium, viz: .10, .20 and .30 M.E. per plant arrange themselves in a straight line relation which is in decided contrast to the growth given by .05 M.E. per plant. This indicated this

TABLE 1.—RELAT ON OF THE TOTAL EXCHANGEABLE CALCIUM TO THE GROWTH AND NODULATION OF SOYBEANS

Calcium per Plant	Average Height	Weight of 50 Plants: Tops	Weight of 50 Plants: Roots	Weight of 50 Plants: Total	Nodules per 50 Plants
M. E.	*cm.*	*gms.*	*gms.*	*gms.*	
0.05	19.0	4.304	1.313	5.617	97
0.10	30.4	6.008	1.643	7.651	221
0.20	32.4	6.621	1.692	8.313	331
0.30	35.6	7.327	1.764	9.091	451

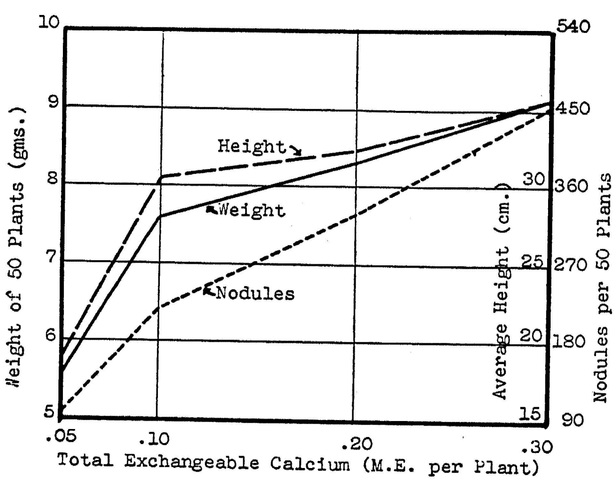

Fig. 2.—Relation of the total exchangeable calcium to the growth and nodulation of soybeans.

smaller amount to be less than required for normal growth under these conditions.

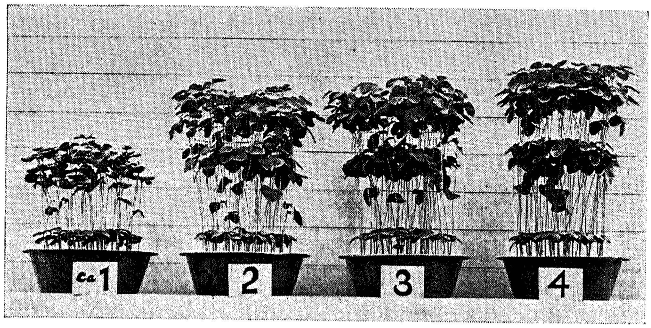

Fig. 3.—Growth of soybeans as related to total exchangeable calcium (increasing calcium from left to right).

Relation to Degree of Calcium Saturation.—It is impossible to make a direct quantitative comparison between the three different groups of series, since each group was grown at a different season. The general climatic growing conditions at the time group B was planted were better than when group A was planted. The same was true in the case of group C as compared to groups A and B. This probably accounts for the greater growth of group C and for the intermediate growth of group B as shown when the data given for these three groups in Tables 2, 3 and 4 are compared. Figures 7, 8 and 9 giving photographs of the separate series in each of these groups also illustrate this improved growth in the latter plantings. The cultures of each series are numbered in sequence according to the increasing degree of saturation of the clay by calcium. Culture numbers 1, 2, 3, 4 and 5 correspond to 40, 60, 75, 87.5 and 97 per cent saturation by calcium, respectively. More effective comparison can be made of these groups by reference to Figure 4 which gives graphs for the height of the different series in the groups, to Figure 5, giving the weight similarly and to Figure 6, treating the nodule production in a like manner.

The three calcium-hydrogen series, which represent a variation in both the degree of calcium saturation and the hydrogen-ion concentration—two variables which are reciprocally related—show that growth and nodulation improved with a decreasing hydrogen-ion concentration and an increasing calcium saturation. Which of these two variables is the more significant factor is not evident in the data from the calcium-hydrogen series alone. Nodulation, as measured by the number of nodules, ran parallel to the general growth of the plants as is indicated when the Ca-H graphs of Figure 6 are compared with those corresponding in Figures 4 and 5. The influence on growth and nodulation by a variation in acidity is shown clearly by the calcium-hydrogen series data in Tables 2, 3 and 4, by the corresponding curves in Figures 4, 5 and 6 by the photographs for this in Figures 7, 8 and 9. When compared with

TABLE 2.—RELATION OF DEGREE OF SATURATION OF THE CLAY BY CALCIUM TO THE GROWTH AND NODULATION OF SOYBEANS (GROUP A, FIRST CROP)

Culture Number	Calcium Saturation	Average Height	Weight of 50 Plants			Nodules per 50 Plants
			Tops	Roots	Total	
	%	*cm.*	*gms.*	*gms.*	*gms.*	
		Calcium-hydrogen Series				
1	40	28.2	3.982	1.003	4.985	121
2	60	33.9	5.363	1.534	6.897	178
3	75	35.0	5.660	1.608	7.268	198
4	87.5	36.7	5.944	1.575	7.519	183
5	97	38.1	6.296	1.610	7.906	185
		Calcium-magnesium Series				
1	40	37.8	5.414	1.216	6.630	74
2	60	43.4	6.465	1.623	8.088	136
3	75	41.5	6.056	1.461	7.517	161
4	87.5	40.1	6.142	1.540	7.682	203
		Calcium-barium Series				
1	40	28.9	4.962	1.172	6.134	119
2	60	31.8	5.224	1.217	6.441	163
3	75	34.7	5.638	1.369	7.007	159
4	87.5	37.5	6.442	1.477	7.919	212

TABLE 3.—RELATION OF DEGREE OF SATURATION OF THE CLAY BY CALCIUM TO THE GROWTH AND NODULATION OF SOYBEANS (GROUP B, FIRST CROP)

Culture Number	Calcium Saturation	Average Height	Weight of 50 Plants			Nodules per 50 Plants
			Tops	Roots	Total	
	%	*cm.*	*gms.*	*gms.*	*gms.*	
		Calcium-hydrogen Series				
1	40	27.7	5.151	1.320	6.471	243
2	60	30.5	5.574	1.338	6.912	294
3	75	31.5	5.938	1.575	7.513	319
4	87.5	31.6	6.116	1.758	7.874	354
5	97	32.4	6.621	1.692	8.313	331
		Calcium-potassium Series				
1	40	26.5	4.937	1.368	6.305	208
2	60	31.8	5.711	1.540	7.251	243
3	75	35.7	6.614	1.581	8.195	251
4	87.5	36.0	6.801	1.815	8.616	304
		Calcium-methylene Blue Series I				
1	40	30.7	6.645	1.465	8.110	358
2	60	29.6	6.658	1.517	8.175	341
3	75	32.6	6.914	1.485	8.399	328
4	87.5	33.4	6.735	1.816	8.551	379
		Average Values for Groups A and B (Calcium-methylene Blue Series Omitted)				
1	40	29.8	4.889	1.216	6.105	153
2	60	34.3	5.667	1.451	7.118	203
3	75	35.7	5.981	1.519	7.500	218
4	87.5	36.4	6.289	1.633	7.922	251
5	97	35.3	6.459	1.651	8.110	258

