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GROWTH AND NUTRITION OF PLANTS AS AFFECTED BY DEGREE OF BASE SATURATION OF DIFFERENT TYPES OF CLAY MINERALS

By T. S. CHU and L. M. TURK

MICHIGAN STATE COLLEGE

AGRICULTURAL EXPERIMENT STATION

SECTIONS OF AGRICULTURAL CHEMISTRY, ANIMAL PATHOLOGY, ANIMAL HUSBANDRY AND BACTERIOLOGY

EAST LANSING

CONTENTS

Growth and Nutrition of Plants as Affected by Degree of Base Satuation of Different Types of Clay Minerals[1]

By TSU SIANG CHU and L. M. TURK[2]

Exchangeable bases held on the surface of soil colloids have been considered by many soil scientists and agronomists to be available to plants. Recent workers, however, have indicated that not all exchangeable bases held on the soil colloidal surface are equally available for plant absorption. Among the factors which affect the availability of exchangeable bases to plants, the nature of colloids, degree of base saturation, and nature of complementary ions are important.

In a study of some chemical properties of orchard soils in relation to satisfactory and unsatisfactory growth of peach trees, the senior author (8) found that two groups of soils supporting trees of different growth vigor, although containing about the same amount of total exchangeable bases, varied greatly in the degree of base saturation owing to the difference in their base exchange capacity. Soils supporting good growth of peach trees had a much higher degree of saturation of total as well as of individual exchangeable bases than those supporting poor growth of peach trees. Although the finding is not considered as a conclusive one in the case of peach trees, it is believed that there exists a relationship between the degree of base saturation of soils and plant growth.

The objectives of this investigation were to attain a better understanding of the significance of the degree of base saturation and the nature of complementary ions in relation to the growth and composition of certain crops, and to evaluate the effect of the nature of clay minerals on the availability of exchangeable cations.

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[1]Thesis submitted by the senior writer to the Graduate School of Michigan State College in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

[2]Professor of Soil Science, National Chekiang University, China; and Professor of Soil Science, Michigan State College, respectively. The writers wish to express their sincere appreciation to Dr. R. L. Cook for taking most of the photographs used in this bulletin and to Dr. N. S. Hall for constructive advice and encouragement during the early stages of the research.

REVIEW OF LITERATURE

Probably one of the first investigators to study the effect of the degree of base saturation on plant growth was Stohmann (36). Using organic colloid, he found in 1864 that the yield of matured corn plants increased with the degree of base saturation. Since then, little knowledge has been accumulated regarding the effect of degree of base saturation of soils on the plant growth until recently when soil workers have taken a renewed interest in this problem.

During the past decade, many papers stressing the importance of degree of base saturation in relation to plant growth have been reported. Thus, Gedroiz (11) and several other investigators working with soils and plant systems found that the exchangeable calcium is available for plant growth only as its degree of saturation is relatively high. Jenny and Cowan (19) found that the growth of soybean plants in Ca-H-clay suspensions was sharply reduced when the degree of calcium saturation fell below 30 per cent of the total exchange capacity. Also working with soybeans, Horner (16) found that with a constant total amount of calcium, the growth of the plants, as measured by both height and weight, increased markedly when the degree of calcium saturation increased from 40 to 60 percent. Albrecht (1), in discussing degree of calcium saturation of clay and nitrogen fixation, concluded that calcium from the same original total supply was delivered into the plants to a much larger extent when it was on a nearly saturated clay than on one only partly saturated. Similar conclusions drawn from the results of soybean experiments also have been reached recently by Mehlich and Colwell (26) and Mehlich and Reed (27).

According to the recent report of Bower and Turk (6), naturally occurring alkali soils high in exchangeable sodium may not furnish an adequate supply of calcium to plants despite the presence of $CaCO_3$. This is in harmony with the finding of Gedroiz (11) that soils saturated with ammonium, sodium or potassium failed to support plant growth even when $CaCO_3$ was added to the cultures.

