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# Nitrogen Fixation and Soil Fertility Exhaustion by Soybeans Under Different Levels of Potassium

CARL E. FERGUSON AND WM. A. ALBRECHT

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## ABSTRACT

A study was made of the influence of potassium on nitrogen fixation, plant composition, and fertility depletion by soybeans. An electrodialyzed colloidal clay of known composition was used as a carrier of this cation in combination with constant amounts of calcium, magnesium, phosphorus, and in some instances, sulfur. Barium was used to vary reciprocally with potassium, thereby maintaining a constant degree of saturation.

In nodulated cultures nitrogen fixation increased as the available potassium increased, when accompanied by constant levels of the other elements. The ratio of nitrogen to carbohydrate was approximately constant. Plants which were non-nodulated were very low in nitrogen and did not fix nitrogen, but, instead, lost to the soil an average of 23.1 per cent of the initial seed supply. The carbohydrate contents of these plants increased tremendously both in percentage and in total with potassium treatment. Crops grown on soils depleted in fertility were nodulated but failed to fix nitrogen. But they produced increasing amounts of carbohydrates as more potassium was present in the plants. Higher potassium treatments caused a decrease in the total amounts of magnesium taken. All the media tended to approach the same degree of saturation of cations other than barium when cropped successively. The efficiency of phosphorus removal by soybeans was increased greatly by potassium treatment. Under certain conditions the crop contents of potassium, nitrogen, and phosphorus were less than those present in the planted seed. The cations calcium and magnesium were always present in the harvested crop in excess of the amounts supplied by the seed.

The study assembles many aspects of soil fertility in their relation to nitrogen fixation by soybeans.

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## INTRODUCTION

An available supply of potassium has long been recognized as a necessity for successful plant growth. Although its specific functions are not completely understood, it is fairly well established that, among other activities, potassium plays an essential role in carbohydrate metabolism, particularly in that phase involving sugar and starch formation. Plants may differ widely in their content of potassium. Some species absorb and retain potassium in such large quantities that they have been designated as "potassium plants." Invariably plants of this nature are high in carbohydrate material.

Calcium is also an indispensable cation in plant nutrition. Here too, as in the case of potassium, plant species differ considerably in their calcium requirements and in their calcium contents. The legumes, for example, are especially exacting in their requirement for this nutrient. This is well demonstrated by the fact that liming of soils low in calcium is an essential practice in order to insure healthy nodule formation, nitrogen fixation, and high quality protein production.

For the purpose of simplicity, protein production in plants can be regarded as the result of the union of two types of compounds: the first, carbohydrates or a substance for which carbohydrate is the precursor, and, the second, available nitrogen. Since potassium is intimately concerned in the formation of carbohydrate material, and since calcium is known to be effective in legume behavior, it appears that the organic chemical constituents of plants may be influenced greatly by the amount of available potassium in relation to other cations.

Such a consideration is of particular significance in legume production since legumes are grown primarily because of their capacity to fix nitrogen and to produce high quality protein. The question might well be raised whether legumes grown under the widely varying soil conditions of kind and amount of nutrients, of ratios between nutrients, and of different degrees of activity of legume bacteria, are necessarily high in nitrogen and protein simply because they are members of the family Leguminosae. Is it not possible

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that soil fertility conditions play a significant part in determining the chemical composition of the organic as well as the inorganic fractions of plant material?

The study reported herein, was undertaken in order to determine more accurately the influence on growth and plant composition by a varying supply of potassium when delivered along with constant amounts of the other fertility items, viz. phosphorus, calcium, and magnesium. Coincident with the study of plant composition, attention was also directed toward the qualitative and quantitative changes brought about in the nutrient supply on the substrate as a result of cropping. It was in the hope of learning more about the relations of potassium to other nutrient cations and their behavior within the soil and the legume plants for nitrogen fixation, that the following study was undertaken.

## HISTORICAL

The widespread occurrence of potassium in plant and animal tissue has been recognized for some time. In 1905 McCallum (29)* investigated a wide range of animal and vegetable tissues. He pointed out the great variation of tissues in potassium content.

Many studies have been made which show the increase in potassium content of plants with potassium fertilization. Among these studies are those by Janssen and Bartholomew (17), Johnston and Hoagland (21), and Hart (13). In many of these studies, "luxury" consumption of the element was indicated at the higher potassium levels.

Fundamental researches on the function of potassium in plant metabolism have revealed that the physiological activities in which potassium plays a significant role probably include; (1) the formation and transformation of carbohydrates; (2) the relation to nitrogen; (3) the catalytic effects and; (4) the formation and storage of oils.

That carbohydrates are formed normally only when the potassium supply is adequate was suggested by Nobbe in 1871 (31). After studying a variety of green plants, Reed (37) concluded that potassium is essential for starch formation. More recently Janssen and Bartholomew (18) (19) have investigated the relationship between the potassium supply and carbohydrate production. For their work with cowpeas they reported a close correlation between the per cent potassium and the total weight of starch and sugars in the plant. Janssen and Bartholomew, and Hart (13) working with sugar cane, found that plants low in potassium were high in re-

*Figures in parenthesis denote the number of the citation in the references on page 51.

ducing and total sugars but lower in starch than plants adequately supplied with potassium.

The lowering of carbohydrate production by potash deficiency is probably closely related to the effect of potash on respiration and carbon dioxide assimilation. Briggs (6) showed in 1922 that respiration could not go on normally in plants with an insufficient supply of potassium. Alten and Goeze (4), in a carefully controlled series of experiments reported that respiration of wheat plants, within limits, was dependent on the amount of potassium supplied. The potassium concentration and carbon dioxide assimilation showed a close correlation. Plants with potassium deficiency aged rapidly and were unable to assimilate carbon dioxide. Maiwald (26) showed that potassium fertilization of plants growing under low light intensities resulted in a considerable increase in the efficiency of carbon dioxide assimilation and dry matter production.

That potassium might possibly be an essential mineral element in protein formation was first suggested by Stocklasa (38). He considered that with adequate supplies of carbohydrate and other materials, protein can be formed either in the presence or absence of potassium. In the dark, protein formation occurred only in the presence of potassium. Loew (24) also suggested that potassium is concerned in protein formation in cells, pointing out as evidence, the large quantities of potassium in seeds containing abundant protein reserves. Although potassium has been reported to be essential for protein formation, yet many workers have reported a decrease in protein concentration by potassium treatment. Janssen and Bartholomew (19) found the percentage of nitrogen to be highest in cowpeas grown in media deficient in this element. Rauterberg and Loofmann (36) grew oats and rye grass under increasing levels of potassium and with three levels of nitrogen. At all levels of nitrogen, the increasing potassium resulted in a declining percentage of total nitrogen. However, the total nitrogen harvested increased with potassium treatment.

The depressing effect of potassium on the feeding capacity of plants for other ions has been given considerable attention. Fonder (8) reported an inverse relation between calcium and potassium contents of alfalfa plants. Johnston and Hoagland (21) showed that with low supplies of potassium, tomatoes absorbed relatively more calcium, magnesium, and phosphorus. Drake and Scarseth (7) noted a lowering of the percentage of calcium and of magnesium in tobacco plants by fertilization with potassium. A chlorotic condition of the tobacco leaves was corrected by applications of magnesium sulfate.

The various studies reported have clearly demonstrated the importance of an adequate supply of potassium for normal plant performance. That it plays a role in carbohydrate metabolism has been recognized and clearly demonstrated. However, the effect of potassium on nitrogen metabolism and protein formation is rather obscure. Information on the influence of potassium on symbiotic nitrogen fixation by legumes is particularly inadequate. The studies suggest that potassium may serve in metabolic processes concerning both carbohydrate and nitrogen. A study of this question by supplying legume plants with variable supplies of potassium, and noting the changes in plant composition should indicate more clearly the influence of this element on nitrogen fixation and plant composition.

## METHODS AND MATERIALS

### Preparation and Description of Hydrogen-Clay*

In order to simulate soil conditions as nearly as possible, and at the same time to provide a medium which could be brought under chemical scrutiny both at the outset and at the end of a cropping season, an electrodialyzed colloidal clay from the subsoil of the Putnam silt loam was used as a carrier for the nutrient cations. Media of this nature have been successfully used previously in similar studies (1), (2), (11). Colloidal clay, of which the chemical and mineralogical properties have been described by Bradfield (5) and Marshall (27) respectively, was separated from the subsoil of the Putnam silt loam. Particles with an effective diameter of less than .200 micron were fractionated by means of the Sharples centrifuge. H-clay was prepared from this fine fraction by electrodialysis, thereby freeing the clay of essentially all adsorbed ions other than hydrogen. The H-clay thus prepared had a pH of 3.6. Its acidic properties were those as shown by the curve of Fig. 1. The total exchange capacities of two samples used were determined and found to be 65 and 68 M E† per hundred grams of clay.

The clay thus prepared is very similar in physical and chemical properties to that part of the soil exchange complex which, through its base exchange properties, is credited with a very dynamic role in the storage and release of nutrient elements to plants (33) (2). Its chemical composition is shown in Table 1. Although it contains a relatively abundant supply of potassium, magnesium, iron, and a small amount of calcium, previous work (3) has shown that during the course of a growing season, with the single exception of

*Hydrogen-clay represents the acid clay after electrodialysis to remove the other cations and replace them by exchangeable hydrogen. It will be spoken of as H-clay.
†M E is used for milligram-equivalents in the following pages.

iron, no significant quantities of these elements within the clay crystal are taken up by plants.

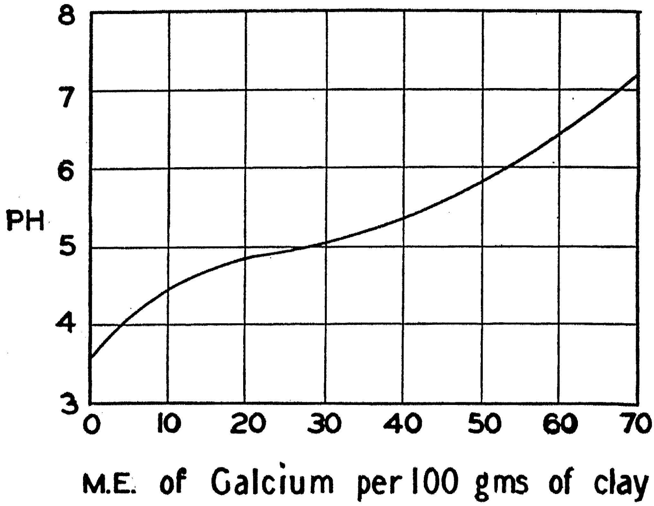


Fig. 1.—Potentiometric titration curve of hydrogen clay by calcium hydroxide.

Carbon and nitrogen analyses of the electrodialyzed clay gave values of 1.56 and 0.157 per cent respectively. This carbon and this nitrogen are held in the colloidal humic matter. Since it represents the more stable colloidal humic residues formed during organic matter decay and retained against electrodialysis, it would seem doubtful whether appreciable quantities of this nitrogen could be brought into an available form during a short cropping period of five weeks. Experimental trials demonstrated the stability of this humic matter.

TABLE 1.—COMPOSITION OF ELECTRODIALYZED PUTNAM COLLOIDAL CLAY* (.2 MICRON FRACTION).

| Element | Per Cent |
|---|---|
| Si | 23.0 |
| Al | 12.77 |
| Fe | 5.73 |
| K | 0.924 |
| Mg | 0.661 |
| Na | 0.422 |
| Ca | 0.177 |
| Mn | 0.0188 |
| C | 1.56** |
| N | 0.157** |

*According to C. E. Marshall (27)
**Analyses by author.

After growing a series of three crops of soybeans on a colloidal clay-sand culture the clay was separated, washed and electrodialyzed again. The carbon content of the clay was the same as that of the original clay, except for only a slight increase. The nitrogen values, however, actually increased, which could be accounted for only by a loss of nitrogen from the soybean crop to the soil. Thus the decomposition of the carbon and nitrogen of the humic residue in the clay surely could not have been contributing much to the crop growth.

## Culture Preparation

The media were prepared by taking a sufficient amount of the H-clay to sorbe the desired quantity of bases and adding the nutrients as hydroxides whenever possible. Barium was used as a balancing cation reciprocating with potassium and thereby maintaining a constant degree of saturation of the clay. The suspensions were allowed to stand for several days after the addition of each of the cations. A definite sequence of additions was followed. This, in order of sequence was, barium hydroxide, magnesium oxide, phosphorus as mono-calcium acid phosphate, calcium hydroxide, and potassium hydroxide. In one series 0.5 M E of the magnesium, as magnesium sulfate, was added to each culture. Proper physical condition of the clay was obtained by the addition of 2000 grams of acid leached quartz sand to the clay suspensions and allowing the mixture to evaporate to optimum moisture.

Soybean plants were grown in two successive sets of media. The first group of plants is designated as Series A and the second, as Series B. Series B differed from Series A in that 0.5 M E of the magnesium was added as magnesium sulfate. Series A was used to produce one crop while series B served for three successive crops without nutrient addition beyond that given initially. Constant amounts of calcium, magnesium, and phosphorus were supplied to all the cultures. Potassium varied from 0 M E to 15 M E, while barium varied reciprocally to the potassium in each series. Treatments and arrangement of the series are schematically shown in Table 2.

Soybeans of the Virginia variety were germinated until the radicles were about 2 cms. long. They were then inoculated with Rhizobium japonicum and planted into the sand-colloidal clay mixture at the rate of fifty per pot. All cultures were in duplicate. Crop one of Series A was grown in the greenhouse during the Fall for a period of six weeks. Crops of Series B were each grown for five weeks. Crop one of Series B was uninoculated and grew outside under a partial shade during July. Crop two grew during October, and crop three was planted the following May. Artificial light was used to supplement daylight during the latter days of the growth period of the Fall crops.

TABLE 2.—NUTRIENTS ADDED BY TITRATION TO CULTURES OF SERIES A AND B.