TABLE 4.—RELATION OF DEGREE OF SATURATION OF THE CLAY BY CALCIUM TO THE GROWTH AND NODULATION OF SOYBEANS (GROUP C, FIRST CROP)

Culture Number	Calcium Saturation	Average Height	Weight of 50 Plants			Nodules per 50 Plants
			Tops	Roots	Total	
	%	*cm.*	*gms.*	*gms.*	*gms.*	
Calcium-hydrogen Series						
1	40	29.3	6.728	2.042	8.770	621
2	60	32.7	7.375	2.071	9.446	648
3	75	32.7	7.625	2.041	10.366	685
4	87.5	32.6	7.950	2.283	10.233	747
5	97	33.6	8.674	2.489	11.163	836
Calcium-methylene Blue Series II						
1	40	32.7	8.353	2.069	10.422	752
2	60	31.9	8.302	2.262	10.564	731
3	75	32.2	8.359	2.381	10.740	725
4	87.5	32.2	8.370	2.344	10.714	724

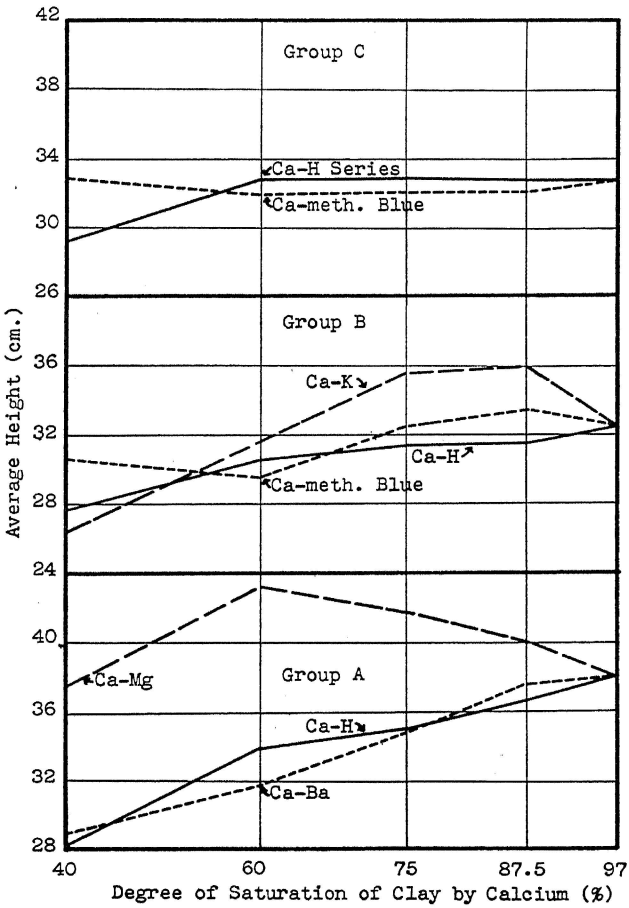

Fig. 4.—Relation of the degree of saturation of the clay by calcium to height of plants.

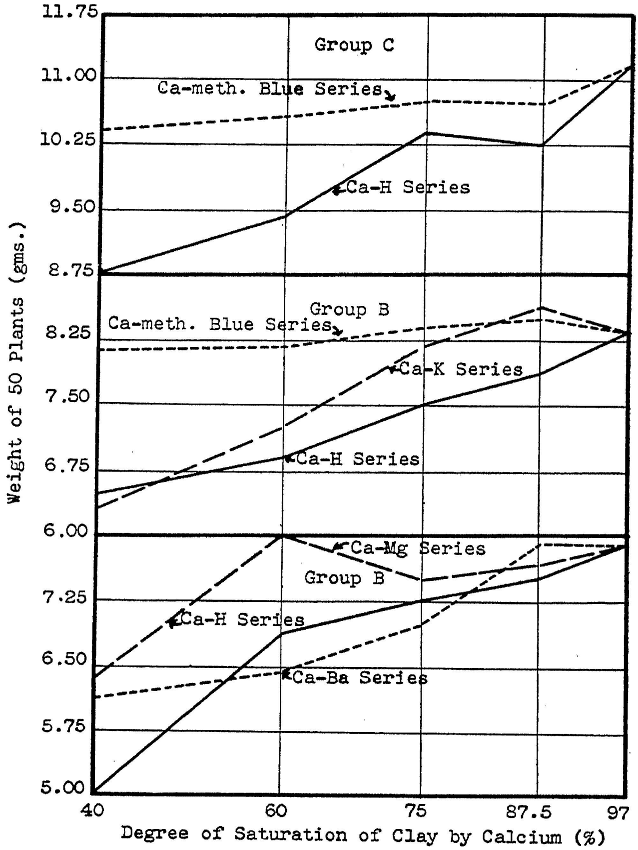

Fig. 5.—Relation of the degree of saturation of the clay by calcium to the weight of plants.

the influence by a variation in the calcium level given in Table 1 and Figures 2 and 3, these indicate most strongly that under these conditions the total amount of available calcium is a more important factor than a variation in the degree of saturation of the clay in calcium, or its concomitant, the hydrogen-ion concentration. These data presented confirm those of Albrecht[1 2].

In those series in which the exchangeable hydrogen was replaced by magnesium, barium or potassium completely enough to result in a neutral reaction, the general variations in growth and nodulation duplicated the results of the calcium-hydrogen series.

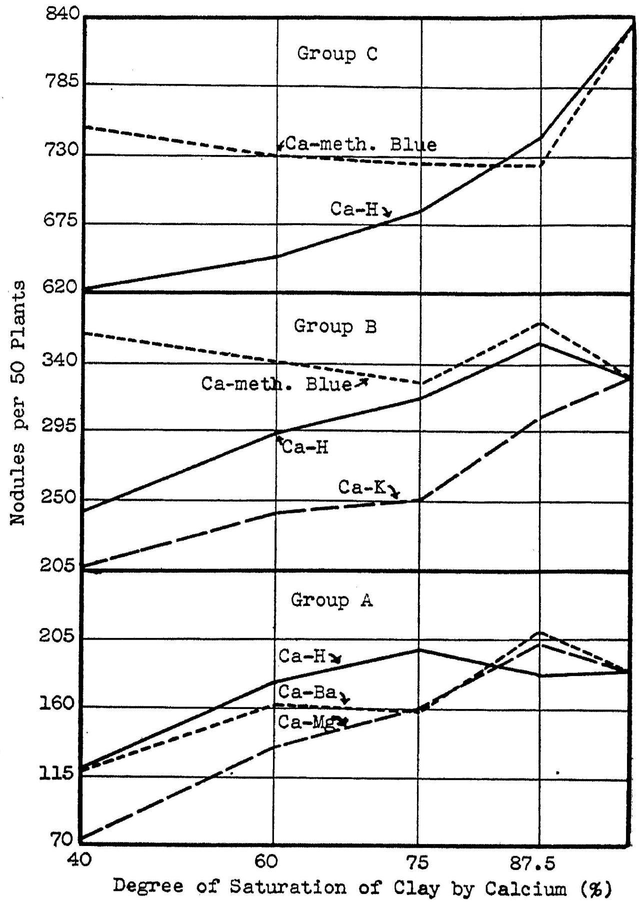

Fig. 6.—Relation of the degree of saturation of the clay by calcium to nodulation of plants.

