APRIL, 1944 RESEARCH BULLETIN 381

UNIVERSITY OF MISSOURI COLLEGE OF AGRICULTURE
AGRICULTURAL EXPERIMENT STATION
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Nitrogen Fixation, Composition and Growth of Soybeans in Relation to Variable Amounts of Potassium and Calcium

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(Publication Authorized April 6, 1944)

COLUMBIA, MISSOURI

SUMMARY AND CONCLUSIONS

A study was made of the influence of variable supplies of exchangeable potassium and calcium on nitrogen fixation and chemical composition of soybeans. Clay cultures, prepared by titrating electrodialyzed colloidal clay with the desired amounts of the nutrient ions, were used. The data obtained warrant the following conclusions:

1. Plant growth and the fixation of nitrogen were increased by additions of both potassium and calcium. Higher levels of calcium stimulated nitrogen fixation to a greater extent than did increments of potassium, which functioned chiefly in the production of carbohydrates.
2. The influence of calcium on growth and nitrogen fixation was more pronounced at low than at high potassium levels.
3. Additions of calcium increased while those of potassium lessened the activity of the plant in utilizing magnesium.
4. A low ratio of potassium to calcium was necessary for maximum nitrogen fixation.
5. Higher nitrogen levels in the plants were closely related to increased potassium intake.
6. In comparison to the non-nodulated plants, the inoculated soybeans were characterized by higher potassium as well as higher calcium and nitrogen contents.
7. The presence of active legume bacteria on the roots of the plants influenced the mineral composition of the crop.
8. The ratios of carbohydrate carbon to nitrogen were significantly lower in the nodulated plants than in those not nodulated.
9. Successive cropping reduced each nutrient ion to approximately the same low level in all cultures.
10. Potassium and phosphorus were absorbed or lost by the plants depending upon the fertility level of the media, but there was no indication of calcium or magnesium movement from the plants back to the soil.

Acknowledgment

The authors express sincere appreciation to Dr. G. N. Hoffer and the American Potash Institute through whose stimulative interest and financial aid the study was made possible.

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INTRODUCTION

That potassium is absolutely essential for plant growth is well recognized. Although its exact role is not known, it is fairly well established that potassium is necessary in the formation of carbohydrates, and possibly in the synthesis of proteins. The high potassium content of certain species of plants was recognized long ago by the early use of wood ashes as a potash fertilizer. The large, but variable, amounts of potassium contained in plants are in decided contrast to the much lesser potassium contents of animal tissues. The value of manure is partially due to the potassium excreted by the animals, whose metabolic processes are unable to utilize the large amount of potassium contained in the feed.

Any farming system which utilizes manure and crop residues does much to maintain a satisfactory level of potassium in the soil. The production of market crops, usually accompanied by the wasting of crop residues and more recently the limited plowing as a means of erosion control, have led in many cases to shortages of soil potassium for crops. As the available supply of this nutrient element declines, symptoms of an unbalanced plant nutrition become evident, particularly when lime and phosphate are applied.

The need for calcium in the nutrition of higher plants has been definitely established. As in the case of potassium, the amount of calcium in the plant varies greatly with the species and with the environmental conditions. Among other things, calcium is unquestionably identified with nodule formation and nitrogen fixation.

Inasmuch as legumes are grown chiefly for their ability to fix atmospheric nitrogen and to produce high quality proteins, wherein potassium and calcium play such significant roles, further carefully controlled studies are needed for a full understanding of the interrelated influence of these two nutrient cations.

Since the colloidal clay technique used so successfully in previous studies of nitrogen fixation permits wide variation in several of the nutrient elements, it was used in this study of the influence on plant growth and composition by variable supplies of exchangeable calcium and potassium on the clay when those of other nutrients were constant.

HISTORICAL

Potassium has long been considered one of the essential plant nutrients. Numerous field trials have shown that potash fertilizers are necessary on many soils. However, potassium has been applied chiefly to non-legumes, while lime and phosphorus are usually recommended for legumes.

The ability of the plant to absorb large amounts of potassium has been shown by many studies. Among others, Hoagland and Martin (20)* and Loehwing (26) found that the potassium content of the plant reflects the capacity of the soil to supply potassium. The growths of plants are closely associated with their consumption of potassium.

The specific role of potassium in plant nutrition has remained somewhat obscure, although it has been the subject of numerous investigations. From the behavior of oats plants, Dickson (12) concluded that potassium influences meristematic activity. The high degree of mobility of potassium and its more intense absorption during early stages of growth have been demonstrated (22). That increments of potassium bring about increased nitrogen fixation in soybeans has been shown by Ferguson (14). Experiments designed to study the effect of potassium on carbohydrate metabolism have lead to somewhat contradictory conclusions. Many investigators (10, 25, 32, 36) are of the opinion that both the formation and translocation of carbohydrates require potassium. The results by Nightingale and his associates (30) caused them to conclude that although potassium is directly or indirectly essential for carbon dioxide assimilation, the translocation of sugars and starch occurs in plants low in potassium. In their work with cowpeas, Janssen and Bartholomew (22) found a close relationship between the concentration of potassium and the total weight of starch and sugars in the plants.

Loew (27) assigned to potassium an essential function in the synthesis of proteins, a role suggested earlier by Stocklasa (33). Loehwing (26) reported that a high ratio of potassium to calcium in plants was associated with a smaller amount of nitrate nitrogen and more organic nitrogen. He concluded that the potassium is an essential factor in protein formation. Similar views were held by Janssen and Bartholomew (22), and Wall (35).

Several workers have reported the beneficial effects of calcium on the growth and nodulation of legumes. The ability of the plant to fix nitrogen is increased as the amount of calcium absorbed by the plant increases (1). Albrecht and Davis (4) concluded that the presence of calcium within the plant is necessary for nitrogen fixation. Horner (21) showed that the amount of calcium taken by the plant depends upon the degree of saturation of the clay with calcium as well as on the level of available calcium in the medium.

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*See list of references cited, beginning on page 35.

A number of writers have suggested the apparent interrelationships which appear to exist between the various nutrient ions. Graham discussed the relative absorption of calcium in relation to magnesium and the significance of the latter in nitrogen fixation by soybeans (17). Evidence of a potassium-calcium relationship has been reported frequently. Fonder (15) found that a physiological balance appears to exist in alfalfa plants between calcium and potassium. A greater calcium content was accompanied by a decrease in potassium. Albrecht (2) suggested that the absorption of larger amounts of potassium by plants in relation to the quantity of calcium may reduce nitrogen fixation in proportion to growth. Potassium may replace calcium to the extent that the widened potassium to calcium ratio reduces the nitrogen-fixing ability of the plant. Similar conclusions have been reached by Hoagland and Martin (20) and by Loehwing (26).

Working with colloidal clay cultures, Ferguson (14) reported an increased consumption of calcium with increments of potassium. Most studies in this connection have utilized aqueous or sand cultures. Needless to say, the conditions existing in colloidal clay cultures should more nearly approximate those of ordinary soils. The relative proportion of nutrient ions absorbed by plant roots may depend largely upon the type of culture in which the roots are functioning. Root absorption from the ionic atmosphere of colloidal particles by exchange (23) may be expected to differ considerably from root absorption from non-colloidal systems. Certainly the energy by which ions are adsorbed by the colloidal soil particles, as well as their relative amounts in the media, should be a factor in regulating their entrance into plants.

The importance of calcium in the fixation of nitrogen by plants has been emphasized. The role of potassium in carbohydrate formation has been rather clearly demonstrated, but the influence of potassium on nitrogen fixation and nitrogen metabolism in legumes as interrelated with those by calcium is still obscure. Our knowledge of the relative consumption of potassium and calcium and their comparative effects on nitrogen fixation and the composition of nodulated legumes is particularly incomplete. It is usually assumed that legumes utilize larger amounts of calcium and lesser amounts of potassium than non-legumes. Is it not possible that the presence of symbiotic bacteria in the roots of legumes may have some influence on the absorption and utilization of these and other nutrient ions? It was in the hope of obtaining additional information on these points that this study was undertaken.

PLAN AND METHODS

A better understanding of the properties and behavior of colloidal clay has made possible the use of this fraction of the soil in the preparation of cultural media (23, 28). Furthermore, the success from the use of such media has been demonstrated (5, 7, 14, 17, 21).

Preparation of Colloidal Clay.—The colloidal clay used in this study was prepared in the manner described by Bradfield (8). A 5 per cent suspension of the electrodialyzed clay had a pH of 3.7 as determined with a glass electrode potentiometer. The acidic properties of the clay are shown by the curve of Fig. 1. The colloidal clay possessed an exchange capacity of 66 milligram equivalents (M. E.) per one hundred grams of the clay.

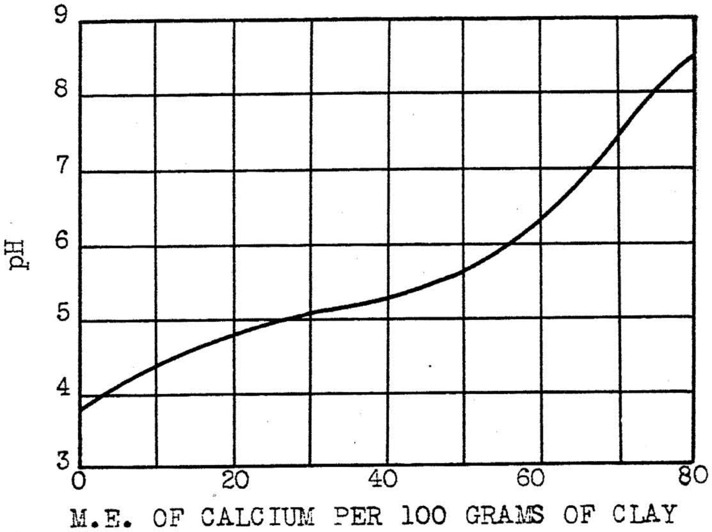

Fig. 1.—Potentiometric titration curve of hydrogen clay by calcium hydroxide.