Series A

(Used for a single crop)

| Culture | Nutrient ions added | | | | |
|---|---|---|---|---|---|
| | Ca | Mg | P | K | Ba |
| No. | M E | M E | M E | M E | M E |
| 1 | 10 | 5 | 3.68 | 0 | 15 |
| 2 | 10 | 5 | 3.68 | 5 | 10 |
| 3 | 10 | 5 | 3.68 | 10 | 5 |
| 4 | 10 | 5 | 3.68 | 15 | 0 |

Series B

(Used for Three Successive Crops)

| Culture | Nutrient ions added | | | | | |
|---|---|---|---|---|---|---|
| | Ca | Mg | P | S | K | Ba |
| No. | M E | M E | M E | M E | M E | M E |
| 1 | 10 | 5 | 3.68 | 0.5 | 0 | 15 |
| 2 | 10 | 5 | 3.68 | 0.5 | 5 | 10 |
| 3 | 10 | 5 | 3.68 | 0.5 | 10 | 5 |
| 4 | 10 | 5 | 3.68 | 0.5 | 15 | 0 |

At the end of the growing period all crops were harvested about midday and placed in the autoclave at five pounds pressure for five minutes in order to stop any enzyme action. After enzyme inactivation they were dried to a constant weight in the oven at 60° C., weighed separately as to tops and roots, and then finely ground together.

## Analytical Methods

Chemical analyses were made for the following constituents: nitrogen, calcium, magnesium, potassium, phosphorus, barium, iron, aluminum, silicon, reducing sugar, total sugar, starch, and hemicellulose. Portions of the finely ground samples were digested by the wet ashing method (9). The elements calcium, magnesium, phosphorus, potassium, iron, silicon, aluminum, and barium, were determined in the digested sample. Plant silica was separated from any contaminating material by the official methods (32). Barium was found both in the hydrochloric acid solution of the ash, and as insoluble barium sulfate in the residue from the silica separation. Methods described by Kolthoff and Sandell (22) were used for the determination of the inorganic elements. Separate portions of the plant material were taken for total nitrogen determinations by the Kjeldahl-Gunning-Arnold method as modified by Murneek and Heinze (30). Carbohydrate analyses were made according to the methods of Shaffer and Somogyi as modified by Heinze and Murneek (14).

## EXPERIMENTAL RESULTS

### "Non-legume" Behavior. Crop One—Series B

The presentation of the experimental results is divided into the following three divisions: (1) non-legume as contrasted to legume behavior under different potassium treatments; (2) declining fertility levels as reflected in yields and crop composition; and (3) the extent of nutrient exhaustion in the soil through nutrient removal by successive croppings. The results reported herewith include the data for one crop of Series A and for three crops of Series B. Attention will first be given Crop one—Series B which was non-nodulated, and although a legume, performed in a manner entirely different from the commonly ascribed legume behavior. The influence of variable supplies of potassium on plant performances are given.

**Variable Potassium in Relation to Growth.**—Although the crop was supplied only the inherent seed nitrogen, yet as is shown in Table 3, relatively good growth in terms of total dry matter yields was obtained. Cultures 1, 2, 3, and 4 produced crops which were 3.39, 4.41, 5.08, and 4.67 times heavier respectively than the weight of the planted seed. Increasing potassium gave corresponding increases in growth, with the exception of the highest potassium treatment, culture 4, which showed a decline below culture 3 in total crop weight. However, it may be noted that the root growth of this culture was largest of all. Growth was very vigorous until the fourth week at which time nitrogen deficiency symptoms were manifested by a cessation of growth, and by the development of a yellowish green color in the leaves. Plate I shows the plants at the time of harvest.

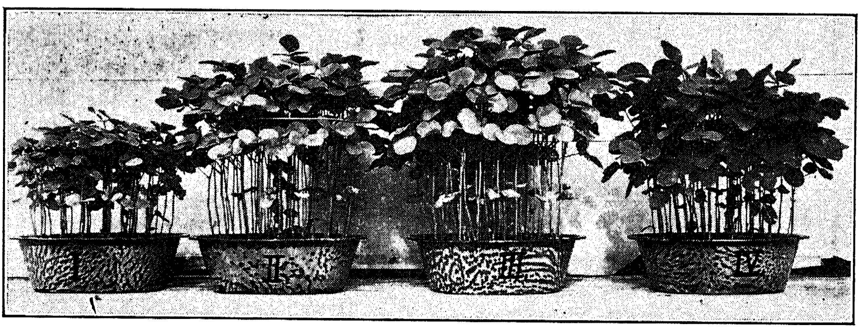


Plate I.—Soybean plants as influenced by increments of potassium. (Crop One—Series B. Cultures I, II, III, and IV had 0, 5, 10, and 15 M E respectively of potassium supplied.)

TABLE 3.—CROPS OF SOYBEANS IN RELATION TO VARIABLE POTASSIUM. (DATA FOR 50 PLANTS. CROP ONE—SERIES B.)

| Culture No. | Application of Potassium M E | Weight of 50 Plants | | | Ratio Tops/Roots | Increase of Tops Over No Potassium % | Increase of Roots Over No Potassium % | Ratio Crop Wt./Seed Wt.* |
|---|---|---|---|---|---|---|---|---|
| | | Tops gms. | Roots gms. | Total gms. | | | | |
| 1 | 0 | 7.821 | 6.878 | 14.699 | 1.14 | ... | ... | 3.39 |
| 2 | 5 | 12.064 | 7.252 | 19.316 | 1.66 | 54.2 | 5.44 | 4.41 |
| 3 | 10 | 15.264 | 7.245 | 22.509 | 2.11 | 95.2 | 5.34 | 5.08 |
| 4 | 15 | 12.582 | 7.643 | 20.225 | 1.65 | 61.0 | 11.12 | 4.67 |

*Fifty seeds weighed 4.43 gms.

TABLE 4.—COMPOSITION OF PLANT MATERIAL IN RELATION TO VARIABLE POTASSIUM. (DATA FOR 50 PLANTS. CROP ONE—SERIES B.)

| Culture No. | Application of Potassium M E | Potassium | | Calcium | | Phosphorus | | Magnesium | | Barium | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. |
| 1 | 0 | 0.73 | 111.2 | 0.44 | 66.7 | 0.196 | 29.3 | 0.34 | 51.8 | 1.44 | 216.3 |
| 2 | 5 | 1.32 | 258.5 | 0.41 | 80.4 | 0.196 | 38.2 | 0.28 | 55.6 | 0.93 | 181.4 |
| 3 | 10 | 1.68 | 379.4 | 0.41 | 92.2 | 0.203 | 45.7 | 0.25 | 56.3 | 0.42 | 94.5 |
| 4 | 15 | 2.18 | 450.3 | 0.43 | 88.7 | 0.214 | 44.1 | 0.23 | 43.6 | 0.00 | 00.0 |

TABLE 5.—CONSUMPTION OF POTASSIUM, CALCIUM, AND NITROGEN IN RELATION TO THE TOTAL AMOUNTS SUPPLIED. (DATA FOR 50 PLANTS. CROP ONE—SERIES B.)

| Culture No. | Potassium | | | Calcium | | | Nitrogen | | |
|---|---|---|---|---|---|---|---|---|---|
| | Supplied* mgms. | Taken mgms. | Taken Per Cent** | Supplied* mgms. | Taken mgms. | Taken Per Cent** | Supplied* mgms. | Taken mgms. | Taken Per Cent** |
| 1 | 178 | 111.2 | 62.4 | 208.1 | 66.7 | 32.0 | 318 | 235.4 | —26.0 |
| 2 | 373.5 | 258.5 | 69.2 | 208.1 | 80.4 | 38.6 | 318 | 241.9 | —23.8 |
| 3 | 569 | 379.4 | 66.7 | 208.1 | 92.2 | 44.3 | 318 | 261.0 | —17.9 |
| 4 | 764.5 | 450.3 | 59.0 | 208.1 | 88.7 | 42.5 | 318 | 243.1 | —23.6 |

*Seed contents were: Potassium 178 mgms., calcium 8.1 mgms., and nitrogen 318 mgms.
**The content of the plants as per cent of the total supplied by the seed and the titration is given. In case of the nitrogen, this percentage represents the increase over the initial nitrogen or per cent fixation.

Something of the morphological nature of the growth is shown by the ratios of tops to roots. With increasing potassium, the ratio of the tops to the roots widened considerably, increasing from a low value of 1.14 in culture 1 with no potassium to 2.11 in culture 3. Culture 4 with a ratio of 1.65 had a lower figure than culture 3 or a close approach to culture 2 at 1.66. Expressed as percentage increase of top growth over culture 1, the culture with treatments of 5, 10, and 15 M E of potassium gave values of 54.2, 95.2, and 61.0 respectively. Percentage increases in root growth were only of the order of 5.44, 5.34, and 11.12. The much larger increase is root growth of culture 4 is also shown by the corresponding culture of Series A crops one and two.

**Potassium Content.**—The amount of potassium present in the plant tissue, expressed either as percentage concentration or total quantity, was in direct relation to the amount offered. The culture treated with 0, 5, 10 and 15 M E of potassium, as Table 4 shows, contained 0.73, 1.32, 1.68, and 2.18 per cent of potassium respectively, or totals of 111.2, 258.5, 379.4, and 450.3 mgms. per culture. When the total potassium content of the crop is plotted as a function of the amount supplied, the graph of Fig. 2 approaches a straight line, curving but slightly with the higher treatments. The percentage of potassium taken from that supplied varied little with the higher treatments. The data of Table 5 show that of the total potassium supplied, which included that in the seed plus that titrated

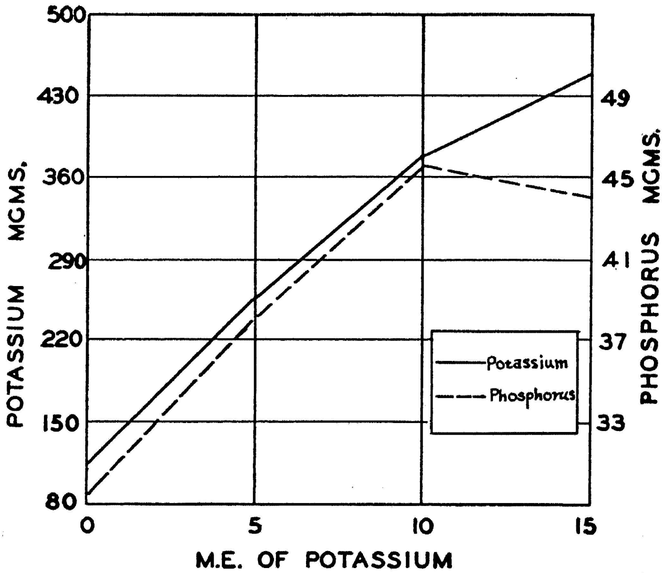


Fig. 2.—Potassium and phosphorus contents of soybeans as influenced by potassium. (Crop One—Series B.)

on the clay, the percentages taken were 62.4, 69.2, 66.7, and 59.0. It is very significant that culture 1 with no titrated potassium, although growing on a medium saturated with bases and approximately neutral at the outset, lost 37.6 per cent of its initial seed potassium, or a loss of 65.8 mgms. of an initial seed supply of 178 mgms. Yet this culture did not show growth irregularities commonly considered as typical potassium deficiency symptoms.

**Nitrogen Content.**—Since the crop was not inoculated with nitrogen fixing bacteria, and since nitrogen was not supplied along with the other nutrients, one would expect to find nitrogen in the plant tissue only to the extent that it occurred in the seed. But, even though this crop produced yields of dry matter ranging from 15.0 to 22.5 grams per culture, which was 3.39 to 5.08 times the weight of the planted seed, there was actually a negative nitrogen balance. All cultures in this crop contained less nitrogen than was in the seed from which they grew. The amount of this loss is given in table

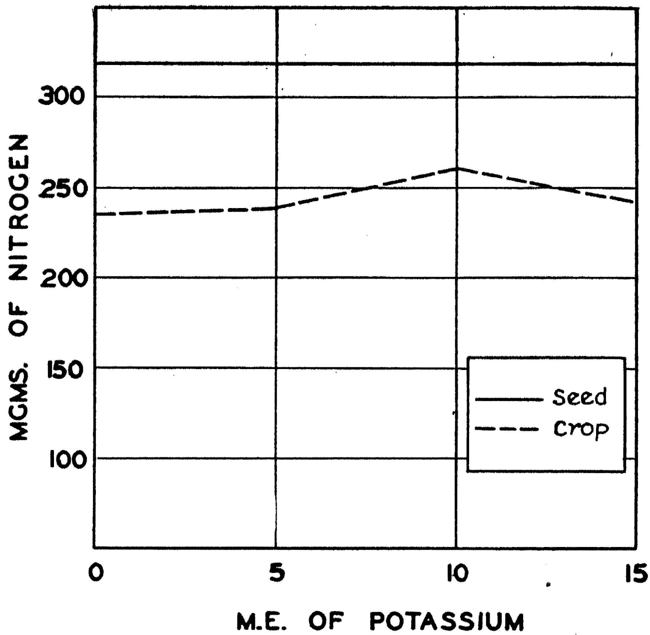


Fig. 3.—Nitrogen losses by non-nodulated soybeans. (Crop One—Series B.)

5 and represented graphically in Fig. 3. Increasing the potassium offered had little effect on this nitrogen loss. This loss is significant, since of the 318 mgms. of nitrogen supplied by the fifty seeds, culture 1, lost 83 mgms. or 26.0 per cent; culture 2, 76 mgms. or 23.8 per cent; culture 3, 57 mgms. or 17.9 per cent; and culture 4, 75 mgms, or 23.6 per cent. These values give a mean loss of 23.1 per

cent of the seed nitrogen back to the soil. So severe was this loss that the nitrogen concentration of the harvested crop ranged from as low as 1.16 per cent to no higher than 1.57 per cent, as is shown in Table 6, on the basis of the dry forage for this legume crop. This percentage content in nitrogen suffered a decrease with the increase in applied potassium.