This was especially true of the nodulation, where the differences as related to the variation in saturation with calcium were more significant than in the calcium-hydrogen series.

Relation to Degree of Saturation by Other Cations.—The addition of magnesium and potassium in the calcium-magnesium and calcium-potassium series, respectively, introduced these two nutrient elements as additional variable growth factors in these two series. This is shown by the general stimulation of growth in these two series. When magnesium was present in the exchangeable

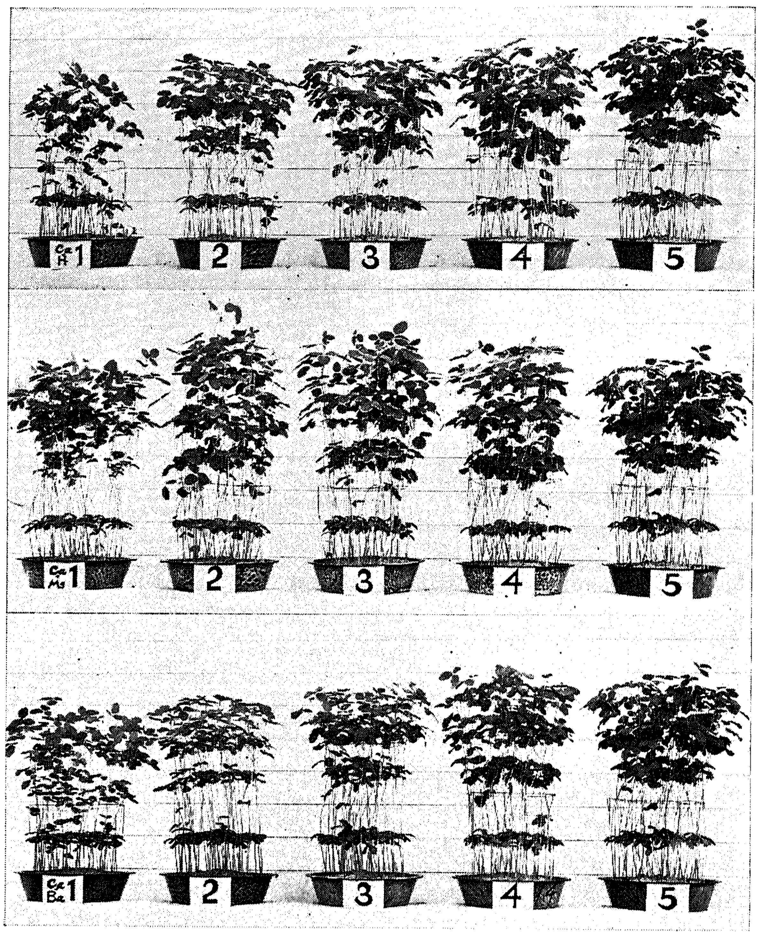

Fig. 7.—Growth of soybeans as related to degree of calcium saturation (Group A, first crop, increasing saturation from left to right).

form, the height was especially increased as shown in Figure 4. This increased with an increasing availability of magnesium until the complex was 60 per cent saturated with calcium and 37 per cent saturated with magnesium, but decreased to the lowest value where the proportion of calcium to magnesium was 40 to 60. Similar variations in weight shown graphically in Figure 5 were found to exist, although not as definitely as those for height. For the lower potassium values, there was a marked increase in height and

Fig. 8.—Growth of soybeans as related to degree of calcium saturation (Group B, first crop, increasing saturation from left to right).

weight. However, with a relatively greater increase in available potassium which was accompanied by a decrease in saturation by calcium, the growth diminished at a greater rate than in the calcium-hydrogen series. Despite these irregularities in the magnitude of the growth associated with the introduction of magnesium and potassium to the cultures, the degree of nodulation was consistently below that of the calcium-hydrogen series.

The introduction of barium into the complex as a substitute for hydrogen gave results very similar to those obtained in the cal-

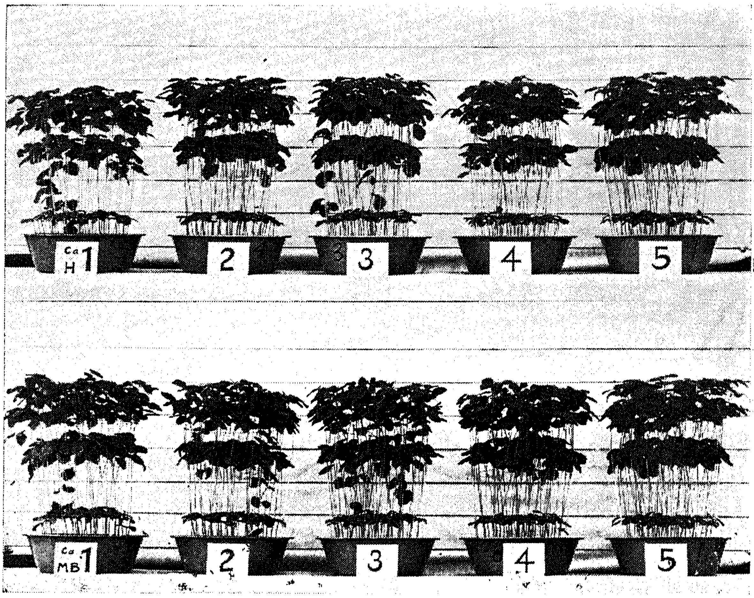

Fig. 9.—Growth of soybeans as related to degree of calcium saturation (Group C, first crop, increasing saturation from left to right).

cium-hydrogen series, indicating that the barium and hydrogen ions may have had approximately the same effect on the plants. Since barium is not an essential element for plant growth, it should not be expected to behave like magnesium or potassium.

The general similarity of the results, obtained by substituting these readily exchangeable ions for the hydrogen ion of the unsaturated colloidal complex, indicates that the variation in growth of these plants in an acid soil is not necessarily related to the variation in the hydrogen-ion concentration, but rather to its concomitant, namely, the degree of calcium saturation.

The calcium-methylene blue series gave different results. The substitution of this strongly adsorbed and slowly exchangeable ion for the hydrogen ion resulted in eliminating the influence of the variation in the degree of saturation of the clay by calcium, as the growth and nodulation of the plants were very similar in all of the calcium-methylene blue cultures. This is evident in Figures 4, 5 and 6 in which the graphs for these series run almost horizontally while those for the other series represent a rise with increasing calcium saturation. The two methods employed in the preparation of the methylene blue clay systems had no influence upon the results. That is, no difference was evident in the growth of the plants in the cultures prepared by mixing methylene blue-clay with calcium-clay and in those prepared by introducing the methylene blue cation into the hydrogen system first and then completing the saturation of the complex with calcium. This suggests that the relative energy of adsorption of the various ions, used supplementary to calcium in the colloidal complex, is an important factor in determining the observed influence of the variation of the degree of saturation of the clay by calcium on the behavior of plants grown in cultures of the clay. Those ions which are very strongly adsorbed, such as the methylene blue cation, reduce the effect of a variation in calcium saturation to a very low degree; while potassium which is not as strongly adsorbed has the opposite effect. The chemical composition of the plants also points to this fact discussed more fully with the composition data.