Preparation of Cultures.—The method of preparing the cultural media has been given, among others, by Horner (21), and Ferguson (14). Two sets of soybeans were each supplied three constant amounts of potassium and each potassium level combined with two different levels of calcium. The nutrient ions, as given in Table 1, were titrated on to the colloidal clay so as to supply them in exchangeable forms. Sufficient barium was added as a supplementary ion to each culture to maintain a constant degree of base saturation of the clay. This clay was then mixed with sufficient acid-washed quartz sand to insure desirable physical conditions for plant growth.

Two groups of soybeans, designated as Series A and Series B, were grown. Series B consisted of the modulated soybeans and Series A was grown without bacterial infection. Soybeans of the Virginia variety were used. Each treatment was grown in duplicate for a period of five weeks. The two crops were grown in the greenhouse during May and early June of succeeding years. At the end of the growth period the tops and roots of the plants were harvested separately, dried, weighed, and then were finely ground and mixed together.

TABLE I.- IONS ADDED TO CLAY CULTURES BY TITRATION

Series A
(Used for three successive crops)

Culture No.	Ions Added (Milligram Equivalents)				
	K	Ca	Mg	P	Ba
1	5	10	10	7.5	25
2	10	10	10	7.5	20
3	15	10	10	7.5	15
4	5	20	10	7.5	15
5	10	20	10	7.5	10
6	15	20	10	7.5	5

Series B
(Used for a single crop)

1	5	10	10	7.5	20
2	10	10	10	7.5	15
3	15	10	10	7.5	10
4	5	20	10	7.5	10
5	10	20	10	7.5	5
6	15	20	10	7.5	0

Analytical Methods.—Samples of the plant material were digested by heating with a mixture of nitric and perchloric acids (16). The barium, calcium, magnesium, potassium, and phosphorus were determined in aliquots of the hypdrochloric acid solution of the ash using accepted methods (18, 24, 31).* The ash residue was purified (31) and reported as silicon. The nitrogen determinations were made by the modified Kjeldahl method (29). The analysis of the fractions—total sugars, and starch and hemicellulose combined—were made according to a modification of the method of Shaffer and Somogyi (19). The residues from the carbohydrate determination were used for the estimation of cellulose and lignin by the procedure described by Crampton (11). The analytical data represent the analysis in duplicate of the combined tops and roots of fifty plants.

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*Credit is due Dr. V. R. Ells for the spectrographic determination of magnesium and potassium in a portion of the plant material.

EXPERIMENTAL RESULTS

Legume Behavior Crop One, Series B

Growth of Soybeans.—The rate of maturation of the soybean plants was progressively greater as increasing amounts of potassium were supplied. At the time of harvest, the cotyledons of the plants to which 15 M. E. of potassium were supplied had either fallen or were completely yellow. In cultures supplied with 5 M. E. of adsorbed potassium, the cotyledons showed little evidence of translocation. The plants supplied with 15 M. E. of potassium had slender, weak stems. The calcium level seemed to exert little influence on the strength of the stems. The leaves of the plants growing in cultures treated with 5 M. E. of potassium showed distinct symptoms of potassium deficiency, but the plants of cultures supplied with 15 M. E. of potassium showed only slight symptoms of potassium shortage. The plants of the cultures treated with 10 M. E. of potassium were intermediate in appearance between those of the low and the high potassium cultures.

The growth weights obtained in the plants of this group were approximately proportional to the amounts of potassium supplied, whether at the low or the high calcium level. The cultures supplied with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium produced 9.907, 11.402, and 14.267 grams of oven-dried plant material, according to the data for weights in Table 2. The cultures to which the same increments of potassium were added but combined with 20 M. E. of calcium produced 13.200, 13.945, and 15.255 grams of plant material respectively.

TABLE 2.- GROWTH OF SOYBEANS IN RELATION TO VARIABLE AMOUNTS OF POTASSIUM AND CALCIUM

(Data for 50 plants. Crop 1, Series B)

Culture No.	Treatments M.E. Potassium	 M.E. Calcium	Weight of 50 plants Tops (Gms.)	 Roots (Gms.)	 Total (Gms.)	Ratio Tops/Roots
1	5	10	7.655	2.302	9.907	3.32
2	10	10	9.140	2.262	11.402	4.04
3	15	10	11.170	3.097	14.267	3.61
4	5	20	10.235	2.965	13.200	3.45
5	10	20	10.785	3.160	13.945	3.41
6	15	20	11.923	3.332	15.255	3.58

Increasing the supply of potassium at the lower calcium level brought about a more rapid increase in plant weight than the same increase in the potassium supply at the higher calcium level, as shown in Fig. 2. These results point to the influence of potassium in stimulating vegetative growth when the calcium supply is limited.

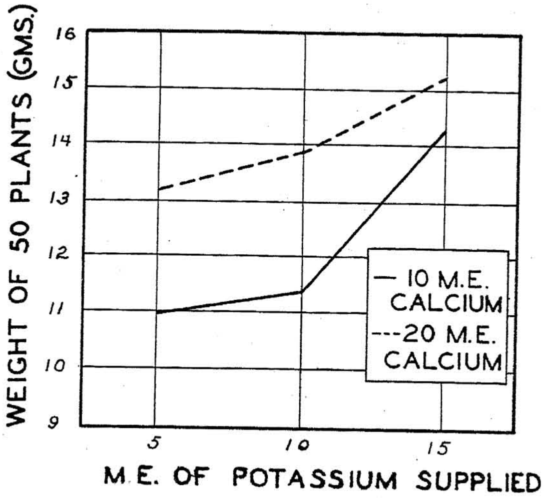

Fig. 2.—Growth of soybeans as influenced by variable amounts of potassium and calcium. (Crop 1, Series B).

At each amount of potassium, a higher yield of plant material was obtained at the higher calcium level, as indicated by the graphic presentation of the data in Fig. 2. The difference between the weights of oven-dried plant material produced at the two calcium levels was greatest when the amount of potassium supplied was 5 M. E., and least when it was 15 M. E. Thus calcium exerted a greater influence on growth when the available supply of potassium was low. Not only did greater total plant growth accompany the larger calcium supply, but there was a corresponding increase in root weight as well as top weight.

Nitrogen Fixation.—Both the potassium and calcium influenced the nitrogen fixation of soybeans grown in colloidal clay-sand cultures and supplied with variable levels of these nutrient cations.

The concentration of nitrogen in the plant material declined as the potassium supply increased. The cultures supplied with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained 3.99, 3.30, and 3.24 per cent nitrogen respectively. Those treated with the same amounts of potassium but with 20 M. E. of calcium contained 4.00, 3.43, and 3.04 per cent nitrogen. The data are given in Table 3. The decrease in the concentration of nitrogen in the plant tissue was affected only slightly by the calcium supplied. The trend was the same at the low and at the high calcium levels. The nitrogen in the plant material expressed as percentage of dry weight was a direct reciprocal of vegetative growth. Since a greater potassium supply brought about increased growth, the amount of nitrogen per unit weight of plant tissue was reduced although the total nitrogen in fifty plants increased with the potassium supply.

TABLE 3.- NITROGEN FIXATION IN SOYBEANS IN RELATION TO VARIABLE AMOUNTS OF POTASSIUM AND CALCIUM

(Data for 50 plants. Crop 1, Series B)

Culture No.	Treatments M.E. Potassium	 M.E. Calcium	Number of Nodules per 50 plants	Nitrogen* Per Cent	 Total Mgms.	 Fixed Mgms.
1	5	10	151	3.99	394.7	117.7
2	10	10	217	3.30	376.4	99.4
3	15	10	347	3.24	462.4	185.4
4	5	20	273	4.00	519.9	242.9
5	10	20	318	3.43	479.7	202.7
6	15	20	438	3.04	463.4	186.4

*Fifty seeds had 277 mgms. nitrogen.

The cultures treated with 20 M. E. of calcium produced a greater yield and a greater total amount of nitrogen in the crop, but the concentration of nitrogen in the plants declined with increasing potassium with the low value of this series where a high calcium supply was associated with the highest level of potassium. This was not quite as low as the highest in the series with 10 M. E. of calcium.

Nitrogen fixation at the low calcium level increased from the lowest to the highest level of potassium, though as shown in Table 3, the amount of nitrogen in the culture supplied with 10 M. E. of potassium was less than that in the other two. When 20 M. E. of calcium were supplied, the nitrogen fixation and the total nitrogen declined as the potassium supply increased. Cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained respectively 394.7, 376.4, and 462.4 mgms. of nitrogen in fifty plants. The plants to which 20 M. E. of calcium were available at the same potassium levels contained 519.9, 479.7, and 463.4 mgms. of total nitrogen.

The marked beneficial effect of a greater calcium supply on nitrogen fixation is shown by the graphic presentation of the data in Fig. 3. This influence was particularly significant at low potassium levels where the ratio of the calcium to the potassium supplied was wide. At the high potassium level there was little difference between the amount of nitrogen fixed in cultures supplied 10 M. E. and 20 M. E. of adsorbed calcium. The fact that the number of nodules on the cultures increased with additions either of calcium or potassium indicates the favorable effect of each of these nutrient cations on bacterial infection, although the calcium supply influenced the efficiency of the microorganisms in nitrogen fixation the more significantly.