TABLE 6.—NITROGEN CONTENT IN RELATION TO VARIABLE POTASSIUM. (DATA FOR 50 PLANTS. CROP ONE—SERIES B.)

| Culture No. | Application of Potassium M E | Nitrogen in 50 Plants Per Cent | Total mgms. | Fixed mgms. | Seed Nitrogen Lost Per Cent |
|---|---|---|---|---|---|
| 1 | 0 | 1.57 | 235.4 | —82.6 | 26.0 |
| 2 | 5 | 1.24 | 241.9 | —76.1 | 23.8 |
| 3 | 10 | 1.16 | 261.0 | —57.0 | 17.9 |
| 4 | 15 | 1.18 | 243.0 | —74.9 | 23.6 |

**Significance of Nutrient Losses.**—The possibility of a reverse movement of nutrients, particularly from plants growing on highly adsorptive substrates has been recognized for some time. Lundegardh (25) suggested that there might be a competition between plant colloids and soil colloids for nutrient cations and that possibly some cations could be lost to the substrate. Albrecht (1) working with different Ca-H-clays found in some cases that the harvested crops had less of certain elements than the seed from which they grew.

Thomas (39) suggested that plants may lose potassium back to the soil after the formation of blossoms. Petrie (35) found that the total potassium decreased in plants after maturity was reached. He found no loss of calcium however. More recently Jenny (20) has shown that excised roots, although still undergoing respiration, lost potassium readily when immersed in certain kinds of clays. H-clay was most effective in removing potassium.

Since there was no loss of plant parts during the growth and harvesting of the crop it may be assumed that the nitrogen unaccounted for in the harvested plants, moved into the sand-colloidal clay substrate. The evidence for a movement of this kind is further substantiated by the analyses of the substrates which are to be given on page 40.

It is of interest that cultures 1, 2, 3, and 4 developed from lots of seed weighing 4.43 grams per culture produced dry matter to the extent of 3.39, 4.41, 5.08, and 4.67 times their initial seed weight and at the same time suffered an average loss of 23.1 per cent of the initial seed nitrogen back to the soil. These increments in dry matter, regardless of the high nitrogen loss, are probably accounted for by the fact that the dry matter produced was largely carbohydrate in composition. Since it contains little or no nitrogen, only a minimum amount of nitrogen needs be present for its production. Carbohydrate synthesis and storage were stimulated tremendously by the absorption and retention of increasing amounts of potassium.

These data emphasize the fallacy of judging the value and quality of hays solely on the basis of appearance or species, with no consideration of the soil conditions under which they were produced. It is possible to harvest a crop of soybeans containing less nitrogen than was contained in the planted seed.

The foregoing data suggest that a certain level of available potassium must be present on the clay to prevent a migration of seed potassium back to the soil, even though the clay may be completely saturated and approximately neutral at the outset. The relatively good growth made by plants losing potassium, is possible because of the seed content of potassium, which is high enough to supply the plants' potassium needs for a relatively long period of time after germination.

**Carbohydrate Content.**—The carbohydrates varied in close parallel with the growth, according to Fig. 4. Both reducing sugars and total sugars decreased in percentage with increasing potassium supplied. Cultures supplied with 0, 5, 10, and 15 M E of adsorbed po-

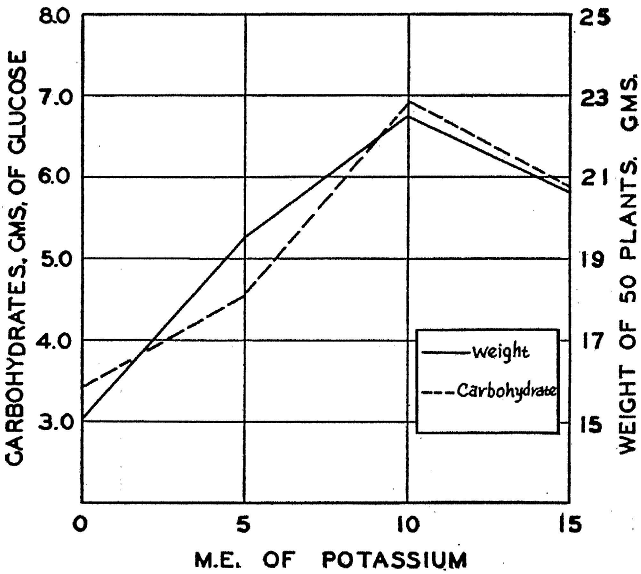


Fig. 4.—Growth and total available carbohydrates as influenced by variable potassium. (Crop One—Series B.)

tassium contained 2.16, 1.92, 1.85, and 0.94 per cent reducing sugars respectively as is shown by Table 7. The relatively low level of

TABLE 7.—CARBOHYDRATE CONTENT OF PLANT MATERIAL AS INFLUENCED BY POTASSIUM. (DATA FOR 50 PLANTS. CROP ONE—SERIES B.)

| Culture No. | Sugar | | | | Starch | | Hemicellulose | | % Reducing Sugar of the Total Sugar |
|---|---|---|---|---|---|---|---|---|---|
| | Reducing | | Total | | | | | | |
| | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. | |
| 1 | 2.16 | 324 | 3.89 | 582 | 8.39 | 1263 | 10.40 | 1563 | 55.7 |
| 2 | 1.92 | 374 | 2.68 | 523 | 10.63 | 2078 | 9.94 | 1940 | 71.6 |
| 3 | 1.85 | 418 | 2.42 | 544 | 17.35 | 3913 | 11.11 | 2499 | 76.5 |
| 4 | 0.94 | 195 | 1.31 | 271 | 15.52 | 3210 | 11.59 | 2396 | 71.8 |

TABLE 8.—CONSUMPTION OF PHOSPHORUS, MAGNESIUM, AND BARIUM IN RELATION TO THE TOTAL AMOUNTS SUPPLIED. (DATA FOR 50 PLANTS. CROP ONE—SERIES B.)

| Culture No. | Phosphorus | | | Magnesium | | | Barium | | |
|---|---|---|---|---|---|---|---|---|---|
| | Supplied* | Taken | | Supplied* | Taken | | Supplied* | Taken | |
| | mgms. | mgms. | Per Cent** | mgms. | mgms. | Per Cent** | mgms. | mgms. | Per Cent** |
| 1 | 70 | 29.3 | 41.9 | 71.6 | 51.8 | 72.3 | 1030.2 | 216.3 | 21.0 |
| 2 | 70 | 38.2 | 54.6 | 71.6 | 55.6 | 77.6 | 686.8 | 181.4 | 26.4 |
| 3 | 70 | 45.7 | 65.3 | 71.6 | 56.3 | 78.6 | 343.4 | 94.5 | 27.6 |
| 4 | 70 | 44.1 | 63.0 | 71.6 | 43.6 | 60.8 | .... | .... | .... |

*Seed contents were: Phosphorus 32 mgms., magnesium 10.8 mgms., and barium 0.00 mgms.
**The content of the plants as per cent of the total supplied by the seed and the titration is given.

sugars may be explained by the low rate of photosynthetic activity at the time of harvest, which was an effect of the extreme nitrogen shortage. Nevertheless, carbohydrate was stored in abundant quantities during the early growth period as is shown by the very high starch content of all cultures. The effect of potassium in bringing about an increase in the percentage and in the total starch is very evident. Cultures 1 to 4 show starch contents of 8.39, 10.65, 17.35, and 15.52 per cent or totals of 1.263, 2.078, 3.913, and 3.210 grams respectively. Expressed as percentage increase in total starch over culture 1, cultures 2, 3, and 4 gave values of 64.5, 210, and 154 per cent respectively. The hemicellulose remained almost constant in per centage concentration. The data show that in plants with low nitrogen but with increasing supplies of available potassium and constant amounts of other nutrient elements, the rates of carbohydrate synthesis and storage are increased tremendously.

**Cation and Phosphorus Intake.**—The calcium concentration in the plant tissue remained fairly constant with increasing potassium. Since more growth was obtained with potassium increments, the total calcium also increased. (See Table 4, page 13). Cultures 1 to 4 show total calcium contents of 66.7, 80.4, 92.2, and 88.7 mgms. respectively, which represent a consumption of 32.0, 38.6, 44.3, and 42.5 per cent of the 208.1 mgms. as total calcium supplied as shown in Table 5. Here again, as in all cases before, culture 4 failed to show an increase over the culture 3.

The percentage content of phosphorus of the plant material was almost constant as given in Table 4, page 13 but the total phosphorus harvested showed significant increases as more potassium was supplied with a single exception. Cultures supplied 0, 5, 10, and 15 M E of potassium contained 29.3, 38.2, 45.7, and 44.1 mgms. of phosphorus respectively, or 41.9, 54.6, 65.3, and 63.0 per cent of the constant supply of 70 mgms. as given in Table 8. Thus the total phosphorus consumption by soybeans was increased by the presence of increasing amounts of available potassium.

Unusually large concentrations of any nutrient cation in the plant tissue are ordinarily reflected by reciprocal concentrations of some other cation or cations. The amount of magnesium in the plant tissue, expressed as percentage of dry weight, decreased regularly and consistently with potassium treatment as shown in table 4. Cultures given treatments of 0, 5, 10, and 15 M E of potassium had magnesium contents of 0.34, 0.28, 0.25 and 0.23 per cent respectively. Since more growth was made by the potassium treated cultures, total magnesium, with the exception of culture 4, increased. It is significant to note that the quantities of magnesium taken by these cultures represents 72.3, 77.6, 78.6, and 60.8 per cent of the total supply of 71.6 mgms. offered as is shown by the data of table 8. The efficiency of absorption and retention of magnesium by soybeans when supplied on a colloidal clay under these conditions, was of about the same magnitude as for potassium.

Barium was supplied as the reciprocal of the potassium. Interestingly, its amount in the plant material expressed either as per cent of the dry weight or as total milligrams per culture was directly proportional to the amounts supplied. Although barium is regarded as a non-essential element for plant growth, yet considerable quantities were assimilated as is shown in Table 4. Cultures 1, 2, and 3 contained 1.44, 0.93, and 0.42 per cent respectively. Culture 4 had no barium supplied either in the seed or clay. The percentage taken of the total barium supplied was the lowest of all the cations. From a total supply of 1030, 687, and 343 mgms. only 21.0, 26.4, and 27.6 per cent respectively, were removed in the crop tissue as shown in Table 8.

These data suggest that barium is taken in relatively large amounts with apparently no significant injury to the crop growth. As an inert cation to occupy part of the adsorption capacity and yet give no plant injury it seems to have served very well.

**Legume Behavior. Crop one—Series A**

Unlike the crop described previously as a non-legume behavior, crop one of Series A was inoculated with active legume bacteria and fixed nitrogen. The influence of variable supplies of potassium on growth, nitrogen fixation, ion absorption, and plant composition are of interest.

**Variable Potassium in Relation to Growth.**—Potassium treatment brought about increased growth, which was approximately proportional to the amount of potassium supplied. Plate II shows the plants at the time of harvest. Cultures supplied 0, 5, 10, and 15 M E of potassium produced 11.880, 14.219, 15.036, and 16.007 gms. of plant material as is given in Table 9 and shown graphically by Fig. 5. There is an interesting relationship between roots and tops. The cultures from 1 to 4 inclusively had top : root ratios of 1.81, 2.14, 2.32, and 2.35 respectively. The much greater per cent increase in top growth than root growth is also shown in table 9 expressed as percentage increase in both top and root growth over culture 1. Culture 4 with the highest level of potassium, as in Series B, showed a marked increase in root growth over culture 3. These results indicate that there is no strict proportionality between top growth and the extent of root absorbing surface.

Plate II.—Soybean plants as influenced by increments of potassium. (Crop One—Series A. Cultures I, II, III, and IV were supplied 0, 5, 10, and 15 M E respectively of potassium.)

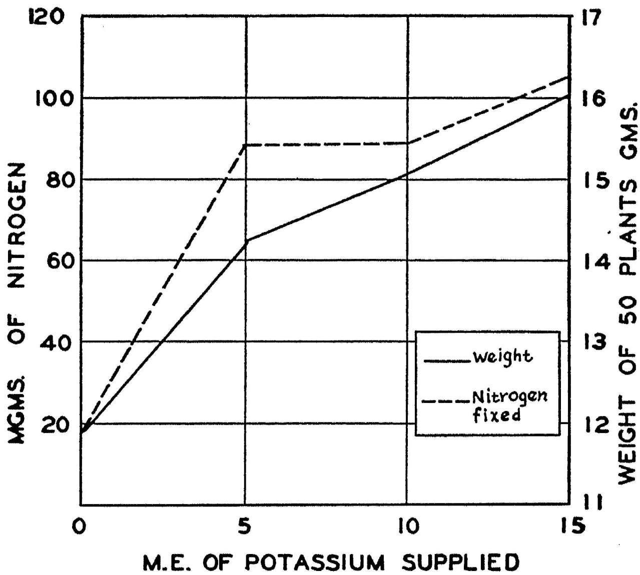


Fig. 5.—Growth and nitrogen fixation as influenced by variable potassium. (Crop One—Series A.)

TABLE 9.—CROPS OF SOYBEANS IN RELATION TO VARIABLE POTASSIUM. (DATA FOR 50 PLANTS. CROP ONE—SERIES A.)

| Culture No. | Application of Potassium M E | Weight of 50 Plants Tops gms. | Roots gms. | Total gms. | Increase Over No Treatment % Tops | Roots | Ratio Tops/Roots |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 7.641 | 4.238 | 11.880 | ... | ... | 1.81 |
| 2 | 5 | 9.688 | 4.531 | 14.219 | 26.8 | 6.93 | 2.14 |
| 3 | 10 | 10.506 | 4.530 | 15.036 | 37.5 | 6.90 | 2.32 |
| 4 | 15 | 11.220 | 4.787 | 16.007 | 46.9 | 12.95 | 2.35 |

**Potassium Content.**—Potassium intake in this nitrogen fixing crop followed the same general behavior as that of the "non-legume," crop one of Series B. The data presented in Table 10 show that the potassium, expressed either as per cent or total amount, was in direct relation to the amount supplied. Cultures given 0, 5, 10, and 15 M E of potassium contained 88.5, 223.7, 369. 8, and 471.4 mgms. respectively at the time of harvest. This high potassium intake had a depressing effect on the absorption of some other elements. This crop was very similar to crop one Series B in percentage consumption of the total amount supplied, since 49.6, 59.8, 65.0, and 61.6 per cent of the total amounts supplied were taken. The high mobility of potassium was again shown by culture 1 which had no titrated potassium. Although the medium was completely saturated and approximately neutral at the outset, about fifty per cent of the initial seed supply of potassium was lost to the clay. This suggests again that a certain concentration of available potassium must be present on the clay for soybeans if they are to retain even their initial seed potassium during a cropping season.