Second Crop, Group A

After the removal of the plants in group A, the cultures were immediately replanted. The growth and nodulation of this second crop are shown in Table 5 and Figure 10. The absorption of different amounts of calcium from the different cultures by the first crop disturbed the original conditions as to the amount and degree of saturation of the clay by calcium. The calcium level per plant was reduced from the original value of 0.20 M.E. in the number 1 cultures, to 0.145 M.E. in culture number 5 and to intermediate values in the other cultures. Similar reductions occurred in the

TABLE 5.—RELATION OF DEGREE OF SATURATION OF THE CLAY BY CALCIUM TO THE GROWTH AND NODULATION OF SOYBEANS (GROUP A, SECOND CROP)

Culture Number	Ca Saturation	Ca per Plant	Average Height	Weight of 50 Plants			Nodules per 50 Plants
				Tops	Roots	Total	
	%	M. E.	cms.	gms.	gms.	gms.	
			Calcium-hydrogen Series				
1	36.6	0.183	22.1	5.043	1.468	6.511	210
2	49.0	0.163	28.0	5.683	1.775	7.458	299
3	59.0	0.157	27.5	5.860	1.530	7.390	335
4	66.1	0.151	27.1	5.883	1.467	7.350	340
5	70.2	0.145	30.4	6.145	1.699	7.844	362
			Calcium-magnesium Series				
1	35.4	0.177	32.7	6.344	1.524	7.868	290
2	47.6	0.159	32.7	6.694	1.707	8.401	326
3	57.5	0.153	32.0	6.137	1.694	7.831	306
4	63.5	0.145	31.9	6.324	1.963	8.287	331
			Calcium-' arium Series				
1	36.8	0.184	22.5	4.927	0.955	5.882	273
2	51.1	0.170	24.2	5.128	1.181	6.309	360
3	60.5	0.161	24.5	5.349	1.120	6.469	306
4	66.6	0.152	27.7	5.473	1.382	6.855	333

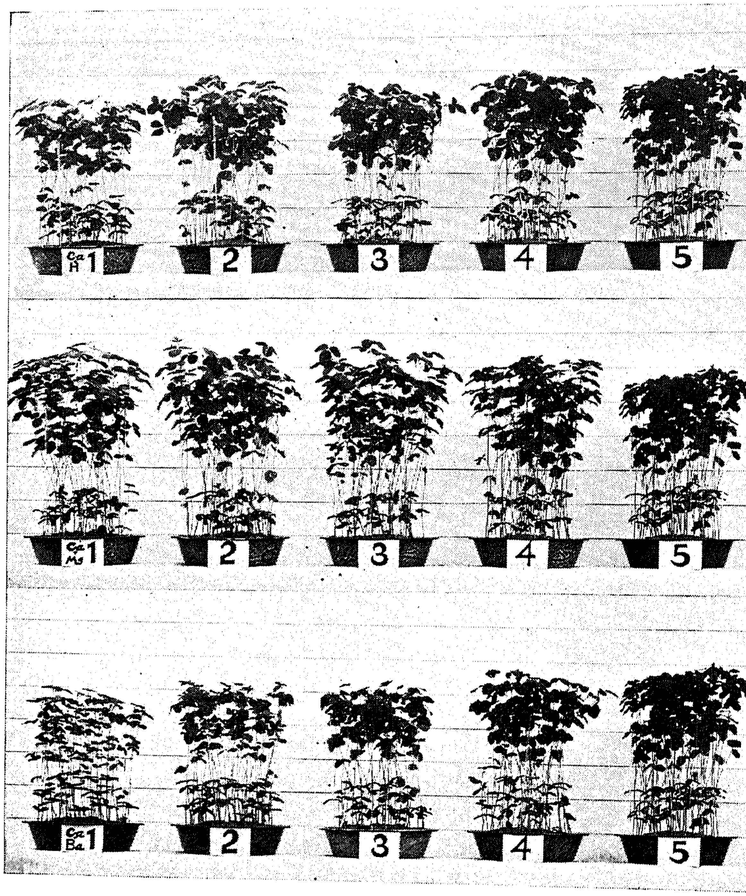

Fig. 10.—Growth of soybeans as related to degree of calcium saturation (Group A, second crop, increasing saturation from left to right).

degree of saturation by calcium, so that the number 1 cultures were lowered from the original value of 40 per cent to about 36 per cent and culture number 5 from the original value of 97 per cent to 70 per cent. Thus, in each series of cultures there was a decreasing calcium level in conjunction with an increasing degree of saturation of the clay by calcium. These two opposite controlling factors should tend toward a greater uniformity of the various cultures, consequently tending to produce less variation in growth. The results show, however, that a general decrease in growth and nodulation accompanied a decrease in the degree of calcium saturation in the calcium-hydrogen and calcium-barium series. This indicates that the variation in degree of calcium saturation more than counterbalanced the opposite variation in calcium level. The differences in growth were only about 50 per cent as great as those of the first crop and therefore less significant. No consistent variation occurred in the calcium-magnesium series. This is probably due to the presence of available magnesium, which is a growth promoting factor. The decided increase in nodulation of the second crop over that of the first may have been due to better inoculation resulting from a better establishment of the infecting organism with a lapse of time, or it may have been the result of the more favorable environmental growing conditions which prevailed during the period of growth. In general, the results of the second crop confirm the conclusions deducted from the results of the first crop.

CHEMICAL COMPOSITION OF PLANT MATERIAL

Calcium and Nitrogen

The chemical analyses of the plant material show interesting relationships between the nature and extent of saturation of the clay adsorptive complex with bases and the composition of the crop. A good correlation also existed between the calcium content of the plants and the general growth and nodulation.

The amount of atmospheric nitrogen fixed was taken as the difference between the amount in the plants and that originally presented in the seeds, since the electrodialyzed clay, quartz sand and distilled water introduced no additional nitrogen. The analysis of the seed used in groups A and B gave an average nitrogen content of 326.7 ± 2.6 mgm. per 50 seeds. Seven samples of 50 seeds each, which had been soaked and sprouted similarly to those planted, were analyzed and the difference between the minimum and maximum values was 9.3 mgm. A different sample of seed was used in planting group C, because that used in groups A and B had partially lost its vitality due to age. Analyses on seven samples of these seeds gave an average of 362.8 ± 5.3 mgm. of nitrogen per 50 seeds with a maximum variation of 18.7 mgm.

Influence of Varying Calcium Levels.—The effect of a variation in the total amount of available calcium upon the nitrogen content of the plants is given in Table 6 and Figure 11. The calcium contents of the plants are also included. There is a very good correlation between the quantities of total nitrogen and total calcium,

TABLE 6.—RELATION OF THE CALCIUM LEVEL TO THE CHEMICAL COMPOSITION OF THE PLANT MATERIAL

Ca per Plant M. E.	Amount in 50 Plants					pH of Clay		
	Nitrogen			Calcium		At Start	At Close	
	%	Total mgm.	Fixed mgm.	%	Total mgm.		Obs.	Calc.*
0.05	5.533	310.8	−15.9	0.586	32.9	6.90	4.95	5.25
0.10	4.372	334.6	7.9	0.765	58.5	6.90	5.15	5.25
0.20	4.150	345.0	18.3	0.838	69.6	6.90	5.25	5.45
0.30	4.016	365.1	38.4	0.940	85.4	6.90	5.40	5.60

*Observed and calculated values, respectively. See Page 33.