It has been suggested by some investigators that the kind of complementary ions present on the colloidal surfaces may affect the availability of the other exchangeable ions. Using purely chemical methods, Seatz and Winters (34) were able to prove that much more potassium was released from the exchangeable complex when the complementary ion was dominantly calcium than when it was dominantly hydrogen. Previous work done by Peech (31) has also substantiated this theory by chemical analysis.

The effect of the nature of complementary ion on the nutrient absorption by plants also was demonstrated by the experiments of Jenny and Ayres (18), using excised barley roots. Their results are in general agreement with those mentioned above. However, results conflicting with them have also been reported by many workers. According to Albrecht and Schroeder (2), the degree of H-ion saturation is in general a helpful factor in mobilizing calcium, magnesium and other cations into plants, although it does not affect the availability of potassium.

Contradictory results regarding the degree of base saturation in relation to cation availability to plants may be attributed partly to the difference in the nature of clay minerals. Elgabaly, *et al.* (10) found that the uptake of Zn and K by barley roots was affected by the type of clay mineral.

Studies by Mehlich and Colwell (26) and by Allaway (4) showed that calcium uptake by plants was greater from soils or colloids representing the 2:1 lattice type. Recently, working with peanuts, Mehlich and Reed (28) found that for any given level of calcium, the calcium content of the peanut shells was highest when the plants were grown in the kaolinitic-type colloid; but, on the other hand, the highest content of calcium in the plants was found in those growing in the organic-type colloid.

EXPERIMENTAL

MATERIALS USED

In the present investigation, a Wyoming bentonite from the American Colloidal Company, known as "volclay", was used as a source of montmorillonitic clay and a commercial kaolin, as a source of kaolinitic clay. The "volclay", as described by the producers, is 90 per cent montmorillonite and in its natural state is predominately saturated with sodium. The exchange capacity per 100 grams of electrodialyzed bentonite, as determined by the usual ammonium acetate leaching method, was 86 m.e., and of electrodialyzed kaolin, 3.8 m.e.

Besides the two exchange materials mentioned above, a soil having a relatively low degree of base saturation also was sampled from a peach orchard near Benton Harbor, Michigan. The soil is classified as a Fox sandy loam. It has an exchange capacity of 9.8 m.e. per 100 grams, and is about 25 percent saturated with bases. Differential thermal curves of the colloidal fraction of the soil indicate the predominance of the clay mineral illite.[3]

Pure quartz sand was mixed with the bentonite and kaolin in the greenhouse experiments. Rapid chemical tests on a dilute HNO_3 extract of the sand showed the absence of major cations and anions.

PREPARATION OF COLLOIDAL CLAYS

Much time was required to prepare the mineral colloids with the desired cation ratios. In the present study, the colloids were first electrodialzyed, then the respective cations were introduced as salts in the desired ratios. The electrodialyzing cell used was composed of three wooden chambers of the Bradfield type (7) arranged in a parallel manner. It had a maximum capacity of about 8,500 milliliters in the central compartment and 2,500 milliliters in each of the side compartments. Porous porcelain plates about 50 millimeters or 0.25 inch thick were used as membranes. A perforated gold sheet having an area of 6 x 2.75 inches served as the anode and an ordinary copper wire screen having an area of 9.5 x 6.5 inches served as the cathode. The electrodes were placed 20-22 centimeters apart. An adjustable high-resistance rheostat and an ordinary ammeter were connected in series with the cell with 220 volts, d.c., as the source of current. At times three such cells were connected in parallel and run simultaneously. By frequent renewal of the electrodialysates and stirring of the colloidal suspension, the process of electrodialyzing a 3 percent suspension of bentonite could be completed in about 80 to 98 hours. In case of kaolin, an 8-10 percent suspension was used for electrodialysis, and the process was completed in a much shorter time than for the bentonite.