TABLE 10.—NITROGEN FIXATION BY SOYBEANS IN RELATION TO VARIABLE POTASSIUM. (DATA FOR 50 PLANTS. CROP ONE—SERIES A.)

| Culture No. | Application of Potassium M E | Number of Nodules per 50 Plants | Amount in 50 Plants: Potassium Per Cent | Potassium Total mgms. | Nitrogen Per Cent | Nitrogen Total mgms. | Nitrogen Fixed mgms. |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 453 | 0.74 | 88.5 | 2.81 | 335.7 | 17.7 |
| 2 | 5 | 438 | 1.69 | 223.7 | 2.86 | 405.5 | 88.5 |
| 3 | 10 | 618 | 2.51 | 369.8 | 2.70 | 406.9 | 88.9 |
| 4 | 15 | 629 | 2.94 | 471.4 | 2.64 | 423.3 | 105.3 |

Fifty seed contained 318 mgms. of nitrogen and 178 mgms. of potassium.

**Nitrogen Fixation and Nodule Formation.**—Nitrogen fixation and nodule formation increased from the lowest to the highest level of potassium as is shown by the data of Table 10. Fig. 5 shows that increased growth was accompanied by a corresponding increase in nitrogen fixation. The percentage of total nitrogen declined, with the exception of culture 2, as the potassium supply increased. The favorable effect of treatment on bacterial infection and nodule formation is also indicated by the large numbers of nodules which were present on the cultures. The potassium treatment increased the carbohydrate production markedly in the "non-legume" performer; but in this case of the legume performer, although the potassium in the tissue increased from 0.74 per cent in culture 1 to 2.94 per cent in culture 4 or a four fold increase, yet nodule formation, nitrogen fixation, and protein production were enhanced considerably.

**Carbohydrate Content.**—Since this crop was actively functioning in nitrogen fixation and protein production, consequently the organic composition of the plant tissue differed from that of crop one —Series B, which was performing as a non-legume. The reducing sugar values, according to the data of Table 11, are very similar to those of the non-nitrogen fixing crop, namely 1.91, 1.91, 1.04, and 0.96 per cent respectively for cultures 1, 2, 3, and 4. The decrease in this constituent is to be expected if one of the functions of potassium is to accelerate the conversion of sugar to starch. Values for total sugar are somewhat erratic but show a downward trend with increasing potassium added to the soil. The starch contents were much lower in magnitude than in the preceding crop. These values were 3.37, 2.64, 3.62, and 3.25 per cent for cultures supplied with increasing potassium in that order. That this crop was functioning in a manner entirely different from that of crop one—Series B is further shown by the nearly constant ratio of available carbohydrate carbon to nitrogen in Fig. 8, page 35.

**Cation and Phosphorus Intake.**—The calcium concentrations in the plant tissue, according to the data of Table 12, were approximately constant, varying only from 0.43 to 0.48 per cent. The total calcium absorbed by the plants increased with increasing quantities of postassium supplied, so that cultures given 0, 5, 10, and 15 M E took 57.6, 60.2, 66.1, and 70.4 mgms respectively of calcium. These values represent 27.6, 28.9, 31.8, and 33.8 per cent of the constant total supply of 208.1 mgm. of calcium. That calcium should have decreased only slightly in percentage and yet have shown an increase in total quantity in the plant material in spite of the tremendous saturation of the tissue with potassium can probably be accounted for by the fact that magnesium showed regular and consistent decrements both in percentage concentration and in total amount metabolized as the potassium treatments increased. The increase in tissue production by the treated cultures also served to raise the total amount of calcium utilized.

With increasing potassium supply, magnesium decreased regularly both in percentage and in total amount as is indicated by Table 12 and shown graphically in Fig. 6. The plant tissue from cultures supplied 0, 5, 10, and 15 M E of potassium contained 0.473, 0.369, 0.297, and 0.236 per cent, of magnesium or totals of 56.2, 50.8, 44.3, and 37.7 mgms. respectively. In spite of the declining magnesium utilization, the growth and the nitrogen fixation both continued to increase as more potassium was taken. The percentage absorption of the initial magnesium supplied by the seed and titration, ranged from a high of 78.5 per cent to a low of 52.7 per cent, as is shown in Table 13.

TABLE 11.—CARBOHYDRATE CONTENT OF PLANT MATERIAL AS INFLUENCED BY VARIABLE POTASSIUM. (DATA FOR 50 PLANTS. CROP ONE—SERIES A.)

| Culture No. | Sugar | | | | Starch | | Hemicellulose | | % Reducing Sugar of Total |
|---|---|---|---|---|---|---|---|---|---|
| | Reducing | | Total | | | | | | |
| | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. | |
| 1 | 1.91 | 227 | 4.06 | 483 | 3.37 | 401 | 14.69 | 1.745 | 47.0 |
| 2 | 1.91 | 255 | 4.09 | 566 | 2.64 | 360 | 13.90 | 1.811 | 45.0 |
| 3 | 1.04 | 157 | 2.94 | 444 | 3.62 | 544 | 12.93 | 1.943 | 35.1 |
| 4 | 0.96 | 154 | 3.01 | 482 | 3.25 | 520 | 9.32 | 1.492 | 31.9 |

TABLE 12.—COMPOSITION OF PLANT MATERIAL IN RELATION TO VARIABLE POTASSIUM. (DATA FOR 50 PLANTS. CROP ONE—SERIES A.)

| Culture No. | Application of Potassium M E | Potassium | | Calcium | | Magnesium | | Phosphorus | | Barium | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. |
| 1 | 0 | 0.74 | 88.5 | 0.48 | 57.6 | 0.473 | 56.2 | 0.229 | 27.9 | 1.02 | 121.6 |
| 2 | 5 | 1.69 | 223.7 | 0.43 | 60.2 | 0.369 | 50.8 | 0.206 | 27.6 | 0.82 | 114.9 |
| 3 | 10 | 2.51 | 369.8 | 0.43 | 66.1 | 0.297 | 44.3 | 0.213 | 31.2 | 0.55 | 83.0 |
| 4 | 15 | 2.94 | 471.1 | 0.44 | 70.4 | 0.236 | 37.7 | 0.195 | 31.2 | ... | ... |

Fifty soybean seed contained 178 mgms. of potassium, 10.8 mgms. of magnesium, 8.1 mgms. of calcium, and 23.8 mgms. of phosphorus.

TABLE 13.—CONSUMPTION OF PHOSPHORUS, MAGNESIUM AND BARIUM IN RELATION TO THE TOTAL AMOUNTS SUPPLIED. (DATA FOR 50 PLANTS. CROP ONE—SERIES A.)

| Culture No. | Phosphorus | | | Magnesium | | | Barium | | |
|---|---|---|---|---|---|---|---|---|---|
| | Supplied* | Taken | | Supplied* | Taken | | Supplied* | Taken | |
| | mgms. | mgms. | Per Cent** | mgms. | mgms. | Per Cent** | mgms. | mgms. | Per Cent** |
| 1 | 61.8 | 27.9 | 45.2 | 71.6 | 56.2 | 78.5 | 1030.2 | 121.6 | 11.8 |
| 2 | 61.8 | 27.6 | 44.7 | 71.6 | 50.8 | 71.0 | 686.8 | 114.9 | 16.7 |
| 3 | 61.8 | 31.2 | 50.5 | 71.6 | 44.3 | 61.9 | 343.4 | 83.0 | 24.3 |
| 4 | 61.8 | 31.2 | 50.5 | 71.6 | 37.7 | 52.7 | .... | ... | ... |

*Seed contents were: Phosphorus 23.8 mgms., magnesium 10.8 mgms., and barium 0.00 mgms.
**The content of the plants as per cent of total supplied by the seed and the titration is given.

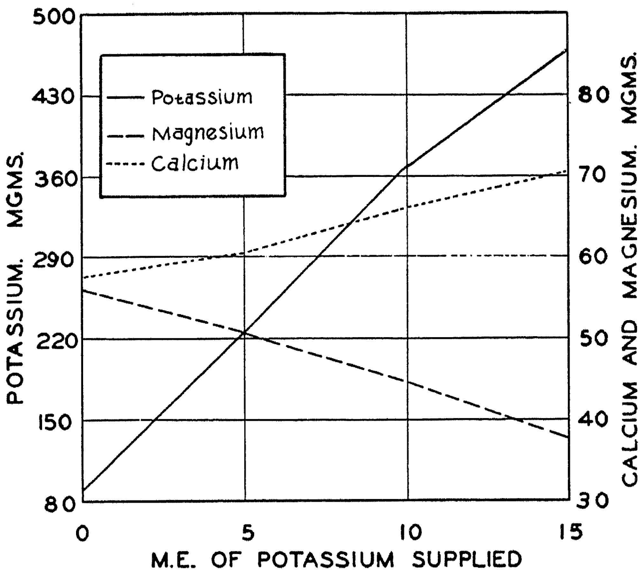


Fig. 6.—Potassium, magnesium, and calcium contents of soybeans as influenced by variable potassium. (Crop One—Series A.)

According to the data of Table 12, page 24, phosphorus was present in the plant tissue in amounts ranging from 0.229 per cent in culture 1 to 0.195 per cent in culture 4. However, the total phosphorus increased slightly. The utilization of phosphorus varied between 45 and 50 per cent of that initially supplied by seed and titration, as is shown in Table 13. This is lower for this anion than that for potassium, and higher than that for calcium, both cations, as given in Table 14.

### Effects on Crop Growth and Composition by Reductions in Soil Fertility. (Crop two—Series B).

In order to learn of the effects of declining fertility levels on growth, nitrogen fixation, nutrient absorption, and plant composition the media of crop one—Series B were used to produce two additional crops, without additional treatment. Both of these additional crops were inoculated with legume bacteria. There was a fallow period of 6 months following the growth of the second crop and before the planting of the third. The fallow sand-clay cultures were watered regularly to prevent the clay from developing undesirable physical properties.

**Growth.**—Throughout the entire period of growth, the second crop showed no irregularities associated with nitrogen deficiencies. But,

TABLE 14.—CONSUMPTION OF POTASSIUM, CALCIUM, AND NITROGEN IN RELATION TO THE TOTAL AMOUNTS SUPPLIED. (DATA FOR 50 PLANTS. CROP ONE—SERIES A.)

| Culture No. | Potassium Supplied* mgms. | Potassium Taken mgms. | Potassium Taken Per Cent** | Calcium Supplied* mgms. | Calcium Taken mgms. | Calcium Taken Per Cent** | Nitrogen Supplied* mgms. | Nitrogen Taken mgms. | Nitrogen Taken Per Cent** |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 178 | 88.5 | 49.6 | 208.1 | 57.6 | 27.6 | 318 | 335.7 | 5.56 |
| 2 | 373.5 | 223.7 | 59.8 | 208.1 | 60.2 | 28.9 | 318 | 406.5 | 27.8 |
| 3 | 569 | 369.8 | 65.0 | 208.1 | 66.1 | 31.8 | 318 | 406.9 | 27.9 |
| 4 | 764.5 | 4714 | 61.6 | 208.1 | 70.4 | 33.8 | 318 | 423.3 | 33.1 |

*Seed contents were: Potassium 178 mgms., calcium 8.1 mgms., and nitrogen 318 mgms.
**The content of the plants as per cent of the total supplied by the seed and the titration is given. In case of the nitrogen, this percentage represents the increase over the initial nitrogen in the seed or per cent fixation.

TABLE 15.—GROWTH OF SOYBEANS IN RELATION TO DECLINING FERTILITY. (DATA FOR 50 PLANTS. CROP TWO—SERIES B.)

| Culture No. | Application of Potassium M E | Weight of 50 Plants: Tops gms. | Weight of 50 Plants: Roots gms. | Weight of 50 Plants: Total gms. | Ratio Tops/Roots | Nodules No. | Per Cent Increase Over No Treatment: Tops | Per Cent Increase Over No Treatment: Roots |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 6.933 | 3.177 | 10.485 | 2.20 | 268 | .... | .... |
| 2 | 5 | 7.095 | 3.073 | 10.377 | 2.31 | 242 | 1.46 | —3.28 |
| 3 | 10 | 7.287 | 3.408 | 11.375 | 2.14 | 263 | 4.21 | 7.30 |
| 4 | 15 | 8.327 | 4.175 | 13.602 | 2.00 | 304 | 19.10 | 31.40 |

at the end of the third week, symptoms which are commonly associated with potassium deficiency began to appear. A light yellowing around the marginal areas of the older leaves, immediately followed by the development of brownish areas of wrinkled necrotic tissue was the usual course. These symptoms may be observed in Plate III. Analyses of the tissue showed that all the cultures were very low in potassium. The relatively low harvest of dry matter per culture, as given in Table 15, was a result of the lower level of nutrients offered.