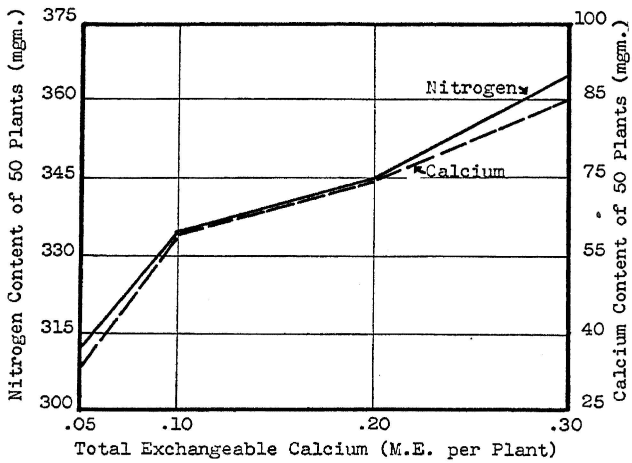

Fig. 11.—Relation of the total exchangeable calcium to the chemical composition of the plant material.

each of which increased with an increasing calcium level. Differences of 54.3 and 52.5 mgm. of nitrogen and calcium, respectively, occurred between the lowest and the highest calcium levels. The data indicate that there was an increasing fixation of nitrogen as the calcium level was increased from 0.05 to 0.30 M.E. per plant. The negative value for the lowest calcium level indicates that there was a net loss of nitrogen from the plants in this culture. The question as to whether there was no fixation and only a loss of nitrogen from these plants, or that the loss outbalanced the fixation, is not apparent from the data. If a similar loss occurred in the other three cultures, then it is evident that the amount of fixation was greater than that indicated by the data, because it would be necessary to overcome the loss before a gain could be registered. Nevertheless, a net difference of 54.3 mgm. of nitrogen per 50 plants between the extremes of the calcium supply used suggests that the effectiveness of legumes as nitrogen fixers is very closely associated with their ability to secure sufficient calcium.

Influence of Varying Degree of Saturation by Calcium and Other Mineral Cations.—The differences noted above in the nitrogen and calcium contents of plants grown on a range of calcium

TABLE 7.—RELATION OF DEGREE OF SATURATION OF THE CLAY BY CALCIUM TO THE CHEMICAL COMPOSITION OF THE PLANT MATERIAL (GROUP A, FIRST CROP)

Culture Number	Amount in 50 Plants					pH of Clay		
	Nitrogen			Calcium		At Start	At Close	
	%	Total mgm.	Fixed mgm.	%	Total mgm.		Obs.	Calc.*
			Calcium-hydrogen Series					
1	5.777	288.0	−38.7	0.507	25.2	5.10	4.85	5.00
2	4.588	316.4	−10.3	0.651	44.8	5.50	5.25	5.20
3	4.482	325.8	−0.9	0.702	50.9	5.90	5.30	5.30
4	4.489	337.5	10.8	0.764	57.1	6.45	5.35	5.40
5	4.324	341.9	15.2	0.800	63.2	6.85	5.25	5.50
			Calcium-magnesium Series					
1	4.598	304.9	−21.8	0.468	31.2	6.90	5.40	5.90
2	3.868	312.9	−13.8	0.613	49.3	6.90	5.35	5.45
3	4.131	310.5	−16.2	0.734	54.9	6.85	5.30	5.45
4	3.967	304.8	−21.9	0.824	63.0	6.90	5.30	5.40
			Calcium-barium Series					
1	5.141	315.3	−11.4	0.386	23.9	6.90	5.75	6.50
2	4.863	313.2	−13.5	0.594	38.0	6.85	5.55	6.25
3	4.532	317.5	−9.2	0.672	47.0	6.85	5.60	5.95
4	4.392	347.8	21.1	0.707	56.2	6.85	5.45	5.65

*Observed and calculated values, respectively. See Page 33.

TABLE 8.—RELATION OF DEGREE OF SATURATION OF THE CLAY BY CALCIUM TO THE CHEMICAL COMPOSITION OF THE PLANT MATERIAL (GROUP B, FIRST CROP)

Culture Number	Amount in 50 Plants					pH of Clay		
	Nitrogen			Calcium		At Start	At Close	
	%	Total mgm.	Fixed mgm.	%	Total mgm.		Obs.	Calc.*
			Calcium-hydrogen Series					
1	4.92'	318.5	−8.2	0.601	38.9	5.10	4.95	5.00
2	4.755	328.7	2.0	0.7 3	50.7	5.30	5.15	5.20
3	4.383	329.3	2.6	0.783	58.8	5.85	5.25	5.30
4	4.303	338.8	12.1	0.857	67.5	6.30	5.20	5.35
5	4.150	345.0	18.3	0.838	69.6	6.90	5.25	5.45
			Calcium-potassium Series					
1	4.993	314.8	−11.9	0.452	28.5	6.85	5.75	5.75
2	4.503	326.5	−0.2	0.589	42.7	6.85	5.50	5.45
3	4.193	343.6	16.9	0.653	53.5	7.00	5.45	5.40
4	4.191	361.1	34.4	0.815	70.2	6.90	5.30	5.35
			Calcium-methylene Blue Series I					
1	4.109	333.2	6.5	0.917	74.4	6.85	5.55	6.15
2	4.067	332.5	5.8	0.821	65.1	6.85	5.40	6.00
3	4.033	338.7	12.0	0.744	62.5	6.90	5.35	5.80
4	4.062	347.3	20.6	0.754	64.4	6.90	5.30	5.60
			Average Values for Groups A and B (Calcium-methylene Blue Series Omitted)					
1	5.050	308.3	−18.4	0.485	29.6	-----	- - -	-----
2	4.489	319.5	−7.2	0.634	45.1	-----	-----	-----
3	4.337	325.3	−1.4	0.707	53.0	-----	-----	-----
4	4.267	338.0	11.3	0.793	62.8	-----	-----	-----
5	4.236	343.5	16.8	0.819	66.4	-----	-----	-----

*Observed and calculated values, respectively. See Page 33.

levels from 0.05 to 0.30 M.E. per plant were duplicated in general, in the other plant series in which the total supply of calcium was kept constant at 0.20 M.E. per plant, while the degree of saturation of the clay by calcium varied from 40 to 97 per cent. The composition data are given in Tables 7, 8, 9 and 10 and are shown graphically in Figures 12 and 13.

There was a consistent increase in the amounts of nitrogen and calcium in the plants as the saturation by calcium increased, regardless of whether hydrogen, magnesium, barium or potassium was used as the ion supplementary to the varying calcium saturation, as the rising curves for these particular ion series in Fig-

TABLE 9.—RELATION OF DEGREE OF SATURATION OF THE CLAY BY CALCIUM TO THE CHEMICAL COMPOSITION OF THE PLANT MATERIAL (GROUP C, FIRST CROP)

Culture Number	Amount in 50 Plants					pH of Clay		
	Nitrogen			Calcium		At Start	At Close	
	%	Tota mgm.	Fixed mgm.	%	Total mgm.		Obs.	Calc.*
Calcium-hydrogen Series								
1	4.539	398.1	35.3	0.609	53.4	4.95	4.80	4.70
2	4.417	417.2	54.4	0.669	63.2	5.20	5.05	4.95
3	4.132	424.7	61.9	0.899	93.2	5.65	5.15	5.05
4	4.087	418.2	55.4	0.981	91.2	6.30	5.30	5.20
5	3.874	432.4	69.6	0.856	95.5	6.90	5.25	5.25
Calcium-methylene Blue Series II								
1	4.087	428.3	65.5	1.021	106.4	6.95	5.65	5.80
2	4.032	425.9	63.1	1.043	110.2	6.95	5.40	5.45
3	3.979	427.3	64.5	0.981	105.3	7.00	5.40	5.30
4	3.936	421.7	58.9	0.993	106.4	7.00	5.35	5.20

*Observed and calculated values, respectively. See Page 33.