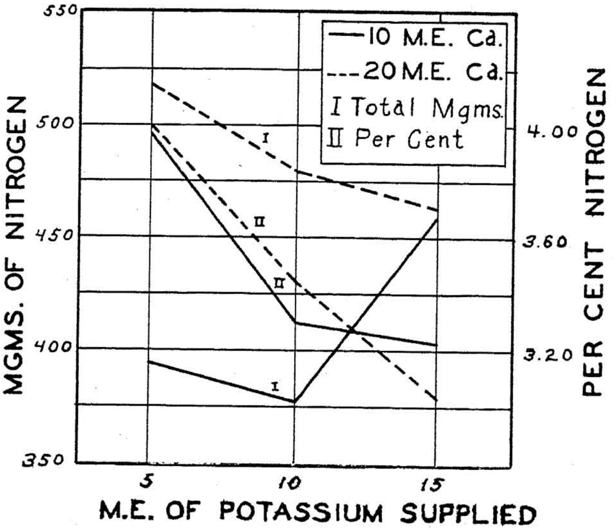

Fig. 3.—Nitrogen content of soybeans as influenced by variable amounts of potassium and calcium. (Crop 1, Series B).

Carbohydrate Contents.—The concentration of total sugars in the plant materials decreased as the supply of potassium increased. This is shown in the data assembled in Table 4. In the cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium, the plant tissue contained 1.80, 1.60, and 1.34 per cent total sugars respectively. The concentrations in the cultures supplied with the same levels of potassium along with 20 M. E. of calcium were 1.42, 1.41, and 0.90 per cent. Again because of increased growth, the total amount of sugars found in fifty plants increased as the supply of potassium increased, with the exception of the culture treated with 15 M. E. of potassium and 20 M. E. of calcium.

A greater calcium supply resulted in a slight decrease in the concentration of total sugars; however, there was no consistent difference in the total amounts of sugars in the plants at the two calcium levels.

Although there was little difference due to treatment in the fraction composed of starch and hemicellulose, the total lignin and cellulose in the plant materials increased with increments of potassium at both calcium levels.

In general, the ratio of the available carbohydrate carbon to nitrogen in the plant tissue increased as the supply of potassium increased, as shown in Table 4. It is particularly interesting that the narrowest ratio of carbon to nitrogen was found in the culture in which the narrowest ratio of potassium to calcium was supplied. That the increments of potassium increase the nitrogen fixation has been shown in Table 3, but the data of Table 4 indicate that increased amounts of exchangeable potassium influence more markedly the production of carbohydrates in the plants. The level of calcium supplied to the plants had no significant influence on the ratio of the carbon to the nitrogen in the plant material. The relationship is shown graphically in Fig. 4.

TABLE 4.- CARBOHYDRATE CONTENTS OF PLANT MATERIAL IN RELATION TO VARIABLE AMOUNTS OF POTASSIUM AND CALCIUM

(Data for 50 plants. Crop 1, Series B)

Culture No.	Total sugars		Starch + Hemicellulose		Cellulose		Lignin		Ratio C*/N	Ratio K/Ca Supplied
	Per Cent	Total Mgms.	Per Cent	Total Mgms.	Per Cent	Total Mgms.	Per Cent	Total Mgms.		
1	1.80	178	17.23	1714	20.57	2039	8.95	887	5.8	1
2	1.60	183	13.57	1550	22.89	2607	10.24	1166	7.8	2
3	1.34	191	13.08	1869	21.40	3052	9.43	1345	6.8	3
4	1.42	189	15.30	2027	24.14	3187	8.22	1123	5.6	0.5
5	1.41	195	12.27	1713	23.43	3068	10.16	1439	6.4	1
6	0.90	137	15.01	2286	22.04	3362	10.46	1610	7.8	1.5

*Carbohydrate carbon only was used in calculating this ratio.

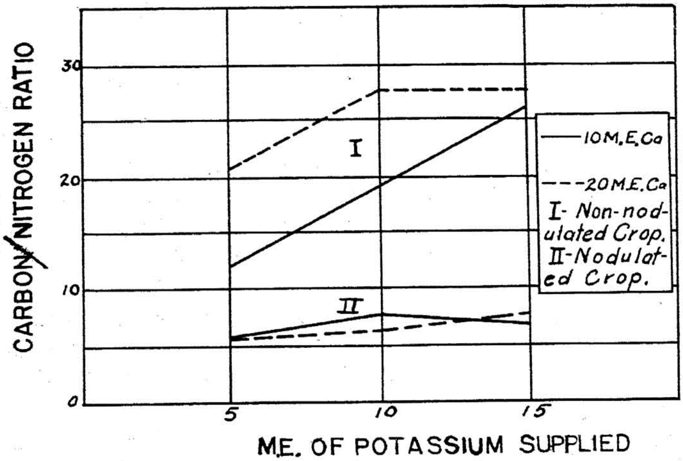

Fig. 4.—Ratios of carbohydrate carbon to nitrogen in soybeans as influenced by variable amounts of potassium and calcium and by nitrogen fixation.

Potassium Contents.—The concentration of potassium in the plant materials showed a direct relation to the amount of potassium supplied. The cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained respectively 2.85, 3.87, and 4.34 per cent of potassium, as given in Table 5. Cultures offered the same amounts of adsorbed potassium but supplied with 20 M. E. of calcium contained 2.13, 3.30, and 3.96 per cent of potassium. The lower concentration of potassium at the higher calcium level may be explained chiefly by the increased growth induced by the additional calcium.

TABLE 5.- COMPOSITION OF SOYBEANS AS INFLUENCED BY VARIABLE AMOUNTS OF POTASSIUM AND CALCIUM

(Data for 50 plants. Crop 1, Series B)

	Treatments		Potassium		Calcium		Magnesium		
Culture No.	M.E. Potassium	M.E. Calcium	Per Cent	Total Mgms.	Per Cent	Total Mgms.	Per Cent	Total Mgms.	Ratio K/Ca Absorbed by the Plants
1	5	10	2.85	282.4	0.40	39.1	0.588	58.2	7.2
2	10	10	3.87	442.1	0.53	47.0	0.455	51.9	9.4
3	15	10	4.34	620.0	0.38	54.6	0.356	50.9	11.3
4	5	20	2.13	280.9	0.70	91.9	0.668	88.3	3.1
5	10	20	3.30	460.2	0.70	98.3	0.463	64.8	4.7
6	15	20	3.96	600.6	0.67	101.5	0.379	57.8	5.9

The total quantity of potassium in the plant tissue was primarily a matter of the potassium supply offered by the soil. The cultures supplied with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained respectively 282.4, 442.1, and 620.0 mgms. of potassium. The plants of cultures given the same potassium treatments but supplied with 20 M. E. of calcium contained 280.9, 460.2, and 600.6 mgms. of potassium. That the potassium content is almost a linear function of the supply is evident from the graphic presentation of the data in Fig. 5. The potassium content of the plants was very slightly lower at the higher calcium level.

The portion of the available potassium taken by the plants of each culture increased somewhat as higher levels of potassium were offered, as shown by the data of Table 6. In all cultures, however, the plants took up a rather large percentage of the potassium available. Cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium utilized 76.1, 78.2, and 81.5 per cent of the potassium supplied. The plants consumed 75.8, 81.4, and 79.0 per cent of the available potassium in cultures supplied with the same amounts of potassium but with 20 M. E. of calcium. Although the plants which were offered 5 M. E. of potassium utilized this nutrient element nearly as efficiently as the plants supplied with higher levels, the appearance of the plants indicated pronounced symptoms of potassium deficiency.

TABLE 6.- CONSUMPTION OF POTASSIUM, CALCIUM, AND MAGNESIUM IN RELATION TO THE TOTAL AMOUNTS SUPPLIED

(Data for 50 plants. Crop 1, Series B)

Culture	Potassium			Calcium			Magnesium		
	Supplied	Taken		Supplied	Taken		Supplied	Taken	
No.	Mgms.	Mgms.	Per Cent	Mgms.	Mgms.	Per Cent	Mgms.	Mgms.	Per Cent
1	371.5	282.4	76.1	209.9	39.1	18.6	132.1	58.2	44.1
2	566	442.1	78.2	209.9	47.0	22.4	132.1	51.9	39.3
3	761.5	620.0	81.5	209.9	54.6	26.1	132.1	50.9	38.5
4	371.5	280.9	75.8	409.9	91.9	22.4	132.1	88.3	66.8
5	566	460.2	81.4	409.9	98.3	24.0	132.1	64.8	49.1
6	761.5	600.6	79.0	409.9	101.5	24.8	132.1	57.8	43.8

*Amounts supplied include that by titration and in seeds. Fifty seeds contained 176 mgms. Potassium, 9.9 mgms. Calcium, and 8.9 mgms. Magnesium.

There was little difference between the efficiency of potassium consumption because of the difference in the calcium levels, according to the graph in Fig. 5.