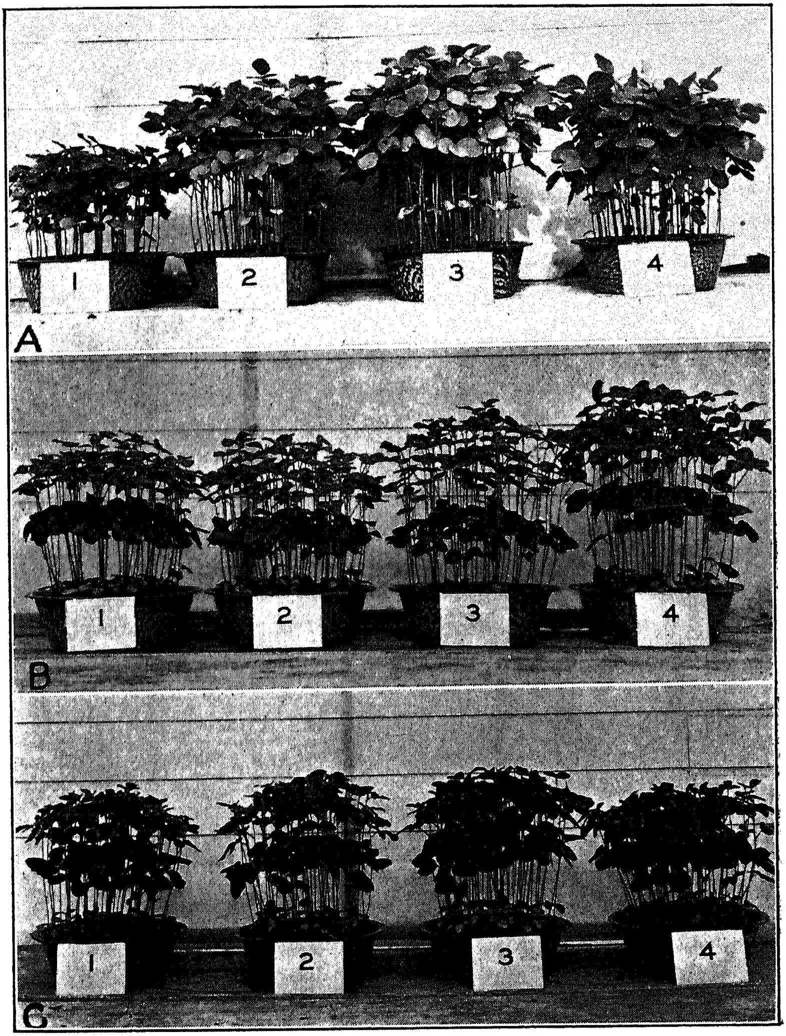


Plate III.—Soybean plants as influenced by declining fertility. A, B, and C represent crops one, two, and three respectively of Series B.

The ratios of tops to roots varied from a low of 2.00 in culture 4 to a high of only 2.31 in culture 2, as is shown in Table 15. These values are much higher than the corresponding ratios of crop one of the same series, which were 1.14, 1.66, 2.11, and 1.65 for increasing potassium treatments in that order. However, they are of the same magnitude as those of crop one—Series A. Top-root ratios seem to be closely correlated with the nitrogen metabolism, since the crop which did not fix nitrogen made extensive root growth while crop one of Series A fixed nitrogen and made relatively larger proportion of top to root growth. All cultures of this second crop were well nodulated, and there was no great variation in number of nodules per culture.

**Potassium Content.**—The potassium contents of the harvested cultures increased with the increasing potassium treatment, but yet the harvested potassium represented a loss from the seed supply in all cultures, except culture 4. The potassium contents of cultures 1, 2, 3, and 4, according to the data of Table 16 were 91.2, 105.8, 157.0, and 195.9 mgms. respectively. The losses from the initial seed potassium by cultures 1, 2, and 3 represent 49.7, 41.4, and 13.3 per cent respectively of the 181 mgms. supplied by the seed. In the preceding crop, cultures 2 and 3 absorbed and retained the titrated potassium in abundant quantities, but the second crop on these cultures did not take up any of the remaining titrated potassium. On the converse, it contributed part of the initial seed potassium to the soil. Culture 1 was again "fertilized" by seed potassium.

TABLE 16.—NITROGEN FIXATION BY SOYBEANS AS INFLUENCED BY DECLINING FERTILITY. (DATA FOR 50 PLANTS. CROP TWO—SERIES B.)

| Culture No. | Application of Potassium M E | Crop Weight gms. | Nitrogen Per Cent | Nitrogen Total mgms. | Nitrogen Fixed mgms. | Potassium Per Cent | Potassium Total mgms. |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 10.485 | 3.31 | 346 | 28 | 0.87 | 91.2 |
| 2 | 5 | 10.377 | 3.34 | 346 | 28 | 1.02 | 105.8 |
| 3 | 10 | 11.375 | 3.33 | 378 | 60 | 1.38 | 157.0 |
| 4 | 15 | 13.602 | 3.18 | 433 | 115 | 1.44 | 195.9 |

Fifty seeds contained 318 mgms. of nitrogen and 181 mgms. of potassium.

**Nitrogen Fixation and Nodule Formation.**—Nitrogen fixation and nodule formation increased from the lowest to the highest levels of potassium, as is shown by the data of Table 16 and graphically by Fig. 7. Cultures originally supplied with 0, 5, 10, and 15 M E of potassium fixed 28, 28, 60, and 115 mgms. of nitrogen respectively. Thus, liberal quantities of nodules were formed in cultures 1, 2, and 3 and nitrogen was fixed, in spite of the fact that potassium was being lost back to the clay in quantities sufficient to show characteristic potassium deficiency symptoms in the growing plants. The amount of seed potassium was sufficient to support plant growth for a period long enough for nodulation and nitrogen fixing processes to take place.

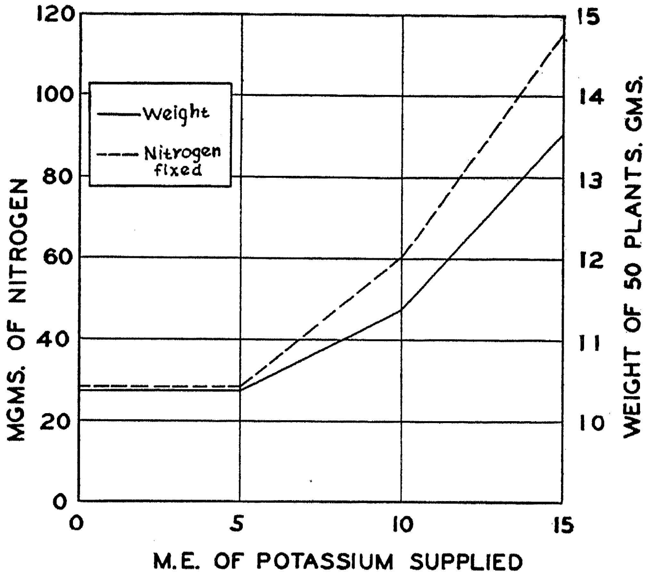


Fig. 7.—Growth and nitrogen fixation as influenced by variable potassium under declining levels of fertility. (Crop Two—Series B.)

**Absorption of Bases and Phosphorus.**—The calcium contents of the second crop, according to the data of Table 17, were higher in percentage than in the preceding crop. This probably can be accounted for by the lower potassium absorption and considerably smaller yields of dry matter. The amounts of calcium removed and of nitrogen fixed showed a close correlation. The low percentage concentration and total amount of magnesium was the result of the very high magnesium consumption by the preceding crop, since from 60.8 to 78.6 per cent of the titrated magnesium had been removed by crop one. Cultures 1, 2, 3, and 4 contained only 21.2, 19.8, 21.7, and 30.0 mgms. of magnesium respectively. Culture 4 took up the largest quantity of magnesium since, as is shown in Table 8, page 18, this culture had the largest amount of magnesium remaining after crop one.

The phosphorus contents showed the usual decline with lower fertility levels. The beneficial effect of the higher levels of potassium on phosphorus consumption was shown in this crop by the increase in phosphorus of cultures 3 and 4 over the initial seed supply, while cultures 1 and 2, with low levels of potassium, lost some initial

TABLE 17.—COMPOSITION OF PLANT MATERIAL AS INFLUENCED BY DECLINING FERTILITY. (DATA FOR 50 PLANTS. CROP TWO—SERIES B.)

| Culture No. | Application of Potassium M E | Potassium | | Calcium | | Magnesium | | Phosphorus | | Barium | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. |
| 1 | 0 | 0.87 | 91.2 | 0.64 | 67.1 | 0.20 | 21.2 | 0.272 | 28.5 | 1.09 | 114.8 |
| 2 | 5 | 1.02 | 105.8 | 0.54 | 56.0 | 0.19 | 19.8 | 0.277 | 28.7 | 0.71 | 73.7 |
| 3 | 10 | 1.38 | 157.0 | 0.53 | 60.2 | 0.19 | 21.7 | 0.290 | 33.2 | 0.32 | 36.9 |
| 4 | 15 | 1.44 | 195.9 | 0.57 | 78.2 | 0.22 | 30.0 | 0.263 | 35.7 | ... | ... |

Fifty soybean seeds contained 181 mgms. of potassium, 11.5 mgms. of magnesium, 8.9 mgms. of calcium and 32.8 mgms. of phosphorus.

TABLE 18.—CARBOHYDRATE CONTENT OF PLANT MATERIAL AS INFLUENCED BY DECLINING FERTILITY. (DATA FOR 50 PLANTS. CROP TWO—SERIES B.)

| Culture No. | Sugar | | | | Starch | | Hemicellulose | | % Reducing Sugar of the Total |
|---|---|---|---|---|---|---|---|---|---|
| | Reducing | | Total | | | | | | |
| | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. | Per Cent | Total mgms. | |
| 1 | 6.80 | 711 | 8.68 | 907 | 4.21 | 440 | 10.77 | 1102 | 78.4 |
| 2 | 5.96 | 632 | 7.46 | 787 | 4.11 | 441 | 9.94 | 1031 | 79.8 |
| 3 | 5.03 | 570 | 8.60 | 978 | 4.09 | 465 | 12.71 | 1445 | 58.5 |
| 4 | 4.95 | 674 | 7.69 | 1046 | 5.19 | 705 | 12.73 | 1698 | 64.4 |

seed phosphorus to the soil. They retained only 28.5 and 28.7 mgms. respectively of the initial seed supply of 32.8 mgms. Even phosphorus, which is usually found in complex chemical combinations in the plants, can be lost from the living plant when it is growing on a highly absorptive medium carrying a low supply of bases and a low degree of base saturation.

**Carbohydrate Production.**—The percentage concentration of the reducing sugars decreased with the increasing residual potassium, as is shown in Table 18. The total sugars were considerably higher, both in concentration and in totals, than in the corresponding cultures of the preceding crop. This difference may be explained by the extreme nitrogen hunger of the first crop at the time of harvest. It is significant that the starch percentages and totals were relatively constant. The low starch contents are in sharp contrast to those of crop one of the same series, but show a close similarity to crop one of the nitrogen fixing series. This relationship is further shown by the performance of a third crop on this medium. Hemicellulose increased in total but varied somewhat in percentage concentration.

**Significance of Fertility Levels as Revealed in Plant Performances.**—The fertility level at which crop two was performing was still sufficiently high to permit nitrogen fixation. It is significant that nitrogen fixation can occur in plants which show a net loss of potassium and of phosphorus at the time of harvest, as was the case for cultures 1 and 2.

The fact that potassium absorption and retention occurred only in culture 4 may be explained by the lower level of bases and lower degree of potassium saturation. There is also the possibility of fixation of potassium into a non-exchangeable or unavailable form. Tests made on the soil after growing a third crop showed that a considerable quantity of the potassium originally titrated into the soil could not be recovered from the soil as exchangeable potassium by the customary exchange reagents.

## Effects on Crop Growth and Composition by Further Reductions in Soil Fertility. (Crop three—Series B).

The legume behavior under very low fertility levels was represented by crop three, since there were no additional treatments added to the soil. The various plant performances as influenced by declining fertility levels are decidedly suggestive of the soil's importance.

**Growth.**—The amount of growth made by crop three is given in Table 19. A residual effect on yields by the potassium originally provided as increasing levels is still in evidence. Cultures 1, 2, 3, and 4 produced yields of 11.938, 12.364, 14.504, and 12.420 grams respectively. These yields are significant when one considers that all cultures showed definite symptons of mineral deficiencies, particularly such as are usually associated with a lack of potassium. In addition, symptoms usually ascribed to a lack of magnesium and of phosphorus were exhibited by some of the cultures. Plate III, row C, page 27, shows the appearance of the crop at the time of harvest.

The root growth in relation to the growth of tops was markedly influenced by the low level of the fertility elements supplied. A greater portion of the dry matter produced was carried by the tops. The ratios of tops to roots gave values of 2.52, 2.53, 2.59, and 3.04 respectively. The preceding crop had ratios considerably smaller than these suggesting that with declining fertility a smaller relative amount of the crop is left as root organic matter in the soil for the succeeding crop.

TABLE 19.—GROWTH AND NODULATION OF SOYBEANS AS INFLUENCED BY DECLINING FERTILITY. (DATA FOR 50 PLANTS. CROP THREE—SERIES B.)

| Culture No. | Application of Potassium M E | Weight of 50 Plants: Tops gms. | Roots gms. | Total gms. | Ratio Tops/Roots | Nodules No. |
|---|---|---|---|---|---|---|
| 1 | 0 | 8.536 | 3.402 | 11.938 | 2.52 | 103 |
| 2 | 5 | 8.860 | 3.504 | 12.364 | 2.53 | 106 |
| 3 | 10 | 10.471 | 4.033 | 14.504 | 2.59 | 50 |
| 4 | 15 | 9.337 | 3.083 | 12.420 | 3.04 | 1 |

**Potassium Content.**—Potassium intake, according to Table 20, showed a negative balance with the single exception of culture 4, which increased slightly. The amounts of potassium harvested in cultures 1 and 2 exceed those harvested in the corresponding cultures of the previous crop. This is not wholly unexpected. There was actually more potassium supplied to the cultures of crop three, than to those of crop two since some of the seed potassium of the previous crop had gone to the soil and had "fertilized" it with potassium. This fertilization was not of inconsiderable magnitude

TABLE 20.—NITROGEN FIXATION AND POTASSIUM CONTENT AS INFLUENCED BY DECLINING FERTILITY. (DATA FOR 50 PLANTS. CROP THREE—SERIES B.)

| Culture No. | Application of Potassium M E | Crop Weight gms. | Nitrogen: Per Cent | Nitrogen: Total mgms. | Nitrogen: Fixed mgms. | Potassium: Per Cent | Potassium: Total mgms. |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 11.938 | 2.55 | 305 | —13 | 1.12 | 133.8 |
| 2 | 5 | 12.364 | 2.68 | 331 | 13 | 1.30 | 160.6 |
| 3 | 10 | 14.504 | 2.21 | 320 | 2 | 1.05 | 151.8 |
| 4 | 15 | 12.420 | 2.70 | 330 | 12 | 1.50 | 193.8 |

Fifty seeds contained 318 mgms. of nitrogen and 181 mgms. of potassium.

as cultures 1, 2, and 3 of the preceding crop lost 90, 75, and 24 mgms. of potassium respectively, back to the soil.