TABLE 10.—RELATION OF DEGREE OF SATURATION OF THE CLAY BY CALCIUM TO THE CHEMICAL COMPOSITION OF THE PLANT MATERIAL (GROUP A, SECOND CROP)

Culture Number	Amount in 50 Plants					pH of Clay		
	Nitrogen			Calcium		At Start	At Close	
	%	Total mgm.	Fixed mgm.	%	Total mgm.		Obs.	Calc.*
Calcium-hydrogen Series								
1	4.841	315.2	−11.5	0.536	34.9	4.85	4.65	4.70
2	4.513	336.6	9.9	0.656	48.9	5.25	4.35	5.00
3	4.599	340.0	13.3	0.662	48.9	5.30	4.50	5.05
4	4.802	352.9	26.2	0.667	49.0	5.35	4.65	5.05
5	4.365	342.4	15.7	0.709	55.6	5.25	4.45	4.80
Calcium-magnesium Series								
1	4.385	345.0	18.3	0.495	38.9	5.40	4.90	5.15
2	4.007	336.6	9.9	0.600	50.4	5.35	4.50	4.95
3	4.547	356.2	29.5	0.647	50.7	5.30	4.50	4.95
4	4.229	350.5	23.8	0.718	59.5	5.30	4.40	4.80
Calcium-barium Series								
1	5.189	305.0	−21.7	0.463	27.2	5.75	5.50	5.55
2	5.009	316.0	−10.7	0.552	34.8	5.55	5.15	5.30
3	4.479	289.7	−37.0	0.599	38.8	5.60	5.05	5.25
4	4.376	300.0	−26.7	0.644	44.2	5.45	4.95	5.20

*Observed and calculated values, respectively. See page 33.

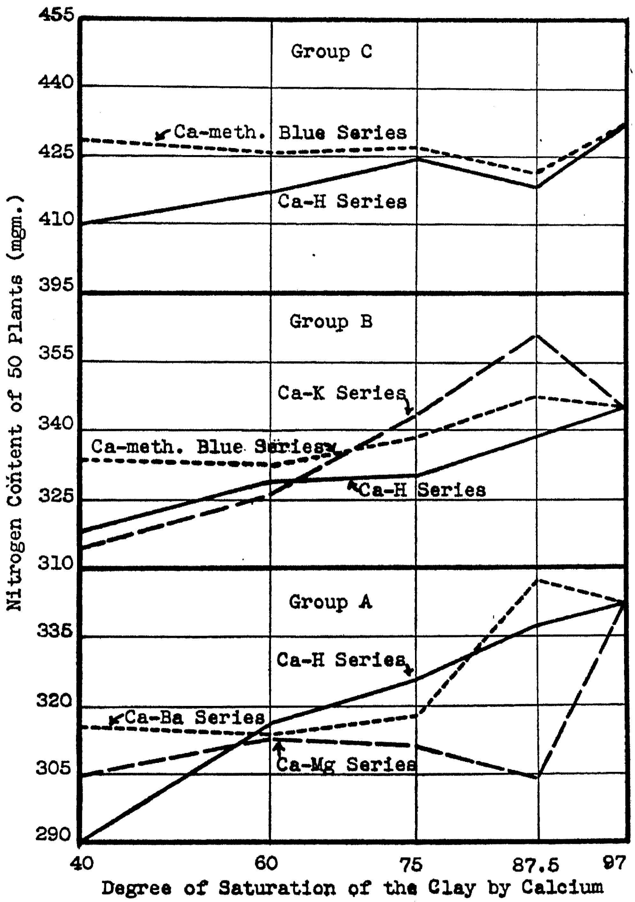

Fig. 12.—Relation of the degree of saturation of the clay by calcium to the nitrogen content of plants.

ures 12 and 13 indicate. This relation did not hold as well for the calcium-magnesium series in the case of nitrogen, which resulted in approximate equal losses in each culture. The irregularities in the height and weight of the plants from the calcium-potassium series in Figures 4 and 5 were absent in the case of calcium absorption and nitrogen fixation noted for this series. In fact, the slopes of these calcium and nitrogen curves were steeper for this series than in the calcium-hydrogen series. This duplicates the behavior as to nodulation. Although the nitrogen percentages decrease in the

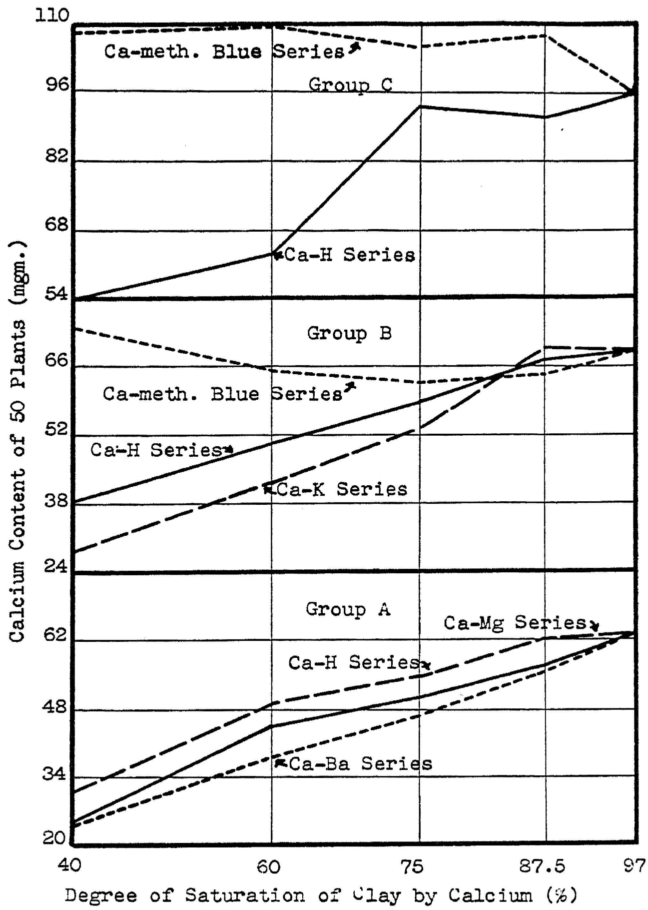

Fig. 13.—Relation of the degree of saturation of the clay by calcium to the calcium content of plants.

reverse order from that of the other properties, it should be pointed out that such a variation has little or no significance because these values are due to a more rapid decrease in the weight of the plants compared to the corresponding decrease in the weight of nitrogen. The values expressing the amount of nitrogen in terms of its weight are more significant than those in terms of percentages.

The composition of the second crop grown in the cultures of group A is given in Table 10. Irregularities similar to those found in the growth and nodulation were also found for the amount of nitrogen and calcium in the plants. There was a general but inconsistent increase in these elements with an increasing degree of saturation of the clay by calcium. The improved nitrogen fixation of the second crop as compared to the first crop was probably associated with better inoculation. However, this was not true of the calcium-barium series as there was a negative fixation in each culture. The reason for this inconsistency is not evident.