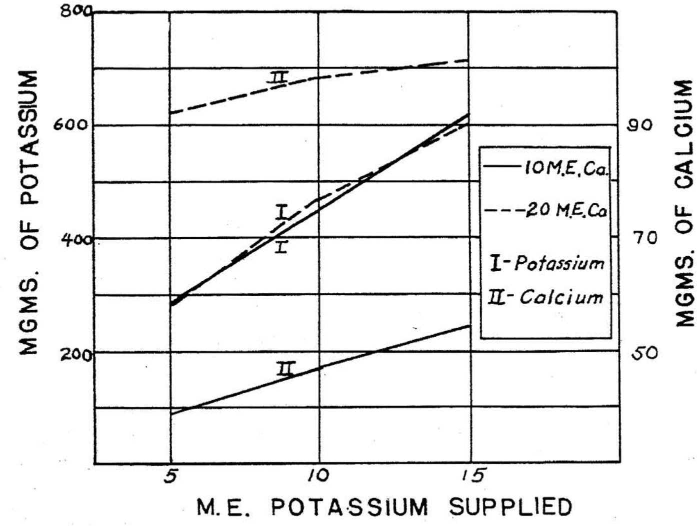

Fig. 5.—Potassium and calcium contents of soybean plants as influenced by variable amounts of potassium and calcium. (Crop 1, Series B).

Calcium Contents.—The concentrations of calcium in the plant tissue, according to the data of Table 5, were roughly constant at each level of calcium offered. In the cultures supplied with 20 M. E. of calcium, however, the concentrations were considerably higher than in those given 10 M. E. of calcium. The concentrations declined somewhat at higher levels of potassium even when the calcium supply was doubled.

The total amounts of calcium taken by the plants, at both calcium levels, increased as larger quantities of potassium were available, as shown by the data of Table 5. The cultures supplied with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained 39.1, 47.0, and 54.6 mgms. of calcium respectively. Culture given the same potassium treatments but supplied with 20 M. E. of calcium contained respectively 91.9, 98.3, and 101.5 mgms. of calcium. The total calcium contained in fifty plants was increased by additions of both potassium and calcium, as shown by the graph in Fig. 5. However, a higher calcium supply resulted in a much greater increase in the calcium content.

The total calcium in the plant tissue represents 18.6, 22.4, and 26.1 per cent of the constant supply of 209.9 mgms. of calcium offered in cultures 1, 2, and 3; and 22.4, 24.0, and 24.8 per cent of the 409.9 mgms. offered in cultures 4, 5, and 6, as shown in Table 6. It is interesting that the increased efficiency of calcium utilization by the plants was associated with increased root weight occasioned by higher nutrient levels as increments of potassium were available.

Phosphorus Contents.—In general, the concentrations of phosphorus in the plant materials declined as increments of potassium were offered. This is shown in Table 7. The cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained respectively 0.454, 0.418, and 0.378 per cent of phosphorus. With the same levels of potassium but coupled with 20 M. E. of calcium, the plants contained 0.383, 0.323, and 0.330 per cent of phosphorus. An increased calcium supply resulted in a decrease in the concentration of phosphorus. The decline in phosphorus concentration, which was occasioned by additions of both calcium and potassium, can be attributed to the increased yields of plant material as a result

TABLE 7.- PLANT CONTENTS OF PHOSPHORUS, SILICON, AND BARIUM IN RELATION TO VARIABLE POTASSIUM AND CALCIUM

(Data for 50 plants. Crop 1, Series B)

Culture No.	Treatments		Phosphorus		Silicon		Barium	
	Potassium M. E.	Calcium M. E.	Per Cent	Total Mgms.	Per Cent	Total Mgms.	Per Cent	Total Mgms.
1	5	10	0.454	44.4	2.54	251.2	1.52	151.4
2	10	10	0.418	47.8	2.15	246.0	0.65	74.4
3	15	10	0.378	53.9	1.46	208.2	0.28	39.4
4	5	20	0.383	50.5	1.60	211.0	0.36	47.6
5	10	20	0.323	45.9	1.08	151.1	0.22	30.2
6	15	20	0.330	50.4	0.81	124.5	0.00	0.0

of higher fertility levels. Although increments of potassium supplied to the plants brought about no significant difference in the concentration of calcium at each calcium level, increasing supplies of potassium were associated with decreasing concentrations of phosphorus.

Increments of potassium increased, however, the total phosphorus contents of the plants in the cultures treated with 10 M. E. of calcium. Cultures which offered the same supplies of potassium with 20 M. E. of calcium grew plants which were roughly equal in contents of total phosphorus, and not so widely different from those given 10 M. E. of calcium. Plants supplied with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained respectively 44.4, 47.8, and 53.9 mgms. of phosphorus. Those offered the same amounts of potassium supplied at the higher calcium level contained 50.5, 45.9, and 50.4 mgms. of phosphorus.

That the utilization of the phosphorus offered to the plants in colloidal clay cultures is more efficient as the ratio of the potassium to the calcium in the medium becomes wider is indicated by the data obtained in this work to substantiate those reported by Ferguson (14). In the cultures supplied with 10 M. E. of calcium, the plants used 39.0, 42.0, and 47.4 per cent of the phosphorus offered respectively at levels of 5, 10, and 15 M. E. of potassium. The ratios of potassium to calcium offered were in the order 1, 2, 3. The plants of cultures treated with 20 M. E. of calcium and the same potassium levels presented narrower ratios of potassium to calcium and the per cent of the phosphorus supplied which was utilized by the plants was more nearly constant.

The greater intake of phosphorus from a constant supply with additions of both calcium and potassium again suggests that increased root area is a factor in nutrient absorption by plants.

Magnesium Contents.—The concentrations of magnesium in the plant materials decreased regularly with additions of potassium, as shown by the data of Table 5. The plant tissue from cultures supplied with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained 0.588, 0.455, and 0.356 per cent of magnesium respectively; and that from cultures treated with the same levels of potassium but with 20 M. E. of calcium contained 0.668, 0.463, and 0.379 per cent of magnesium. While more exchangeable potassium decreased magnesium concentration, a higher calcium supply resulted in a greater concentration of magnesium. Magnesium in total amounts decreased regularly with increments of potassium, as is indicated by the data of Table 5. Plant tissue from cultures which offered 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained respectively 58.2, 51.9, and 50.9 mgms. of magnesium. That from treatments with the same levels of potassium combined with 20 M. E. of calcium had 88.3, 64.8, and 57.8 mgms of magnesium.

The magnesium content of the plant material, expressed either as percentage or as total amount in fifty plants, was increased by a greater calcium supply. The data are presented graphically in Fig. 6. The absorption by the plant of the magnesium supplied by the seed and by titration decreased as the amounts of potassium offered increased, but the utilization by the plants of the available magnesium was more efficient at the higher calcium level.

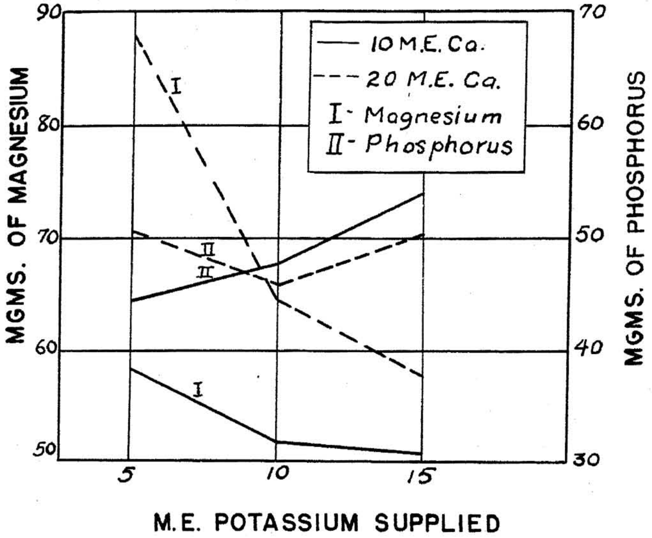

Fig. 6.—Magnesium and phosphorus contents of soybeans as influenced by variable amounts of potassium and calcium. (Crop 1, Series B).

Barium and Silicon Contents.—Inasmuch as barium and silicon are not plant nutrients, they are classed together. Even though barium is a cation, whereas silicon functions as an anion, their behaviors as influenced by varying potassium and calcium treatments were similar. The amounts of each as concentrations and as totals contained in the plant tissue declined as increments of potassium were supplied.

Barium was supplied in amounts reciprocal to those of the variable cations—potassium and calcium. The amount of barium adsorbed on the colloidal complex, therefore, decreased with increments of the potassium and calcium. The barium contents of the plant tissue, expressed either as percentage or as total milligrams per culture, were directly proportional to the amounts supplied. Cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained 1.52, 0.65, and 0.28 per cent of barium respectively. In cultures treated with the same levels of potassium but with 20 M. E. of calcium, the concentrations of barium were found to be 0.36, 0.22, and 0.00 per cent. These data are given in Table 7, and the barium treatments are shown in Table 8.

TABLE 8.- CONSUMPTION OF BARIUM, PHOSPHORUS, AND NITROGEN IN RELATION TO THE TOTAL AMOUNTS SUPPLIED*

(Data for 50 Plants. Crop 1, Series B)

Culture No.	Barium Supplied Mgms.	Barium Taken Mgms.	Barium Taken Per Cent	Phosphorus Supplied Mgms.	Phosphorus Taken Mgms.	Phosphorus Taken Per Cent	Nitrogen Supplied Mgms.	Nitrogen Taken Mgms.	Nitrogen Taken Per Cent **
1	1373.6	151.4	11.0	113.7	44.4	39.0	277	394.7	142.5
2	1030.2	74.4	7.2	113.7	47.8	42.0	277	376.4	135.9
3	686.8	39.4	5.8	113.7	53.9	47.4	277	462.4	166.9
4	686.8	47.6	6.9	113.7	50.5	44.4	277	519.9	187.6
5	343.4	30.2	8.8	113.7	45.9	40.4	277	479.7	173.2
6	0.0	0.0	-	113.7	50.4	44.4	277	463.4	167.3

*Fifty seeds contained 0.00 mgms. Barium, 36.2 mgms. Phosphorus, and 277 mgms. Nitrogen.
**In the case of nitrogen there was an increase over the amount supplied because of nitrogen fixation.