**Nitrogen Fixation and Nodule Formation.**—Although cultures 1, 2, 3, and 4 were nodulated to the extent of 103, 106, 50, and 1 nodule respectively per culture, none demonstrated any significant gain in nitrogen in the form of nitrogen fixation as is shown in Table 20. The failure of this crop to fix nitrogen in any significant amounts may be explained by the critically low levels of calcium, magnesium, and phosphorus in the cultures. All these elements are required in liberal quantities if nitrogen fixation is to proceed normally. Potassium could not have been the limiting factor for nitrogen fixation, since cultures 1 and 2 of the preceding crop contained less potassium, but yet produced greater numbers of nodules and fixed more nitrogen than the corresponding cultures of crop three.

**Cation and Phosphorus Intake.**—The calcium contents, as are given in Table 21, were very low, both in percentage and total. The concentrations were all below 0.45 per cent, the value suggested by Graham (11) as minimal for nitrogen fixation by soybeans in similar experiments. Magnesium was also very low, both in percentage and total, but was above the level supplied by the seed. In every case, even though the plants lost some of their initial potassium, phosphorus, or nitrogen, yet the magnesium and the calcium were always present in amounts in excess of that delivered by the seed. These two nutrient elements were always taken from the soil and were not contributed to the soil by the seed. Phosphorus totals showed a net loss to the soil in all cultures.

**Carbohydrate Production.**—It is of interest and of considerable importance to notice the composition of the dry matter of plants which did not fix nitrogen in significant amounts, because of the extremely low level of bases and of phosphorus. The deficient supply of bases and phosphorus did not cause a cessation of photosynthetic activity since the reducing sugar contents as given by Table 22, were of the same order of magnitude as those of the preceding crop. The failure of the plants to fix nitrogen in quantity had not, at the time of harvest, been reflected in a lower content of reducing and total sugars, as was the case in crop one—Series B which was not nodulated.

The percentages and totals of starch were surprising. After two croppings, the cultures initially treated with increments of potassium showed increasing starch contents both in percentage concentration and in total. This effect was brought about, not by a greater movement of potassium from the soil into the plant, but, by

TABLE 21.—COMPOSITION OF PLANT MATERIALS AS INFLUENCED BY DECLINING FERTILITY. (DATA FOR 50 PLANTS. CROP THREE—SERIES B.)

| Culture No. | Application of Potassium M E | Calcium Per Cent | Calcium Total mgms. | Magnesium Per Cent | Magnesium Total mgms. | Phosphorus Per Cent | Phosphorus Total mgms. | Barium Per Cent | Barium Total mgms. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0.39 | 46.0 | 0.156 | 18.6 | 0.232 | 27.7 | 0.72 | 86.2 |
| 2 | 5 | 0.41 | 50.7 | 0.183 | 22.7 | 0.236 | 29.2 | 0.42 | 51.1 |
| 3 | 10 | 0.27 | 39.5 | 0.144 | 20.9 | 0.204 | 29.7 | 0.10 | 15.3 |
| 4 | 15 | 0.30 | 37.3 | 0.162 | 20.0 | 0.249 | 30.4 | ... | ... |

Fifty soybean seeds contained 181 mgms. of potassium, 8.9 mgms. of calcium, 11.5 mgms. of magnesium, 32.8 mgms. of phosphorus and no barium.

TABLE 22.—CARBOHYDRATE CONTENTS OF PLANT MATERIALS AS INFLUENCED BY DECLINING FERTILITY. (DATA FOR 50 PLANTS. CROP THREE—SERIES B.)

| Culture No. | Sugar, Reducing, Per Cent | Sugar, Reducing, Total mgms. | Sugar, Total, Per Cent | Sugar, Total, Total mgms. | Starch Per Cent | Starch Total mgms. | Hemicellulose Per Cent | Hemicellulose Total mgms. | % Reducing Sugar of Total |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 6.38 | 761 | 9.08 | 1081 | 7.16 | 855 | 10.52 | 1258 | 70.3 |
| 2 | 5.55 | 683 | 8.08 | 995 | 8.38 | 1039 | 9.90 | 1225 | 68.7 |
| 3 | 6.06 | 874 | 8.20 | 1191 | 11.21 | 1625 | 10.46 | 1518 | 73.8 |
| 4 | 4.66 | 569 | 6.86 | 844 | 12.84 | 1801 | 10.24 | 1270 | 67.9 |

a decrease in the amount lost from the plant back to the soil. Since nitrogen was not being fixed, and inconsiderable quantity of sugar was needed for protein synthesis, consequently the increase in carbohydrates produced as a result of greater amounts of potassium metabolized was stored as starch. Cultures 1, 2, 3, and 4 contained 7.16, 8.38, 11.21, and 12.84 per cent respectively of this particular carbohydrate.

**Significance of Further Fertility Decline as Revealed by Plant Performance.**—These starch contents were much higher than those of the nitrogen fixing crops, but were of about the same magnitude as those of the non-nodulated crops. Both crops probably stored starch as the result of a lack of nitrogen, but the fundamental causes for their nitrogen hunger were widely different. In one, all the fertility elements were present in abundance, but active legume bacteria were withheld. In the other, legume bacteria were present, but the fertility elements, particularly calcium, magnesium, and phosphorus were too low to permit symbiotic fixation. However, this important fact stands out, namely, that under the level of bases and phosphorus, which was so low that nitrogen fixation did not occur in appreciable quantities, yet the plants were still able to carry on photosynthesis and to produce appreciable yields of dry

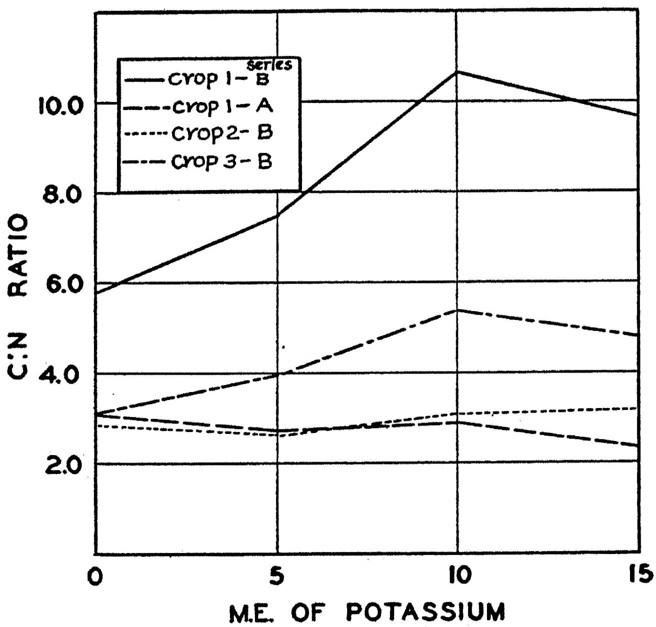


Fig. 8.—Ratios of available carbohydrate carbon to nitrogen of plant material as influenced by variable potassium and different levels of fertility.

matter that were much higher in carbohydrate relative to protein than is the case in the normal nitrogen fixing plants. A comparison of the carbohydrate carbon to nitrogen ratios of the different crops is shown graphically in Fig. 8.

Under declining soil fertility, the plant's protein manufacturing processes are evidently the first to discontinue. Carbohydrate production, even in legumes, apparently continues under a much lower supply of fertility elements since the plants, which showed net losses of phosphorus, and of potassium, and which had very low supplies of nitrogen, magnesium, and calcium, were still able to produce appreciable quantities of starches and sugars.

## Soil Exhaustion

The efficiency of a nutrient cation, when applied to the soil, is closely related to the rate of its removal and degree to which it is exhausted by the feeding activities of plants. Soil factors which have been shown to influence the rate and extent of fertility removal by crops, include among others: (1) the total amount of cation present in an available form; (2) the degree of saturation of the soil by the cation; and (3) the amount and nature of the other cations present. (16). The Series B was used to study the effect of continuous cropping in relation to the above factors. Changes in the soil were easily followed, since records were kept of all nutrient additions to the soil by titration and by the seed, and of nutrient removals in the crops. The difference between the amount of a nutrient element harvested and that supplied was considered to be the amount left in the culture medium in the available form. This assumption is not entirely correct since small quantities of nutrients may pass from the unavailable form in the clay crystal into an available form. However, the extent of this change (3) is so small as to preclude this possibility as a source of significant supplies of plant nutrients during a short period of five weeks. It is also possible that nutrients in an available or exchangeable form may become unavailable.

**Depletion of Bases in the Soil.**—Continuous cropping reduced the level of bases, other than barium, in cultures 1, 2, 3, and 4 from saturations of 50, 66.6, 83.3, and 100 per cent respectively to very low levels. All cultures, after the third crop, were saturated to but 25 to 35 per cent with bases other than barium as is shown by Fig. 9. This low level was approached regardless of the initial treatment. Cultures supplied with higher amounts of potassium declined most rapidly in base saturation since potassium was most easily taken up. The critically low level of bases present in the soil

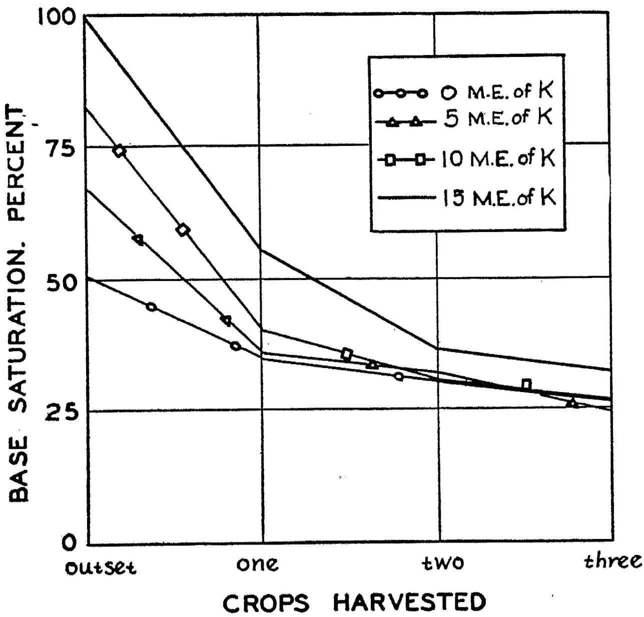


Fig. 9.—Decline of bases, other than barium, as influenced by continuous cropping.

TABLE 23.—DIFFERENT DEGREES OF ACIDITY, pH, AS A RESULT OF SUCCESSIVE CROPS.

| Culture No. | Application of Potassium M E | Outset | After First Crop | After Second Crop | After Third Crop |
|---|---|---|---|---|---|
| 1 | 0 | 6.60 | 5.50 | 5.02 | 4.44 |
| 2 | 5 | 6.70 | 5.34 | 4.80 | 4.25 |
| 3 | 10 | 6.75 | 5.05 | 4.55 | 4.25 |
| 4 | 15 | 6.75 | 4.80 | 4.40 | 4.20 |

was not without its effect on crop performance, as was indicated. As further evidences of the extreme unsaturation of the media, there are the very high degrees of acidity in all cultures, as given by the pH values in Table 23. All cultures had pH values below 4.5 after the third crop. Base saturation changes of each culture as influenced by cropping are shown graphically by Fig. 10 in which the outstanding feature is the increase in saturation by hydrogen with successive cropping.

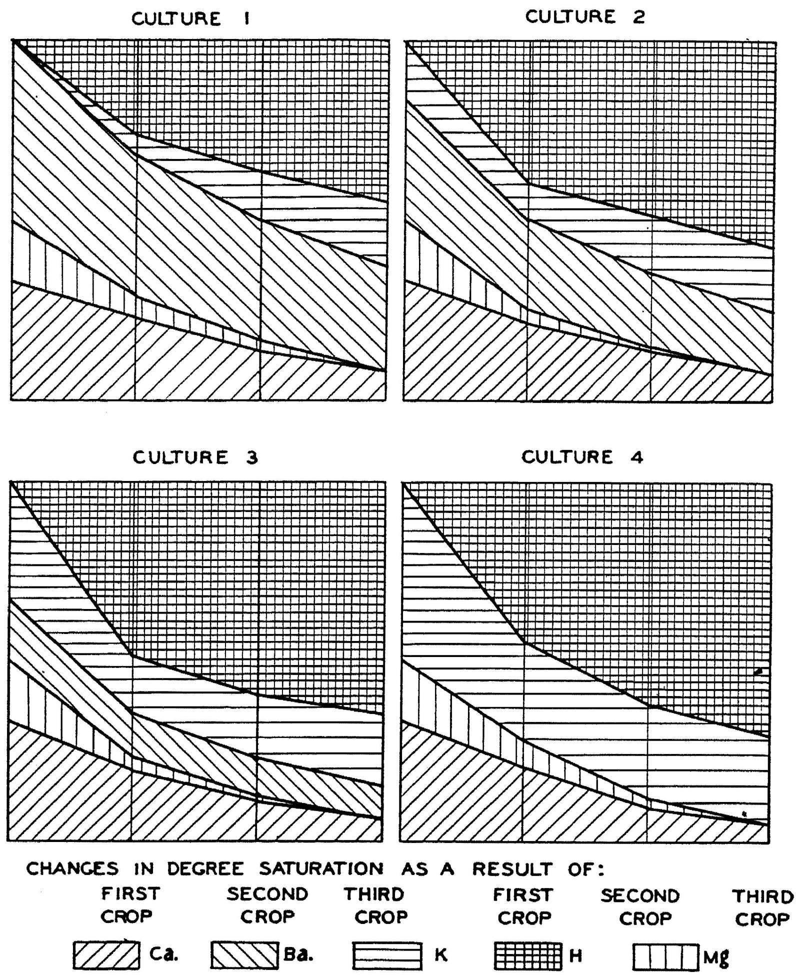


Fig. 10.—Changes in the degree of saturation by the different cations as a result of successive croppings.