Influence of Varying Degree of Saturation by Calcium and Methylene Blue.—As in the case of growth and nodulation, the calcium-methylene blue series showed no consistent or significant variation in the chemical composition of the plants. The plants were able to absorb calcium and promote nitrogen fixation equally as well when grown in a clay system whose complex was 40 per cent saturated as when in a clay system completely saturated by calcium. Here again, the two methods of preparation of the calcium-methylene blue-clays gave the same results.

These results support the preceding suggestion, viz: that the ability of plants to absorb calcium depends upon the amount and the energy of adsorption of the supplementary ion. If this ion is very strongly adsorbed by the clay, as is true for the methylene blue cation, the absorption of calcium from the clay by the plant is not hindered to any great extent, regardless of the relative proportion of calcium to this supplementary ion. On the other hand, an ion which is not as strongly adsorbed by the clay, such as the potassium ion, will have a strong influence upon the plant's ability to secure exchangeable calcium. This effect will be more evident as the proportion of this supplementary ion to calcium increases; or as the degree of saturation of the exchange complex decreases to give a corresponding increase in this supplementary ion.

Jenny and Cowan[11] suggested that plants obtain exchangeable elements from clay by the excretion of hydrogen ions from their roots. These hydrogen ions will replace the various adsorbed ions, which may then be taken into the plant. This theory suggests that if the plants are feeding upon a clay system in which the exchangeable bases are 90 per cent calcium and 10 per cent potassium, the excreted hydrogen ions will replace much more calcium than potassium. Consequently, the plants will be relatively rich in calcium and poor in potassium. However, the reverse process will take place with a clay system only 40 per cent saturated by calcium and 60 per cent saturated by potassium, and the plants will contain a small amount of calcium and a relatively large amount of potassium.

When this viewpoint of the plant's absorption behavior is applied to the calcium-methylene blue system, it results in a different picture. Since the methylene blue cations are very strongly adsorbed by the clay, the hydrogen ions will not replace them to any appreciable extent. Therefore, the full replacing energy of the hydrogen ions will be directed toward the replacement of the calcium. Furthermore, this process should not be appreciably affected by a wide variation in the degree of saturation of the clay by calcium, as long as the balance of the colloidal complex is saturated by methylene blue cations. In this case, the plants should be able to take up equal quantities of calcium from a series of calcium-methylene blue-clay cultures at the same calcium level, regardless of the degree of saturation of the clay by calcium.

In general terms, it may be said, that the amount of absorption of a given exchangeable cation by plants increases with an increase in the degree of saturation of the adsorption complex with this cation, provided the total exchangeable supply of this element is not varied and the supplementary cations may be correspondingly more or less readily replaced under conditions existing in the system.

Calcium, Magnesium, Potassium, Silica and Aluminum

The quantities of calcium, magnesium and potassium in the plants from four series of cultures and also the respective amounts

TABLE 11.—RELATION OF THE DEGREE OF SATURATION OF THE CLAY BY CALCIUM TO THE ABSORPTION OF DIFFERENT IONS BY THE PLANT

Culture Number	Total M. E. in 50 Plants			M. E. Absorbed from Clay by 50 Plants			
	Ca	Mg	K	Ca	Mg	K	Total
			Calcium-hydrogen Series (Group B)				
1	1.95	0.84	2.75	1.54	0.31	0.09	1.94
2	2.54	0.77	2.67	2.13	0.24	0.01	2.38
3	2.94	0.74	2.63	2.53	0.21	−0.03	2.71
4	3.38	0.67	2.60	2.97	0.14	−0.06	3.05
5	3.48	0.68	2.63	3.07	0.15	−0.03	3.19
			Calcium-potassium Series				
1	1.42	0.47	7.34	1.01	−0.06	4.68	5.63
2	2.14	0.57	6.52	1.73	0.04	3.86	5.63
3	2.68	0.60	4.95	2.27	0.07	2.29	4.63
4	3.51	0.73	3.45	3.10	0.20	0.79	4.14
			Calcium-magnesium Series				
1	1.56	4.07	----	1.15	3.54	----	4.69
2	2.47	4.15	----	2.06	3.62	----	5.68
3	2.75	2.52	----	2.34	1.99	----	4.33
4	3.15	1.69	----	2.74	1.16	----	3.90
			Calcium-methylene Blue Series I				
1	3.72	0.62	2.52	3.31	0.09	−0.14	3.26
2	3.26	0.63	2.46	2.85	0.10	−0.20	2.76
3	3.13	0.71	2.64	2.70	0.18	−0.02	2.85
4	3.22	0.77	2.75	2.81	0.24	0.09	3.14

absorbed from the clay by the plants are shown by the data given in Table 11. The total amount of each element in the plants in excess of that contained in the seeds was taken as that absorbed from the clay. Analysis of the seed showed that 50 seeds contained 0.41 ± 0.01, 0.53 ± 0.01 and 2.66 ± 0.04 milliequivalents of calcium, magnesium and potassium, respectively.

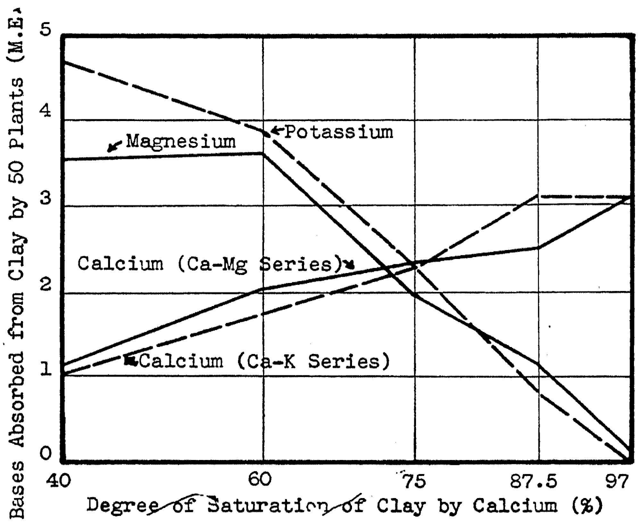

Fig. 14.—Relation of the degree of saturation of the clay by calcium to the bases absorbed by the plants.

Some interesting relationships are found in the data giving the amounts of calcium and potassium, and of calcium and magnesium absorbed from the clay in the calcium-potassium and calcium-magnesium series, respectively. These are shown graphically in Figure 14. As the degree of saturation of the clay by calcium increases, the absorption of calcium increases while that of potassium and magnesium decreases. There were small amounts of calcium and relatively large amounts of the supplementary ions replaced from the clay at the lower degrees of calcium saturation, while the opposite occurred at the higher saturation values.

In those series of clays containing supplementary ions which were more or less readily replaced, namely, hydrogen, potassium, magnesium and barium, the plants were better able to absorb calcium as the degree of saturation of the clay by calcium was increased, while this relation was almost wholly eliminated by the methylene blue cation, which was replaced with difficulty.