The total barium contained in the plant tissue was likewise found to be directly proportional to the amount adsorbed on the clay. Cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained respectively 151.4, 74.4, and 39.4 mgms. of barium. The cultures supplied with the same amounts of potassium but with 20 M. E. of calcium contained 47.6, 30.2, and 0.0 mgms. of barium respectively.

The silicon content of the plant tissue was very similar to that of the barium. As the amounts of nutrient cations adsorbed on the colloidal complex increased the silicon content of the plants decreased. As increments of potassium were supplied at the low calcium level, the concentration of silicon in the plant tissue descreased from 2.54 to 1.46 per cent; and at the high calcium level, silicon decreased from 1.60 to 0.81 per cent, as shown by the data of Table 7. Cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained a total of 251.2, 246.0, and 208.2 mgms. of silicon. The plant tissue from cultures supplied with the same potassium levels but with 20 M. E. of calcium contained respectively 211.0, 151.1, and 124.5 mgms of silicon.

A higher calcium supply resulted in a significant reduction in the silicon content, expressed either as percentage or as total amount, as the graphic presentation of the data in Fig. 7, shows.

It is interesting to note, as the data show, that the silicon delivery to the plants was most pronounced in the cultures supplied with the lowest amounts of nutrient ions. The absorption of barium, however, appeared to be governed more by the amount of barium adsorbed on the clay than by the direct influence of the nutrient cation level of the medium, but again more barium was on the clay as there was less of the nutrient ions.

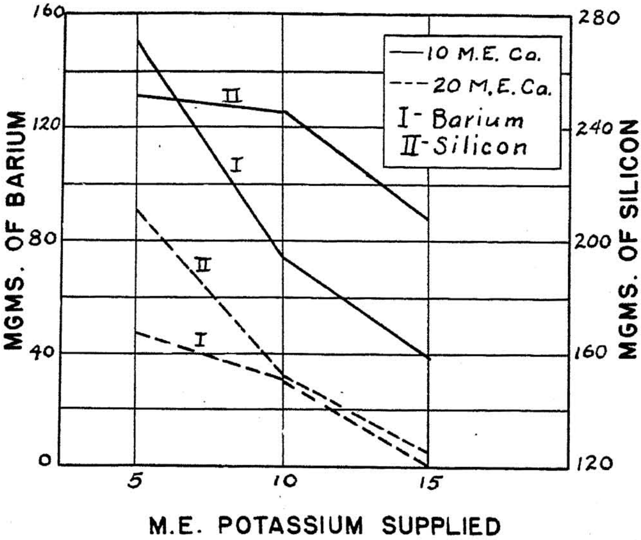

Fig. 7.—Barium and silicon contents of soybeans as influenced by variable amounts of potassium and calcium. (Crop 1, Series B).

Non-Legume Behavior Crop One, Series A

One crop of the soybeans was not nodulated and although a legume taxonomically, it functioned physiologically as a non-legume. In plant performance and behavior this crop served as a means of comparing the other crop as legume with this one of non-leguminous plants.

Growth of Non-nodulated Soybeans.—Although the plants of this series were supplied only the nitrogen contained in the seeds, good growth weights were obtained. The weights of oven-dry plant material increased as increments of potassium were supplied. In the cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium, those weights were 12.865, 19.790, and 19.885 grams respectively. With the same potassium supplies but growing at the higher calcium levels, the dried plant materials weighed 18.955, 22.045, and 22.420 grams. These data are given in Table 9.

Additions of calcium, likewise, brought about increased production of plant material, as shown by the graph of Fig. 8. As in Series B, with leguminous behaviors, so in this Series A with non-leguminous behaviors, the calcium exhibited the greatest influence on growth when associated with the lowest potassium level. Moreover, increasing the supply of potassium at the lower calcium level

TABLE 9.- GROWTH OF SOYBEANS IN RELATION TO VARIABLE AMOUNTS OF POTASSIUM AND CALCIUM

(Data for 50 plants. Crop 1, Series A)

Culture No.	Treatments Potassium M. E.	Treatments Calcium M. E.	Weight of 50 Plants Tops (Gms.)	Weight of 50 Plants Roots (Gms.)	Weight of 50 Plants Total (Gms.)	Ratio Tops/Roots
1	5	10	8.035	4.820	12.855	1.67
2	10	10	14.075	5.715	19.790	2.43
3	15	10	13.815	6.070	19.885	2.28
4	5	20	13.060	5.895	18.955	2.22
5	10	20	16.015	6.030	22.045	2.66
6	15	15*	16.270	6.150	22.420	2.64

Fifty seeds contained 346 mgms. of nitrogen.

*Because the plant material of the culture of Crop 1, Series A initially treated with 15 M.E. of potassium and 20 M.E. of calcium was lost, the plant material from a culture treated with 15 M.E. of potassium and 15 M.E. of calcium was substituted.

resulted in a more rapid increase in the plant weight than the same increments of potassium coupled with the higher calcium level. There was little difference between the ratios of the tops to the roots in the several cultures of this series.

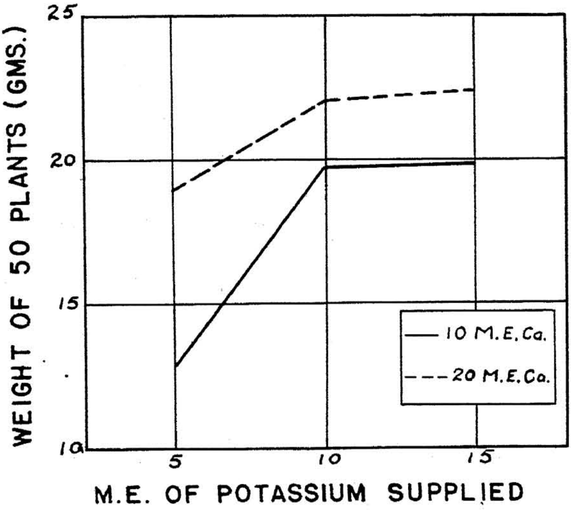

Fig. 8.—Growth of soybeans as influenced by variable amounts of potassium and calcium. (Crop 1, Series A).

At the time of harvest, the maturation of the plants was progressively proportional to the potassium supplied. The cotyledons of the plants treated with 5 M. E. of potassium showed only moderate translocation and the lower leaves were green. All of the plants were erect. On the other hand, both the cotyledons and the lower leaves of plants grown in cultures supplies with 15 M. E. of potassium were quite yellow, showing pronounced translocation of certain constituents, particularly nitrogen, to the upper portions of the plants. The plants of these cultures were slightly lodged, an indication of weak structural material in the stems. Plate I gives a photographic presentation of the appearance. The plants growing in cultures treated with 10 M. E. of potassium were intermediate in appearance.

Plate I.—Growth of soybeans influenced by potassium and calcium. (Crop one, Series A. Increasing potassium from left to right. A represents 10 M. E. and B represents 20 M. E. of calcium.)

The difference in the levels of calcium supplied the plants had little effect on translocation and strength of stems. The leaves of the plants growing in cultures supplied with 5 M. E. of potassium showed distinct symptoms of potassium deficiency.

Nitrogen Content of Non-nodulated Soybeans.—This crop was not inoculated with nitrogen fixing bacteria and nitrogen was not added to the cultures. The nitrogen content of the plant material, expressed as a percentage of dry weight, decreased directly with increased growth. The total nitrogen content, however, was approximately constant, and closely approximated the nitrogen content of the seeds. The pronounced translocation which occurred in the plants supplied with the higher levels of potassium indicated that nitrogen was the factor limiting the growth. That the plants of this series utilized a higher percentage of the available nitrogen is evident from the figures given in Table 15. Other nitrogen features appear in Table 10.

TABLE 10.- NITROGEN CONTENTS OF SOYBEANS IN RELATION TO VARIABLE AMOUNTS OF POTASSIUM AND CALCIUM

(Data for 50 plants. Crop 1, Series A)

	Treatments		Nitrogen			Ratio
Culture No.	Potassium M. E.	Calcium M. E.	Per Cent	Total Mgms.	Ratio C : N	K : Ca Supplied
1	5	10	2.66	341.2	8.5	.5
2	10	10	-	-	-	1.
3	15	10	1.70	347.8	18.6	1.5
4	5	20	2.21	384.5	13.9	.25
5	10	20	1.51	341.2	18.0	.5
6	15	15*	1.50	334.2	18.5	1.

Fifty seeds contained 346 mgms. of nitrogen.

*Because the plant material of the culture of Crop 1, Series A initially treated with 15 M.E. of potassium and 20 M.E. of calcium was lost, the plant material from a culture treated with 15 M.E. of potassium and 15 M.E. of calcium was substituted.

Carbohydrate Contents.—The various carbohydrate fractions of the plant tissue followed closely the increased growth induced by additions of potassium. The rates of carbohydrate synthesis and storage, according to the data of Table 11, were greatly increased by increments of potassium when the nitrogen supply was low. That the total carbohydrate content was considerably higher in the plant material of the non-nodulated crop is evident from a comparison of the data assembled in Table 4 with that of Table 11.