**Potassium Exhaustion.**—In no case was there any potassium removed from the soil to which none had been added by titration. In fact, potassium moved in the reverse direction and the soil of culture 1 gained potassium continually from growing the three crops until it contained about 5.23 M E or an amount equal to 17.3 per cent of the exchange capacity. Culture 2 showed a decline in potassium saturation after the first crop, but continued cropping resulted in an increase in soil potassium. Regardless of

## Table 24.—Potassium Removal by Three Successive Crops.

| Culture No. | Crop 1 | | | Crop 2 | | | Crop 3 | | | Potassium Remaining mgms. | Per Cent Recovery of Potassium |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total K Supplied* mgms. | Taken mgms. | Per Cent Taken | Total K Supplied** mgms. | Taken mgms. | Per Cent Taken | Total K Supplied mgms. | Taken mgms. | Per Cent Taken | | |
| 1 | 178 | 111.2 | 62.3 | 247.8 | 91.2 | 36.7 | 337.6 | 133.8 | 39.8 | 204 | ... |
| 2 | 373.7 | 258.5 | 69.2 | 296.2 | 105.8 | 35.7 | 371.4 | 160.6 | 43.3 | 211 | —7.8 |
| 3 | 569.4 | 379.4 | 66.7 | 370.8 | 157.0 | 42.3 | 394.8 | 151.8 | 38.4 | 243 | 62.2 |
| 4 | 765.1 | 450.3 | 58.9 | 495.4 | 195.9 | 39.6 | 480.5 | 193.8 | 40.4 | 287 | 48.9 |

*Includes titrated potassium plus the seed supply of 178 mgms.
**Titrated potassium unused by Crop 1 plus seed potassium.

the degree of initial potassium saturation, there was a marked tendency for all cultures to attain approximately the same value after continuous cropping.

The recoveries, or the extents of exhaustion, of the titrated potassium of cultures 2, 3, and 4, initially supplied with 5, 10, and 15 M E of Potassium were –7.8, 62.2, and 48.9 per cent respectively, as is shown by Table 24. It is contrary to anticipation that the per cent exhaustion of an applied element should be lowest in the cultures receiving the smallest supply. Potassium loss from the clay to the crop was little influenced by the total cation saturation, as is shown by Fig. 10. Potassium moved in that direction, first in the culture saturated with bases at the outset to 100 per cent.

The nature of the residual potassium in the clay was studied by determining the amounts that could be removed by exchange with neutral normal ammonium acetate. A significant quantity was in a non-exchangeable form since only 19.0, 27.5, 24.1, and 25.8 per cent of the remnant of that originally supplied plus that added by crop growth, in the cultures 1, 2, 3, and 4 respectively were exchanged. These data are assembled in Table 25.

TABLE 25.—EXCHANGEABLE POTASSIUM IN THE SOIL AFTER THREE SUCCESSIVE CROPPINGS.

| Culture No. | Application of Potassium M E | Remaining in Culture* mgms. | Exchangeable mgms. | Exchangeable Per Cent |
|---|---|---|---|---|
| 1 | 0 | 204 | 38.7 | 19.0 |
| 2 | 5 | 211 | 58.2 | 27.5 |
| 3 | 10 | 243 | 58.5 | 24.1 |
| 4 | 15 | 287 | 74.2 | 25.8 |

*Includes remnant of potassium supplied by the initial titration and that contributed by the seeds of crops grown.

**Nitrogen Changes.**—The analyses for total nitrogen of the electrodialyzed clay soils before and after cropping show significant increases in nitrogen content as a result of cropping as given in Table 26. All cultures treated with potassium showed greater increments of nitrogen in the media than was shown by the culture with no treatment. Whether nitrogen was lost from the nodulated

TABLE 26.—CHANGES IN THE TOTAL NITROGEN IN THE SOIL AFTER SUCCESSIVE CROPPING. (MEDIA OF SERIES B.)

| Culture No. | Application of Potassium M E | Nitrogen At Outset mgms. | Nitrogen After Cropping mgms. | Increase in Nitrogen mgms. |
|---|---|---|---|---|
| 1 | 0 | 68 | 102 | 34 |
| 2 | 5 | 68 | 115 | 47 |
| 3 | 10 | 68 | 120 | 52 |
| 4 | 15 | 68 | 116 | 48 |

crops cannot be said since all cultures of the non-nodulated crop lost more nitrogen than was shown as final gain in nitrogen by any soil. These differences may have been due to volatilization of nitrogen from the media. Regardless of the crop or crops from which it came, the significant item is that nitrogen must have passed from the plant to the clay in a soluble state since there was no nitrogen contributed by aerial plant parts, and the amount of material added by sloughing off of root tissue was probably negligible.

**Phosphorus Exhaustion.**—The efficiency of phosphorus absorption into the plant was stimulated by potassium additions. In the three crops, with a total of twelve cultures, there was only one instance in which an increase in applied potassium failed to give a greater percentage of supplied phosphorus taken. The data are given in Table 27. The third crop, which was growing under a very low level of bases and in media of extremely low pH, still showed consistent increases in efficiency of phosphorus removal with increased potassium. Cultures 1, 2, 3, and 4 took up 40.0, 48.3, 56.0 and 63.8 per cent respectively of the total phosphorus supplied by the seed and by the residual titrated phosphorus. Although the percentage taken of the total supplied showed consistent increases in all crops with potassium treatment, yet actually cultures 1 and 2 of crop two and

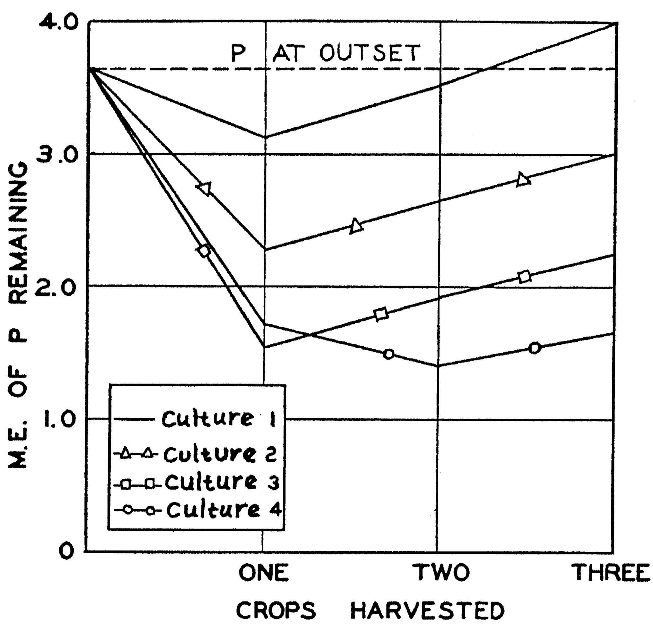


Fig. 11.—Losses and gains in phosphorus by clay, resulting from successive cropping.

TABLE 27.—PHOSPHORUS REMOVAL BY SUCCESSIVE CROPPING. (SERIES B.)

| Culture No. | Crop 1 Total Supplied* mgms. | Crop 1 Taken mgms. | Crop 1 Per Cent Taken | Crop 2 Total Supplied mgms. | Crop 2 Taken mgms. | Crop 2 Per Cent Taken | Crop 3 Total Supplied mgms. | Crop 3 Taken mgms. | Crop 3 Per Cent Taken | Phosphorus Remaining in Cultures mgms. | Per Cent Recovery |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 61.3 | 29.3 | 47.4 | 65.3 | 28.5 | 43.7 | 69.4 | 27.7 | 40.0 | 41.7 | —9.74 |
| 2 | 61.8 | 38.2 | 61.8 | 56.4 | 28.7 | 51.0 | 60.5 | 29.2 | 48.3 | 31.3 | 17.6 |
| 3 | 61.8 | 45.7 | 73.8 | 48.9 | 33.2 | 68.0 | 53.0 | 29.7 | 56.0 | 23.3 | 38.7 |
| 4 | 61.8 | 44.1 | 71.3 | 50.5 | 35.7 | 70.7 | 47.6 | 30.4 | 63.8 | 17.2 | 54.8 |

*The initial titrated supply was 38.0 mgms.
**Titrated phosphorus unused by preceding crop and seed phosphorus.

TABLE 28.—CALCIUM REMOVAL BY CONTINUOUS CROPPING. (SERIES B.)

| Culture No. | Crop 1 Total Ca Supplied* mgms. | Crop 1 Taken mgms. | Crop 1 Per Cent Taken | Crop 2 Total Ca Supplied** mgms. | Crop 2 Taken mgms. | Crop 2 Per Cent Taken | Crop 3 Total Ca Supplied mgms. | Crop 3 Taken mgms. | Crop 3 Per Cent Taken | Calcium Remaining in Cultures mgms. | Per Cent Recovery |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 208.5 | 66.7 | 31.9 | 150.7 | 67.1 | 44.5 | 92.5 | 46.0 | 49.8 | 46.5 | 76.7 |
| 2 | 208.5 | 80.4 | 38.5 | 137.0 | 56.0 | 40.8 | 89.9 | 50.7 | 56.4 | 39.2 | 80.5 |
| 3 | 208.5 | 92.2 | 44.2 | 125.2 | 60.2 | 48.0 | 73.9 | 39.5 | 53.5 | 34.4 | 82.8 |
| 4 | 208.5 | 88.7 | 42.5 | 128.7 | 78.2 | 60.8 | 59.4 | 37.3 | 62.6 | 22.1 | 89.0 |

*The initially titrated supply of Ca was 200.4 mgms. The seed content of Ca was 8.1 mgms.
**Titrated calcium unused by Crop 1 and seed calcium.

all cultures of crop three lost phosphorus back to the soil as is shown by the data of Table 27 and graphically in Fig. 11. The percentage recovery of the initially supplied phosphorus increased tremendously with potassium treatment. In cultures 1, 2, 3, and 4 the amounts as percentage phosphorus recovery were -9.74, 17.6, 38.7, and 54.8 per cent respectively.

**Calcium Exhaustion.**—Calcium recovery from the soil by the crop increased with potassium additions. The percentage recovery of the initial supply was rather high in all cultures as is indicated by the data of Table 28. Even in the cultures of lowest fertility there was no loss of calcium back to the soil.

**Magnesium Exhaustion.**—Magnesium removal by continuous cropping with soybeans shows some very interesting results. From a constant initial supply of 60.8 mgms., cultures 1, 2, 3, and 4 recovered 95.1, 105, 107, and 98.4 per cent respectively. These data are given in Table 29 and shown graphically by Fig. 10, The three crops on cultures 2 and 3 took up 3.5 and 4.3 mgms. more of magnesium than the 60.8 mgms. originally supplied. These differences are probably within the limit of experimental error. Previous work, (3) however, has suggested the possibility of a small magnesium release from the clay to the plant. It is also of interest that the soil at no time gained magnesium by loss from the planted seed. The extent and degree of magnesium exhaustion were very high in view of the fact that the base saturation of the soil was extremely low and showed pH values ranging from 4.5 to 4.2.

**Barium Exhaustion.**—Barium was removed by cropping to a lesser extent than were the other divalent cations. Since it is a non-nutrient, one might expect it to behave in plant nutrition as though it were governed wholly by physico-chemical laws. If this is true, then absorption by the plant should be proportional to the concentration of barium present. That such was the case is strongly indicated by the data of Table 30, since the percentage recovery was almost a constant for all cultures, despite the fact that barium was supplied cultures 1, 2, 3, in amounts varying as widely as 1:2:3. The percentage taken by each crop was approximately constant and the crop contained larger amounts as larger amounts were present. The efficiency of absorption by a given culture decreased considerably with the declining fertility level. Crops 1, 2, and 3 removed on an average 25.0, 14.5, and 10.4 per cent of the supplied amounts respectively.

### Table 29.—Magnesium Removal by Successive Croppings. (Series B.)

| Culture No. | Crop 1 Total Supplied* mgms. | Crop 1 Taken mgms. | Crop 1 Per Cent Taken | Crop 2 Total Supplied** mgms. | Crop 2 Taken mgms. | Crop 2 Per Cent Taken | Crop 3 Total Supplied mgms. | Crop 3 Taken mgms. | Crop 3 Per Cent Taken | Magnesium Remaining in Cultures mgms. | Per Cent Recovery |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 71.6 | 51.8 | 72.3 | 31.3 | 21.2 | 67.8 | 21.6 | 18.6 | 86.1 | 3.0 | 95.1 |
| 2 | 71.6 | 55.6 | 77.7 | 27.5 | 19.8 | 72.0 | 19.2 | 22.7 | 118.0 | —3.5 | 105.5 |
| 3 | 71.6 | 56.3 | 78.7 | 26.8 | 21.7 | 81.0 | 16.6 | 20.9 | 126.0 | —4.3 | 107.0 |
| 4 | 71.6 | 43.6 | 60.8 | 39.5 | 30.0 | 76.0 | 21.0 | 20.0 | 95.2 | 1.0 | 98.4 |

*The initially titrated supply of Mg was 60.8 mgms. The seed content of Mg was 10.8 mgms.
**Titrated magnesium unused by Crop 1 and seed magnesium.