The magnesium content of the plants was higher than that of the seeds in all cultures, except the No. 1 culture of the calcium-potassium series, if one disregards the calcium-magnesium series. It is evident that the plants were able to absorb magnesium from the clay in those cultures to which none was added. This suggests that a portion of the non-exchangeable magnesium existing within the crystal lattice of the colloidal particles may become exchangeable through a partial break down of the crystal lattice. That such a process involving magnesium and potassium may take place has been suggested by Kelly, Dore and Brown[12]. It was found that the plants contained also considerable quantities of silica and aluminum, thus indicating that such a process took place in this case. Further evidence on this point is given by the tendency of the gain in magnesium to increase with an increase in the acidity of the cultures at the close of the growth period, since a lowering of the pH values of the clay should speed up the rate of decomposition of the colloidal particle. Reference to the pH values of the clay for the Ca-H series in Table 8 in conjunction with the values for magnesium absorbed given in Table 11 show this tendency. The data show the same tendencies on the smaller scale in the case of potassium. The negative values indicate a loss of potassium by the plants to the clay.

DATA SUMMARIZATION AS GENERAL AVERAGES

The average values for the growth, nodulation and composition of the corresponding cultures of each of the series of groups A and B are given as a part of Tables 3 and 8 and as Figure 15. The calcium-methylene blue series I is not included in these data, because of the fundamental difference in nature of this series of clays. There is a very striking similarity of the relationship of the degree of saturation of the clay by calcium to the different variable plant characters. The magnitude of each of the characters increases significantly with an increase in the calcium saturation of the clay. However, it should be emphasized that the principal controlling factor in the growth and nitrogen fixation is no doubt the actual supply of calcium in the plant, which is dependent directly upon the proportion of that element in the colloidal complex.

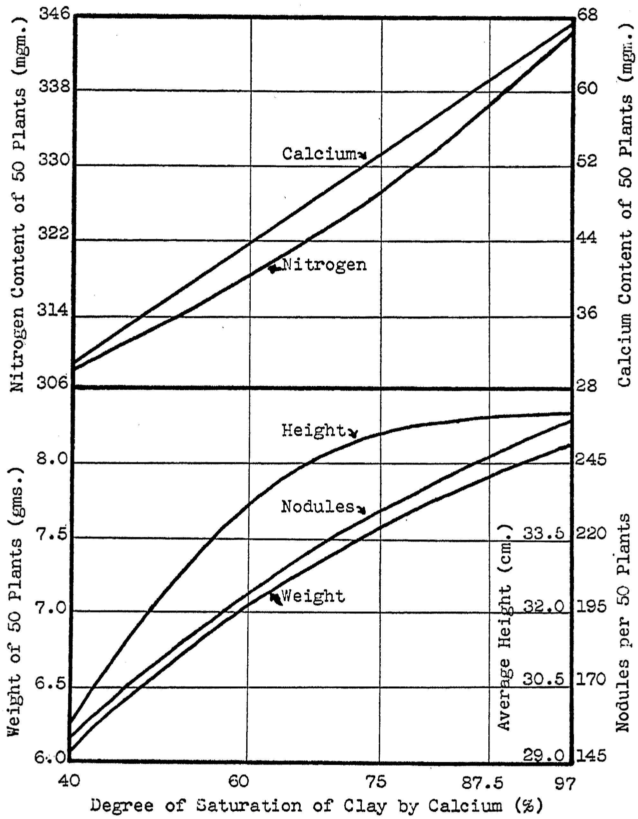

Fig. 15.—Relation of degree of saturation of clay by calcium to the various plant characters (General averages of Groups A and B, calcium-methylene blue series omitted).

REACTIONS CHANGES OF CLAY

After the crop was removed, electrometric determinations of the pH value of the clay were made. If one assumes that the bases absorbed from the clay by the plants are replaced by hydrogen ions, then it is possible to calculate how much change in pH of the clay these added hydrogen ions should bring about by reference to the titration curve shown in Figure 1. These calculated data together with the initial values are given in Tables 7, 8, 9 and 10.

There was a decided increase in the degree of acidity as a result of the activities of the plants. The magnitude of the shift in the pH is dependent upon the quantity of bases removed per unit of clay. In the calcium-hydrogen series, the tendency was for a reversal of the original order of the reaction as shown by the values in Table 10 at the close of the second crop. This was to be expected, since the cultures having a high pH value at the start also contained the smallest amounts of clay and supported the healthiest plants. In the series which had originally a neutral reaction, the shift toward lower pH values was greatest in those cultures with a low clay content. The agreement between the observed and calculated values after the first crop was reasonably close, except for the calcium-barium and calcium-methylene blue series. There was probably some absorption of these two supplementary ions by the plants, which was not considered in the calculations. The observed reaction following the second crop of group A cultures was considerably lower than the calculated values. Another factor tending to lower the pH of the clay, especially in the case following the second crop on account of the time factor, is the probable absorption and assimilation of bases from the clay by the micro-organisms present, which would also increase the degree of acidity.

Discussion

The data obtained in this investigation point out the important role played by calcium in growth and nitrogen-fixing power of the soybean plant. The growth of the plant and especially its ability to fix atmospheric nitrogen are increased as the amount of calcium absorbed by the plant increases—other growth factors remaining constant. These results indicate that the two soil conditions which largely control the amount of calcium absorbed from the soil by the plant are, first, the actual quantity of calcium present in available form, and second, the degree of saturation of the clay adsorptive complex by this element. As the total amount available becomes greater at a constant degree of saturation, the rate of absorption by the plant becomes greater. Under the conditions of this investigation, an increase in the available calcium from a value of 0.05 M.E. per plant to six times that value was accompanied by an increase of over 250 per cent in the amount of calcium in the plants. The better growth and nodulation was directly related to this increase in the calcium absorption by the plants. On the other hand, if the total available supply remains constant and the degree of saturation of the colloidal complex by calcium is increased, there is an accompanied stimulation in calcium absorption and other general plant activities. For the particular soil colloid used in this study, a constant level of exchangeable calcium at 97 per cent saturation for this nutrient element was approximately twice as effective in nodule production as it was at 40 per cent. The total amount of calcium taken up by the crop was more than doubled.

It is suggested by the data obtained that an important condition associated with the observed influence of the degree of calcium saturation of the clay, is the nature of the supplementary cation occupying the balance of the adsorptive complex. If this ion is more readily exchangeable, the degree of calcium saturation will have an influence upon the ability of the plant to absorb significant amounts of calcium, because in the process of excreting hydrogen ions from its roots in order to replace this nutrient from the colloidal complex, the plant will find it necessary to absorb other ions to the partial exculsion of calcium. As the proportion of this supplementary ion is increased, the ability of the plant to secure calcium is decreased. The results show that this process is closely duplicated regardless of whether hydrogen, magnesium, barium or potassium represent the supplementary ion. This suggestion assigns to the hydrogen ion representing moderate to low degrees of acidity, the same influence as that shown by the common nutritive cations in the calcium absorption by plants, and explains the detrimental effect of soil acidity as being due to the decreased absorption of nutritive cations, of which calcium is the most important. A neutral soil having a high proportion of potassium or magnesium should thus behave in a manner similar to that of an acid soil as far as the calcium nutrition of plants are concerned.

If the supplementary ion on the adsorptive complex is very strongly adsorbed and not readily exchangeable, the degree of calcium saturation will have less or possibly no influence upon the amount of calcium or even other readily exchangeable cations, taken by the plants. This gives significant importance to the adsorptive energy of a particular cation as well as the amount present, in controlling the amount available for the plant.

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