The completion of the removal of bases was indicated by rather constant but very low current density (amperage per unit area of the electrode) and was confirmed by the phenolphthalein test on the cathode electrodialysate and pH measurement of the suspension. The unsaturated bentonite and kaolin suspension thus obtained had pH values of about 3.2 and 4.5 respectively.

[3]The writers are indebted to Dr. Ralph E. Grim, Geologist, Illinois State Geological Survey Division, for identifying the clay mineral.

After the electrodialysis had been completed, the flocculated suspension was removed from the cell and dried on a hot plate. The dried bentonite was ground in a steel mill to pass through a 100-mesh sieve. The pulverization of dried kaolin was affected by a wooden pestle in an open tray.

Since the natural content of exchangeable bases in Fox sandy loam was low, no pretreatment for their removal was attempted.

PLAN OF GREENHOUSE EXPERIMENTS

Greenhouse experiments were conducted involving the growing of several different crops in four different cultural media, i.e. bentonite-sand mixture, kaolin-sand mixture, Fox sandy loam and pure quartz sand. The purpose of using pure quartz sand as a culture medium was merely to afford comparisons with treatments made on bentonite and kaolin media so that a better interpretation of the results might be obtained.

On each of the four cultural media, two series of experiments were carried out for different purposes. In the first series of experiments, plants were grown in the cultural media having different degrees of base saturation but with fixed ratios between the major exchangeable bases, i.e. calcium, magnesium and potassium. The principal purpose of this experiment was to study the effect of degree of base saturation on the growth and nutrition of plants. In the second series of experiments, the base exchange capacity of the cultural media was held constant while the ratio between the major exchangeable bases varied within a certain range. The experiments were thus designed to supply information as to the mutual effect of the complementary ions on the growth and nutrition of plants.

Both series of experiments were laid out in the same general pattern. Glazed earthenware jars were employed throughout the investigation. With the exception of the experiments on peach seedlings in Fox sandy loam, which were replicated four times, all greenhouse experiments were run in triplicate. Equal rates of fertilizer applications, involving diammonium acid phosphate and ammonium nitrate, were made to all of the jars unless otherwise mentioned. Solutions of $ZnSO_4$, $FeSO_4$, H_3BO_3 and $MnCl_2$ were also added to each of the cultural jars to give concentrations of 2, 4, 3 and 8 p.p.m. of Zn, Fe, B and Mn respectively in the final clay-sand mixtures. All chemicals used were of c.p. grade.

I. BENTONITE-SAND MIXTURES

From the known exchange capacity of the electrodialyzed bentonite, calculations first were made as to the amount of bentonite required to give 4000 gram mixtures of bentonite and sand the desired base exchange capacity. For the first series of experiments, the treatments involved four levels of base exchange capacity, i.e. 2, 4, 6 and 8 m.e. per 100 grams of the mixture, and each in combination with four degrees of total base saturation, i.e. 20, 40, 60 and 80 percent. For the second series of experiments, the difference among treatments was made only for the ratio between calcium, magnesium and potassium, while the base exchange capacity was constant at 2 m.e. per 100 grams for all of the treatments. A summary of the treatments for both series is given in Table 1.

TABLE 1—*Summary of the treatments of the greenhouse experiments on bentonite-sand mixtures*