### Table 30.—Barium Removal by Successive Croppings. (Series B.)

| Culture No. | Crop 1 Total Supplied* mgms. | Crop 1 Taken mgms. | Crop 1 Per Cent Taken | Crop 2 Total Supplied mgms. | Crop 2 Taken mgms. | Crop 2 Per Cent Taken | Crop 3 Total Supplied mgms. | Crop 3 Taken mgms. | Crop 3 Per Cent Taken | Barium Remaining in Cultures mgms. | Per Cent Recovery |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1030.2 | 216.3 | 21.0 | 813.9 | 114.8 | 14.1 | 699.1 | 86.2 | 12.3 | 612.9 | 40.5 |
| 2 | 686.8 | 181.4 | 26.4 | 505.4 | 73.7 | 14.6 | 431.7 | 51.1 | 11.8 | 380.6 | 44.6 |
| 3 | 343.4 | 94.5 | 27.6 | 248.9 | 36.9 | 14.8 | 212.0 | 15.3 | 7.22 | 196.7 | 42.8 |
| 4 | .... | .... | ... | .... | .... | ... | ... | ... | ... | ... | ... |
| | | Average— | 25.0 | | | 14.5 | ... | | 10.4 | | |

*The seed contained no barium.

**Iron, Aluminum, and Silicon Removal by Plants.**—The intake and exhaustion of the non-nutrient cation, barium, from the adsorbed state suggested that perhaps silicon, aluminum, and iron behaved similarly. Considerable quantities of these elements were present in the electrodialyzed colloidal clay as shown by Table 1, page 9. Although the clay had been electrodialyzed, the data of Table 31 show that significant quantities of these elements were taken in by the plants. The content of iron decreased both in percentage and in total in all crops with increasing potassium supply. The silicon concentration in crop one showed a downward trend with treat-

TABLE 31.—SILICON, ALUMINUM, AND IRON CONTENTS OF PLANT MATERIALS AS INFLUENCED BY POTASSIUM. (DATA FOR 50 PLANTS. SERIES B.)

| Culture No. | Application of Potassium M E | Silicon Per Cent | Silicon Total mgms. | Aluminum Per Cent | Aluminum Total mgms. | Iron Per Cent | Iron Total mgms. |
|---|---|---|---|---|---|---|---|
| First Crop | | | | | | | |
| 1 | 0 | 0.42 | 64.1 | 0.19 | 27.2 | 0.420 | 60.1 |
| 2 | 5 | 0.33 | 64.4 | 0.20 | 39.0 | 0.230 | 45.9 |
| 3 | 10 | 0.26 | 58.1 | 0.14 | 32.6 | 0.075 | 16.9 |
| 4 | 15 | 0.27 | 56.0 | 0.16 | 33.3 | 0.086 | 18.2 |
| Second Crop | | | | | | | |
| 1 | 0 | 0.18 | 19.0 | 0.12 | 13.1 | 0.29 | 31.0 |
| 2 | 5 | 0.19 | 19.6 | 0.09 | 9.9 | 0.19 | 20.4 |
| 3 | 10 | 0.17 | 19.4 | 0.07 | 7.9 | 0.24 | 27.8 |
| 4 | 15 | 0.21 | 29.1 | 0.12 | 17.0 | 0.14 | 19.3 |
| Third Crop | | | | | | | |
| 1 | 0 | 0.18 | 22.0 | .064 | 7.8 | 0.115 | 13.8 |
| 2 | 5 | 0.18 | 22.2 | .074 | 9.2 | 0.098 | 12.1 |
| 3 | 10 | 0.16 | 23.3 | .087 | 12.6 | 0.080 | 11.6 |
| 4 | 15 | 0.13 | 15.1 | .066 | 6.8 | 0.052 | 5.6 |

Fifty seeds contained 0.2 mgms. of iron and only traces of silicon and aluminum.

ment, but in the second and third crops silicon showed no definite trends. It is of interest that the total silicon, iron, and aluminum removed declined with successive croppings, as is shown by Table 32. This decrease cannot be ascribed to a decline in the total silicon aluminum, and iron in the media, since the amounts removed by cropping represent only a very small fraction of the total amounts present. Neither is it due entirely to diminished yields of harvested materials for the decline in the removal of these elements is proportionally greater than the decrease in yields. The third crop pro-

TABLE 32.—REMOVAL OF SILICON, ALUMINUM, AND IRON AS INFLUENCED BY SUCCESSIVE CROPPINGS.

| Crop | Silicon mgms. | Aluminum mgms. | Iron mgms. |
|---|---|---|---|
| First | 242.6 | 131.1 | 141.1 |
| Second | 87.1 | 47.9 | 98.5 |
| Third | 82.6 | 36.4 | 43.1 |

duced as much dry matter as the second crop yet contained less of silicon, aluminum, and iron.

There is suggested the possibility that a part of the silicon, aluminum, and iron of the electrodialyzed clay is present in a form more readily taken in by plants than the major portion. If such were the case, then these elements too would be subject to depletion by successive croppings. This suggesion is supported by some work by Mattson (28) who showed that a part of the iron and aluminum even in an electrodialyzed clay can be liberated simply by washing the clay with solutions of neutral salts. Successive treatments with salt solutions removed correspondingly less of aluminum and iron.

**Significance of Soil Depletion as Reflected by Plant Performances.**—That fertility decline under cropping proceeds at a decreasing rate until a fairly constant level is obtained is a common observation. However, the reverse process, or the building up to that level, by cropping is not commonly observed. The results obtained in the study of the soil exhaustion indicate that this was happening in cultures 1 and 2, with respect to potassium. The ready passage of potassium from living plant roots to an unsaturated colloidal clay has been demonstrated by Jenny and Overstreet (20), working with barley roots. They showed that the rate of depletion was much slower with a saturated clay. The data obtained with soybeans in this study indicate that this reverse movement of potassium, from plants high in this constituent, is not dependent entirely on a highly unsaturated medium, since the reversal of potassium movement occurred from plants grown five weeks, even in soil saturated to 100 per cent initially with barium, magnesium, and calcium. One would infer that in a highly adsorptive medium, such as the soil, a minimal level of available potassium is necessary to prevent the loss of potassium from plants high in this element. The extents of recovery of the initially supplied elements show some very interesting differences as shown by the data assembled in Table 33. The divalent ions moved into the plants in all cases even though the total amount and per cent saturation of the ion on the clay were very low. This was particularly true in the media of the last crop.

TABLE 33.—INITIALLY SUPPLIED NUTRIENTS RECOVERED BY SUCCESSIVE CROPPINGS.

| Culture No. | Application of Potassium M E | Potassium % | Phosphorus % | Calcium % | Magnesium % | Barium % |
|---|---|---|---|---|---|---|
| 1 | 0 | ... | −9.74 | 76.7 | 95.1 | 40.5 |
| 2 | 5 | −7.8 | 17.6 | 80.5 | 105.5 | 44.6 |
| 3 | 10 | 62.2 | 38.7 | 82.8 | 107.0 | 42.8 |
| 4 | 15 | 48.9 | 54.8 | 89.0 | 98.4 | ... |

Calcium behavior was similar to that of magnesium. Both showed a net movement into the plant. Barium was absorbed to a lesser degree than either magnesium or calcium.

The monovalent ion, potassium showed no consistency in direction of movement, going into the plant when sufficient quantities in an available form were supplied in the soil and being lost to the soil under other conditions. Phosphorus and potassium behaved similarly as regards gain or loss by the plant. The total phosphorus removed by cropping was stimulated considerably by potassium treatment.

Nitrogen gains in the cultures were due, in part at least, to losses from crop one, the non-nodulated crop. At the time of harvest this crop was showing marked symptoms of nitrogen deficiency. It seems highly probable that protein nitrogen was being broken into cationic nitrogen, a form which would have a great tendency to unite with the colloidal substrate. The passage of nitrogen from living plant nodules into the substrate has been reported by Virtanen (40) (41). He reported this movement to be greatest with plants growing on substrates such as soil or kaolin.

It is suggested by the data that magnesium intake can occur at levels of saturation so low that phosphorus and potassium are being lost from the plant. The data also suggest that the percentage intake of total magnesium supplied does not decrease greatly under declining fertility levels as was true for potassium. The fact that no loss of seed magnesium occurred under extremely low levels of magnesium saturation emphasizes the properties by which magnesium, once metabolized, must remain within the plant tissue.

The proportionality between barium absorption and the amounts supplied suggests that there was no selective influence by the plant affecting barium intake. Such a suggestion might also be drawn from the fact that barium is not considered as playing any functional role in plant metabolism. Within limits, barium exerted no recognizable injurious effect on plants grown in substrates high in colloid content. From these observations, the use of barium as a cation to be varied reciprocally with any other cation seems to be a justifiable experimental technique.

## DISCUSSION

The results obtained in this study show a definite influence by potassium on nitrogen fixation and plant composition. The total nitrogen content of nodulated soybeans which were well supplied with calcium, magnesium, and phosphorus, increased with increasing potassium treatment. However, its percentage concentration remained almost a constant or decreased slightly with increasing potassium supplied indicating a greater effect of potassium on carbohydrate production. The increased absorption of calcium and phosphorus in the potassium treated cultures prevented these elements from being limiting factors in nitrogen fixation.

From the data presented there is evidence that potassium is a factor in nitrogen fixation and protein formation not only through its stimulation of carbohydrate production but, since the reducing sugars declined while other carbohydrates, such as starch and hemicelluloses, remained constant with increasing potassium additions, it might be inferred that potassium played an additional role in the protein synthesis.

Plants which were inoculated and fixing nitrogen showed no significant changes in the ratio of carbohydrate to protein in the plants at the higher levels of potassium used in the experiment, since proportionately more nitrogen was fixed. However, when nitrogen was deficient either because of non-nodulation or of an insufficient supply and degree of saturation of the other fertility elements, potassium treatments resulted in a tremendous increase in carbohydrate production and storage so that the ratio of carbohydrate to protein widened considerably as a consequence. This is of considerable significance in the production and use of legumes for purposes of forage feed.

All soybeans which were non-nodulated had lost an average of 23 per cent of their original seed nitrogen at the end of a growing period of five weeks. This loss was probably accelerated by the very high absorptive capacity of the media for soluble cationic substances. Soluble cationic nitrogen is found in plants in more or less amounts during the entire growing period. The fact that these plants had just begun to show nitrogen deficiency symptoms may also have been a factor in nitrogen loss since it has been shown (12) that during senescence of plants there is a breakdown of plant proteins into less complex mobile substances some of which presumably might possess cationic properties. Nitrogen losses from nodules of cowpeas to the media have been extensively studied by Virtanen and co-workers. (40) (41). These excreted nitrogen compounds were shown to consist largely of amino acids. He found no evidence of nitrogen excretion from root surfaces of non-nodulated cowpeas which were grown in sand or kaolin.

Since calcium and magnesium are chemically related they might be expected to behave similarly in the processes of nutrient absorption and metabolism by the plant. That there is a similarity in certain performances was indicated, since the data show that in all cases, even under very low levels of fertility, calcium and magnesium always showed a net gain in the plants above the seed contents. There is evidence that the feeding capacities of soybean plants for magnesium and calcium, when supplied in an exchangeable form on a colloidal clay, differ considerably. The magnesium taken as percentage of the total supplied, was, in all cases from one and one-half to two times as great as that for calcium. Magnesium absorption remained high when the magnesium supply and the supply of other bases was so low that phosphorus and potassium were lost from the plants to the soil. The relative positions of calcium and magnesium in the ionic double layer of the exchange complex as it affects their ease of replacement may serve to explain these differences. Magnesium has been shown to be more highly hydrated than calcium and more readily displaced from homionic clays of calcium and magnesium. (10). This explains the common observation that plants may grow on soils with an apparently low content and degree of saturation of exchangeable magnesium and yet show no significant response to applications of magnesium.

## SUMMARY AND CONCLUSIONS

A study was made of the influence of potassium on nitrogen fixation and plant composition of soybeans. An electrodialyzed colloidal clay from the Putnam subsoil was used as a carrier of this cation along with constant amounts of calcium, magnesium, phosphorus, and non-nutrient barium varying reciprocally with potassium.

The effect of fertility depletion by continuous cropping on nitrogen fixation and carbohydrate production was also studied. Attention was given to the rate and degree of depletion from the soil of the various elements by successive croppings of soybeans. On the basis of this work the following facts seem of importance.

1. Nitrogen fixation increased with higher levels of available potassium when accompanied by constant amounts of calcium, phosphorus, and magnesium.

2. The concentration of reducing sugars in both nodulated and non-nodulated crops decreased with increasing potassium treatment.

3. In non-nodulated soybeans the starch content increased tremendously, both in percentage and totals, with the higher levels of available potassium. Soybeans which were nodulated and fixing nitrogen increased in total starch but remained relatively constant in percentage concentration as increments of potassium were supplied.

4. Crops on media which were too low in the fertility items to permit nitrogen fixation and protein production were almost constant in total nitrogen content but contained increasing amounts of carbohydrates, especially starch, in proportion to the amount of potassium metabolized.

5. Soybeans lost potassium from the seed to the soil in cultures with no initial treatment of potassium, even though the soil was fully saturated with bases other than potassium and approximately neutral at the outset.

6. Potassium was taken by plants in relatively large quantities from soil initially saturated with bases and containing potassium in an exchangeable form.

7. The efficiency of phosphate removal by plants was enhanced considerably by potassium treatments.

8. The plants showed a greater relative absorption and depletion of magnesium than of any other cation.

9. All media tended to approach the same degree of saturation of ions other than barium when cropped successively.

10. Potassium, phosphorus, and nitrogen moved from the plant to the soil under certain conditions. The cations, calcium, and magnesium were always present in the harvested crop in excess of the amounts supplied by the seed.

11. Significant quantities of nitrogen were lost back to the soil by non-nodulated soybeans even in the relatively short period of five weeks.

12. Crops growing under a low supply of nitrogen and an adequate supply of bases produced more root growth in relation to tops than crops which were nodulated and which fixed nitrogen.

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