A particularly significant difference occurred in the case of total sugars. As increasing supplies of potassium were offered with 10 M. E. of calcium, the amount of total sugars increased from 529 to 904 mgms. In cultures treated with the same amounts of adsorbed potassium but with the higher calcium level, the amount of total

TABLE 11.- CARBOHYDRATE CONTENT OF PLANT MATERIAL IN RELATION TO VARIABLE AMOUNTS OF POTASSIUM AND CALCIUM

(Data for 50 plants. Crop 1, Series A)

	Total Sugars		Starch + Hemicellulose		Cellulose		Lignin	
Culture No.	Per Cent	Total Mgms.	Per Cent	Total Mgms.	Per Cent	Total Mgms.	Per Cent	Total Mgms.
1	4.12	529	9.90	1270	18.71	2399	11.52	1478
2	-	-	-	-	-	-	-	-
3	4.42	904	18.73	3834	23.19	4744	17.10	3499
4	3.01	524	8.97	1842	27.54	4788	19.10	3325
5	4.83	1073	17.08	3796	25.28	5620	11.71	2604
6	3.81	851	15.62	3508	27.74	5771	10.4	2331

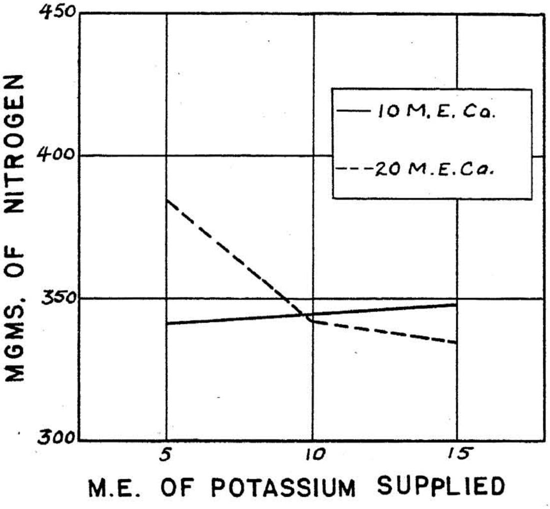

Fig. 9.—Nitrogen content of soybeans as influenced by variable amounts of potassium and calcium. (Crop 1, Series A).

sugars contained in fifty plants increased from 524 to 1073 mgms. In comparison, the content of total sugars in the nodulated crop of Series B varied from a low value of 137 to a high of 195 mgms. This suggests that the greater nitrogen content of the nodulated soybeans brought about a rapid utilization of the simple sugars in protein synthesis. That a greater storage of carbohydrates occurred in the non-nodulated crop during plant growth as a result of the lack of nitrogen is likewise suggested by the data.

The ratio of the carbohydrate carbon to the nitrogen in the plant tissue widened as increased amounts of potassium were available to the plants, as is shown by the calculations assembled in Table 10. At the low calcium level, the ratio increased from 8.5 in the plants supplied with 5 M. E. of potassium to 18.6 in those offered 15 M. E. When a greater amount of calcium was supplied, the ratios increased from 13.9 at the low to 18.5 at the high potassium level.

That there is a significant difference between the ratios of carbohydrate carbon to nitrogen of the plant tissues of nodulated and non-nodulated soybeans is shown by a comparison of the values given in Table 16 and in Fig. 10.

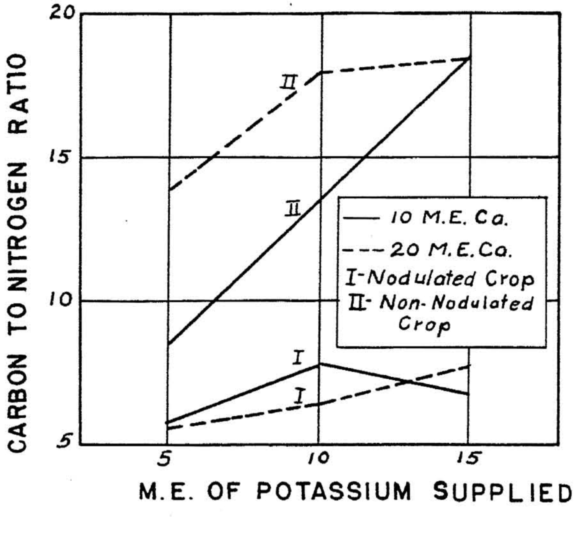

Fig. 10.—Ratios of carbohydrate carbon to nitrogen in soybeans as influenced by nitrogen fixation and variable amounts of potassium and calcium.

Potassium Contents.—The concentrations of potassium in the plant tissues of the non-nodulated soybeans increased as larger amounts of potassium were available. The cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained 1.83, 2.07 and 2.41 per cent respectively of potassium. Those to which the same potassium treatments were supplied at the higher calcium level contained 1.33, 1.80, and 2.10 per cent of potassium. The data are shown in Table 12. At all potassium levels, the concentration of potassium was lowered by a higher calcium supply, but the lower percentage may be explained by the increased growth at the higher calcium level.

TABLE 12.- POTASSIUM, CALCIUM, AND MAGNESIUM CONTENTS OF SOYBEANS AS INFLUENCED BY VARIABLE AMOUNTS OF POTASSIUM AND CALCIUM

(Data for 50 plants. Crop 1, Series A)

Culture No.	Treatments		Potassium		Calcium		Magnesium	
	Potassium M. E.	Calcium M. E.	Per Cent	Total Mgms.	Per Cent	Total Mgms.	Per Cent	Total Mgms.
1	5	10	1.83	234.2	0.43	55.3	0.386	59.4
2	10	10	2.07	408.6	0.29	56.3	0.285	55.6
3	15	10	2.41	479.8	0.26	51.7	0.216	45.8
4	5	20	1.33	251.6	0.60	114.6	0.360	68.0
5	10	20	1.80	398.0	0.51	11.3	0.248	54.8
6	15	15	2.10	470.2	0.39	86.5	0.271	60.5

The total amount of potassium in the plant material was directly proportional to the amount of this element supplied, as is shown by the data of Table 12. The plants to which 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium were available contained respectively 234.2, 408.6, and 479.8 mgms. of potassium. Plants supplied with the same amounts of potassium but with the higher level of calcium contained 251.6, 398.0 and 470.2 mgms. of potassium. The calcium supply had little influence on the absorption of potassium by the plants of the non-nodulated crop as is shown more clearly by the graph in Fig. 11.

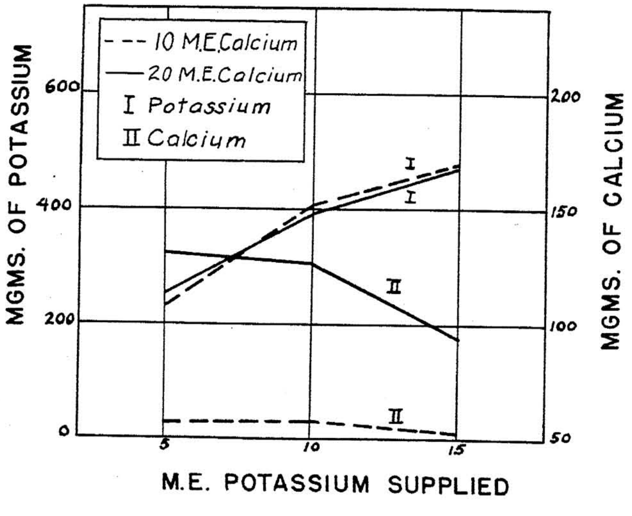

Fig. 11.—Potassium and calcium contents of soybeans as influenced by variable amounts of these nutrient ions. (Crop 1, Series A).

Although the absorption of potassium in the nodulated and non-nodulated crops followed the same general trends, the non-nodulated plants of Series A utilized a lower percentage of the available potassium than did the plants of Series B which were inoculated, as a comparison of the data of Table 6 with that of Table 14 shows. In both crops, the efficiency of potassium absorption by the plants decreased with increments of potassium supplied. A greater calcium supply did not increase the efficiency of potassium utilization.

The ratios of nitrogen to potassium in both the nodulated and non-nodulated crops decreased as increments of potassium were supplied, as shown in Fig. 12. At the low potassium level, the ratios were increased by additions of calcium. In the plants supplied with 15 M. E. of potassium, there was little difference in the ratios of nitrogen to potassium. In general, the increments of potassium decreased the ratios of carbohydrate carbon to potassium in the plant tissues, as the graph of Fig. 13 shows. The larger carbohydrate content of the non-nodulated plants is indicated by their wider ratios of carbon to potassium, as well as by their increased ratios of carbon to nitrogen.

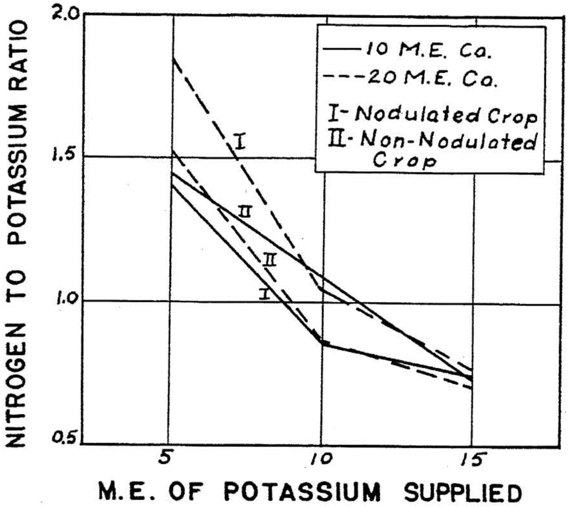

Fig. 12.—Ratios of nitrogen to potassium as influenced by nitrogen fixation and variable amounts of potassium and calcium.

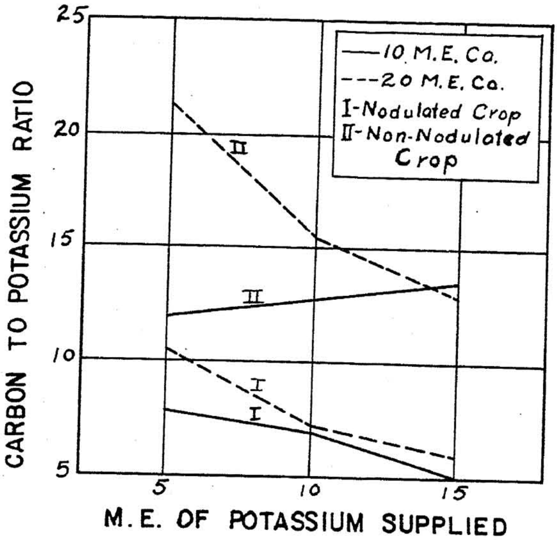

Fig. 13.—Ratios of carbohydrate carbon to potassium as influenced by nitrogen fixation and variable amounts of potassium and calcium.

Calcium and Magnesium Contents.—The calcium contents of the plants in this series were not significantly influenced by variable amounts of potassium. Although the concentration of calcium declined with additions of potassium, the decrease may be attributed to the increased weights of plant material. Cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained a rather constant amount of calcium—namely 55.3, 56.3, and 51.7 mgms. respectively. The cultures supplied with 5 and 10 M. E. of potassium and 20 M. E. of calcium contained respectively 114.6 and 111.3 mgms. of calcium; and culture 6 supplied with 15 M. E. of potassium and 15 M. E. of calcium contained 86.5 mgms. of calcium.

The utilization by the plants of this series of the available calcium was quite constant, ranging from 24.4 to 27.8 per cent. The absorption of calcium by the plants of the nodulated crop was slightly less efficient than that of this crop which did not fix nitrogen.

At both levels of calcium, the concentration of magnesium in the plant tissue decreased as the potassium supply was increased. According to the data of Table 12, the magnesium content expressed as percentage was 0.386, 0.285, and 0.216 per cent respectively in cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium; and 0.360, 0.248, and 0.271 per cent in cultures supplied with the same amounts of potassium but with the higher levels of calcium. The concentration of magnesium was not significantly influenced by the calcium level, a different situation than in soybeans manifesting leguminous behaviors.

The amount of magnesium in fifty plants decreased as increments of potassium were available, as shown by the data of Table 12. The magnesium contents of cultures supplied with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium were respectively 59.4, 55.6, and 45.8 mgms. For cultures treated with the same amounts of potassium but with the higher calcium levels the values were 68.0, 54.8, and 60.5 mgms. As was true in the case of the nodulated crop, calcium brought about an increased total uptake of magnesium.

The efficiency of magnesium absorption decreased as the supply of potassium increased, except in culture 6. The percentages of the available magnesium taken by the plants which fixed nitrogen were approximately the same as those utilized by the non-nodulated crop.

Phosphorus Contents.—The concentrations of phosphorus in this crop were found to be very similar to those in the crop of soybeans which was inoculated. In general, the phosphorus contents as percentages of dry weight decreased with increments of potassium, as is shown in Table 13. The cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained respectively 0.420, 0.343, and 0.297 per cent of phosphorus. The concentrations were respectively 0.324, 0.276, and 0.289 per cent in cultures supplied with the same amounts of potassium at the higher calcium levels. Again, since increased growth resulted from the greater supply of calcium, this nutrient element brought about a decrease in the concentration of phosphorus through increased growth.

TABLE 13.- BARIUM, PHOSPHORUS, AND SILICON CONTENTS OF SOYBEANS IN RELATION TO VARIABLE AMOUNTS OF POTASSIUM AND CALCIUM

(Data for 50 plants. Crop 1, Series A)

Culture No.	Treatments		Barium		Phosphorus		Silicon	
	Potassium M. E.	Calcium M. E.	Per Cent	Total Mgms.	Per Cent	Total Mgms.	Per Cent	Total Mgms.
1	5	10	1.09	140.9	0.420	54.0	2.28	293.2
2	10	10	0.47	96.0	0.343	64.6	1.24	245.8
3	15	10	0.26	51.7	0.297	59.2	1.10	219.6
4	5	20	0.50	95.2	0.324	61.2	1.13	214.1
5	10	20	0.17	37.2	0.276	60.8	0.95	209.4
6	15	15	0.15	32.3	0.289	64.5	0.91	193.9

Cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium contained a total of 54.0, 64.6, and 59.2 mgms. of phosphorus; while those supplied with the same increments of

TABLE 14.- CONSUMPTION OF POTASSIUM, CALCIUM AND MAGNESIUM AS INFLUENCED BY VARIABLE AMOUNTS OF POTASSIUM AND CALCIUM

(Data for 50 plants. Crop 1, Series A)

	Potassium			Calcium			Magnesium		
	Supplied	Taken		Supplied	Taken		Supplied	Taken	
Culture No.	Mgms.	Mgms.	Per Cent	Mgms.	Mgms.	Per Cent	Mgms.	Mgms.	Per Cent
1	363.5	234.2	64.6	212.1	55.3	26.0	132.1	59.4	44.9
2	559	408.6	73.2	212.1	56.3	26.5	132.1	55.6	42.1
3	754.5	479.8	63.7	212.1	51.7	24.4	132.1	45.8	34.8
4	363.5	251.6	69.2	412.1	114.6	27.8	132.1	68.0	51.4
5	559	398.0	71.2	412.1	111.3	27.1	132.1	54.8	41.5
6	754.5	470.2	62.4	312.1	86.5	27.7	132.1	60.5	45.8

Seed contained 168 mgms. Potassium, 12.1 mgms. Calcium, and 8.9 mgms. Magnesium.

TABLE 15.- CONSUMPTION OF BARIUM, PHOSPHORUS, AND NITROGEN IN RELATION TO THE TOTAL AMOUNTS SUPPLIED*

(Data for 50 plants. Crop 1, Series A)

	Barium			Phosphorus			Nitrogen**		
	Supplied	Taken		Supplied	Taken		Supplied	Taken	
Culture No.	Mgms.	Mgms.	Per Cent	Mgms.	Mgms.	Per Cent	Mgms.	Mgms.	Per Cent
1	1717.0	140.9	8.2	113.7	54.0	47.5	346	341.2	98.5
2	1373.6	96.0	6.9	113.7	64.6	56.7	346	-	-
3	1030.2	51.7	5.1	113.7	59.2	52.2	346	347.8	100.2
4	1030.2	95.2	9.2	113.7	61.2	53.8	346	384.5	111.0
5	686.8	37.2	5.4	113.7	60.8	53.6	346	341.2	98.5
6	686.8	32.3	4.7	113.7	64.5	56.7	346	334.2	97.2

*Fifty seeds contained 0.00 mgms. Barium, 36.2 mgms. Phosphorus, and 346 mgms. Nitrogen.
**This crop did not fix nitrogen.

potassium coupled with 20 M. E. of calcium contained 61.2, 60.8, and 64.5 mgms. of phosphorus respectively. From the data of Table 15, it may be said that the total phosphorus consumed by non-nodulated soybeans was increased slightly by increments of both potassium and calcium.

Barium and Silicon Contents.—As in the nodulated crop of soybeans, so the barium content of this crop expressed either as percentage of dry weight or as total amount in fifty plants was found to bear a direct relation to the amount of barium supplied. This is shown in Table 13. The consumption by the plants of the available barium was likewise very similar in the nodulated and non-nodulated crops as a comparison of the date of Tables 8 and 15 shows. From the results obtained, it seems that barium, being a cation, occupies a position in the ionic atmosphere of each colloidal clay particle according to its charge and effective size, and further that its absorption by plant roots is a matter of ordinary physico-chemical behavior.

The silicon contents of the plants declined regularly with increments of both potassium and calcium. The concentrations of silicon in cultures treated with 5, 10, and 15 M. E. of potassium and 10 M. E. of calcium were respectively 2.28, 1.24, and 1.10 per cent. The cultures supplied with the same amounts of potassium but with the higher levels of calcium contained 1.13, 0.95, and 0.91 per cent of silicon. A larger calcium supply brought about a significant decrease in the concentration of silicon particularly at the lower potassium levels. As increments of potassium were offered at the lower calcium level, the plants contained a total of 293.2, 245.8, and 219.6 mgms. of silicon respectively; and at the higher calcium levels there were 214.1, 209.4, and 193.9 mgms. of silicon. As was the case in Series B, the absorption of silicon by the plants depended upon the level of nutrient cations available to the plants rather than upon the base saturation of the adsorbing complex, which was nearly constant in all cultures.

Ratios of Plant Constituents

Calculations of the ratios existing between various plant constituents show some interesting contrasts between the nodulated and the non-nodulated soybeans. The ratios vary according to the increasing potassium combined with each of the calcium levels, as shown by the calculations assembled in Table 16. In most cases, the ratios decrease, in others they increase, as the potassium increases.

TABLE 16.- RATIOS OF PLANT CONSTITUENTS

(Crop 1, Series B (Nodulated)

Culture No.	Treatments K	Ca	Ratios N / Ca	K / Ca	N / K	C / K	C* / N
1	5	10	10.1	7.2	1.40	8.2	5.8
2	10	10	8.0	9.4	0.85	6.6	7.8
3	15	10	8.4	11.3	0.74	5.0	6.8
4	5	20	5.2	3.1	1.85	10.4	5.6
5	10	20	4.9	4.7	1.04	6.7	6.4
6	15	20	4.5	5.9	0.77	6.0	7.8
			Crop 1, Series A (Non-nodulated)				
1	5	10	6.2	4.2	1.45	12.0	8.5
2	10	10	-	-	-	-	-
3	15	10	3.8	5.3	0.73	13.4	18.6
4	5	20	3.3	2.2	1.52	21.3	13.9
5	10	20	3.1	3.6	0.86	15.9	18.0
6	15	15	3.8	5.4	0.71	12.7	18.5

*Carbohydrate carbon.

That protein production per unit of calcium was greater in the nodulated crops is suggested by its higher ratios of nitrogen to calcium. The higher ratios of potassium to calcium in the nodulated soybeans suggest a more liberal absorption of potassium from the soil induced by a higher concentration of nitrogen in the roots, and an adequate calcium supply on the clay. The crops differed only in that the nodulated crops, due to the activity of the legume bacteria, presented an additional supply of nitrogen. Although the colloidal-chemical conditions of the clay of the two sets of media were the same, the more proteinaceous roots of the nodulated cultures were able to take more potassium. The stimulating effect of nitrogen upon the absorption of potassium was pointed out by Breazeale (9), who concluded that the influence of the nitrogen is exerted within the plant tissues and is possibly related in some way with the process of absorption. Additional evidence of the effect of the nitrogen level within the plant tissues upon the intake of potassium is afforded by a comparison of the nitrogen to potassium ratios which are approximately the same at each level of potassium. The greater nitrogen content of the nodulated crop was balanced by an increased absorption of potassium. Although potassium is commonly associated with carbohydrate production, nitrogen fixation was not overshadowed by carbohydrate formation occasioned by the entrance into the plant of additional potassium along with the calcium.

In the nodulated crop, the lower ratios of carbohydrate carbon to nitrogen show that carbohydrate production per unit of potassium taken into the plant is lower with the occurrence of nitrogen fixation than when legume bacteria are absent. When nodulated, the same plant species functions more as a protein former than as a corbohydrate producer, yet consumes a greater amount of potassium. In soybeans that are not fixing nitrogen and where less potassium is absorbed in relation to the calcium, the formation of carbohydrates significantly dominates nitrogen synthesis, as the high ratios of carbon to nitrogen show. The carbon content of the non-nodulated plants is high in relation to the consumption of both potassium and nitrogen.

DISCUSSION

The data obtained in this study point to the importance of both potassium and calcium in the growth and the nitrogen fixation of soybeans. From the fact that the concentration of nitrogen in the plant tissue decreased with increments of potassium at both levels of calcium, it appears that potassium has a greater influence than nitrogen or calcium on carbohydrate formation. The increasing ratios of carbohydrate carbon to nitrogen as additions of potassium were offered leads to the same conclusion.

An available potassium supply may be said to be one of the requirements for protein synthesis, inasmuch as it is rather well established that potassium is essential for the production and translocation of carbohydrates (10, 22, 25), and for the enzymatic reduction of nitrates in the formation of amino acids (13). That higher levels of potassium stimulate carbohydrate production in excess of that required for meristematic activity and protein synthesis is shown by the increasing amounts of the carbohydrate fractions contained in the plant materials. In plants supplied with adequate potassium and abundant nitrogen the carbohydrates failed to accumulate, not because of a lack of these nutrients but probably because carbohydrates were used in large quantities in protein synthesis. The low sugar content of the nodulated crop suggests that such is the case. Nodulated soybeans suggest themselves as better forages because they have the energy value of non-legumes and in addition a higher concentration of protein and minerals.

If a large amount of potassium is available in relation to nitrogen and calcium, then the plant material will be characterized by high carbohydrate and low protein content; which suggests the reason for the "woody" character of plants growing on soils relatively high in potassium. The ecological significance of this relationship has been pointed out by Albrecht (3).

The importance of calcium in nitrogen fixation has been emphasized repeatedly (1, 4, 21). The ability of the plant to fix nitrogen is directly related to increased calcium absorption. The role of calcium appears to be more directly connected with nitrogen fixation as indicated by the higher nitrogen and slightly lower carbohydrate concentrations in the plants grown at the higher calcium level.

Although some calculations presented by Albrecht (6) show that plants apparently secure more calcium than is adsorbed on the surface areas of colloidal clay particles with which the roots come into immediate contact, we may nevertheless reason that greater root surface should result in an increased amount of root-soil contact and, therefore, a larger intake of nutrient ions from the colloidal complex. In this study, increments of potassium brought about increased root weight and greater root development. If we assume that increased root weight is a measure of more extensive root surface, then the larger amount of surface area for contact absorption very probably facilitates the entrance of more calcium. The close agreement between the calculated and actual values of Table 17, which, taking the low treatment as a basis, shows the increased amount of calcium taken by the plants in proportion to the increased root weight for the nodulated crop, indicates that such a supposition is not without some foundation. The presence of an adequate potassium supply in the soil might be an important factor in the ability of the legume plant to take in sufficient calcium for the fixation of nitrogen.

The relative influence of either potassium or calcium appears to depend, at least to some extent, upon the available supply of the other. When the potassium supply was restricted, a higher calcium level greatly increased the growth and nitrogen fixation by the plants. As larger amounts of potassium were available, however, the effect of the greater calcium supply was not so marked, although the influence of a larger calcium supply was still significant. Legumes consume large amounts of potassium but they require so much more calcium that a low ratio of potassium to calcium is necessary for nitrogen fixation, as shown by the greater nitrogen content of the soybeans to which the higher level of calcium was available.

TABLE 17. ACTUAL AND CALCULATED INCREASED CONSUMPTIONS OF CALCIUM IN RELATION TO GREATER ROOT WEIGHT AS INDUCED BY INCREMENTS OF POTASSIUM

Culture No.	Increased Root Weight over Low Treatment (gms.)	Increased Consumption of Calcium by Plants (mgms.)	
		Calculated	Actual
1	–	–	–
2	-0.40	–	–
3	0.795	13.5	15.5
4	–	–	–
5	0.195	7.4	6.0
6	0.367	11.3	9.6

The data obtained in this investigation as well as those reported by Ferguson (14) show a greater production of dry weight by non-nodulated than by nodulated soybeans, although the initial nutrient levels of the cultures were the same in both series. This points out the fallacy in judging legume activity, particularly nitrogen fixation, in terms of tonnage alone. It is of interest, however, that the mineral concentrations in the non-nodulated plants were lower even if the totals were not very different. Apparently the abundant nitrogen in the nodulated crop resulted in an increased utilization of the carbohydrates for protein synthesis so that less vegetative growth occurred. In the plants adequately supplied with potassium and calcium and actively fixing nitrogen, the ratios of the carbohydrate carbon to the nitrogen were significantly lower than in the non-nodulated plants.

The accumulation of nitrates in low potassium plants was first reported by Stocklasa (33), and more recent studies (14, 34) suggest the loss of nitrogen from the plant to the soil under certain conditions. It seems possible that a restricted supply of potassium as well as nitrogen, although adequate for meristematic development, may result in increased growth of plants which are low in protein because of the lack of constituents essential for the synthesis of a large amount of protein; a portion of which becomes the "storage protein". If not utilized in the formation of more complex stable compounds, the nitrogen might conceivably be lost to the soil; particularly during maturation, with the consequent impairment of the nitrogen value of the forage.

That the concentration of the nutrient ions on the colloidal complex is a primary factor in deciding the amounts that move into the plants is indicated by the results obtained in this study. As increments of exchangeable potassium were offered more potassium was absorbed by the plants. The higher level of calcium likewise induced an increased intake of calcium. Since less nutrients on the clay meant more ionic barium on the clay and also more in the plants, it appears that the absorption of barium is regulated more by physico-chemical relations than by physiological factors associated with the roots.

However, the absorption of ions by the plants cannot be related entirely to physico-chemical relationships. The intake of silicon seemed to be limited when an adequate supply of nutrient cations was available; but when low levels of nutrient cations were offered, more silicon moved into the plants from a more or less constant supply. The data show that increased calcium absorption was brought about by increments of potassium, and the presence of a greater nitrogen supply as a result of nitrogen fixation was associated with an increased potassium content of the plant tissue. It was found that additions of calcium enhanced while those of potassium hindered the activity of the plants in utilizing magnesium. These results indicate that the intake of nutrient ions is apparently influenced by both physico-chemical and physiological behaviors, and point to the possibility of numerous interrelationships between ions. As we build up the concept of these interrelationships, might we not in time establish many others not yet recognized or anticipated, but which will aid greatly in the unravelling of the complexities of plant nutrition?

A comparison of some ratios of plant constituents in nodulated and non-nodulated soybeans which were given the same levels of all nutrients except nitrogen shows the decided influence of active legume bacteria upon the mineral consumption by plants. The mere rearranging of the amounts of cations on the soil substrate does not change a legume to a non-legume. In addition to containing a greater amount of calcium and nitrogen, the inoculated legume is characterized by a higher potassium content. Potash deficiencies as well as the lack of lime and phosphorus may be responsible for many legume troubles, as, for example, the failure of medium red clover which is known to have a higher potassium requirement than other legumes.

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