Series	Treatments					Mean pH		Crops grown
	Exchange capacity, m.e./100 gm.	Base saturation, percent				Start	End	
		Ca	Mg	K	Total			
I..........	2	15	3	2	20	4.5	4.6	
	2	30	6	4	40	4.6	4.8	Oats: June 27 to Aug. 8, 1947
	2	45	9	6	60	5.0	5.9	
	2	60	12	8	80	5.3	6.1	
	4	15	3	2	20	4.5	4.6	
	4	30	6	4	40	4.6	4.8	
	4	45	9	6	60	4.9	5.7	
	4	60	12	8	80	5.1	5.9	Rye: Sept. 20 to Nov. 31, 1947
	6	15	3	2	20	4.4	4.5	
	6	30	6	4	40	4.5	4.7	
	6	45	9	6	60	4.8	5.4	
	6	60	12	8	80	5.0	6.2	
	8	15	3	2	20	4.4	4.4	
	8	30	6	4	40	4.5	4.6	
	8	45	9	6	60	4.7	5.5	
II..........	2	30	15	15	60	4.3	4.4	
	2	35	15	15	65	4.4	4.8	
	*2	40	15	15	70	4.6	5.2	
	2	45	15	15	75	4.7	5.4	
	2	50	15	15	80	5.0	5.8	
	2	40	5	15	60	4.8	5.1	Rye: Sept. 20 to Nov. 31, 1947
	2	40	10	15	65	5.0	5.2	
	*2	40	15	15	70	4.6	5.2	
	2	40	20	15	75	4.8	5.4	
	2	40	25	15	80	4.6	5.4	
	2	40	15	5	60	4.7	5.0	
	2	40	15	10	65	4.7	5.2	
	*2	40	15	15	70	4.6	5.2	
	2	40	15	20	75	4.6	5.4	
	2	40	15	25	80	4.7	5.6	

*Identical treatments, actually represented by the same jars in the experiment.

In setting up the greenhouse experiments, the desired amounts of colloids were first placed in one-gallon jars, and solutions of calcium acetate, magnesium nitrate and potassium sulfate added in amounts to supply 20, 40, 60 and 80 percent of total base saturation with a Ca:Mg:K ratio of 75:15:10. The colloids were maintained as thick suspensions for a period of about 3 weeks with occasional mixing. After that, while still moist, they were thoroughly mixed with quartz sand to give desired levels of exchange capacity.

Two crops, Eaton oats and Rosen rye, were grown in succession in the experiment. A moisture content of around 12 percent was maintained for the growth of oats, and about 8 percent (started with 5 percent) for that of rye.

II. KAOLIN-SAND MIXTURES

Owing to its very low exchange capacity a considerable amount of kaolin had to be used in order to afford kaolin-sand mixtures with base exchange capacities comparable to those of bentonite-sand mixtures. The mixtures, being high in kaolin, were low in apparent specific gravity. As a result, each 1-gallon jar could hold only 3500 grams of the mixture.

In precisely the same way as described for preparing bentonite-sand mixtures, kaolin and pure quartz sand were mixed and treated to give two series of experiments. In the first series, the treatments involved two levels of exchange capacity, i.e., 1 and 2 m.e. per 100 grams of mixture, each with four degrees of total base saturation, i.e., 20, 40, 60 and 80 percent, while the ratio of Ca:Mg:K was constant at 75:15:10. In the second series, the exchange capacity was fixed at 1 m.e. per 100 grams for all the treatments, while the Ca:Mg:K ratio was varied as in the bentonite-sand mixtures. The fertilizer applications were the same as those for the bentonite-sand mixtures.

Rosen rye was the first crop grown in the media. During its growth period, the moisture content of the media was maintained at about 12 percent for those having an exchange capacity of 1 m.e. per 100 grams, and 16 percent for those having an exchange capacity of 2 m.e. per 100 grams.

After the rye was harvested, the contents of each jar was added to an equal amount of pure quartz sand and potted into 2-gallon pars in the following manner. Two thousand grams of sand was first spread on the bottom of the 2-gallon jar to facilitate drainage and aeration; then 7000 grams of the kaolin-sand mixture was introduced; and finally a 1-inch layer of about 800 grams of sand was spread over the surface. The purpose of further diluting the mixture with sand and the manner of potting the mixture by layers was to improve the physical properties of the mixture and to prevent the formation of a surface crust.

The same fertilizer applications as were made originally were made to insure sufficient quantities of nitrogen, phosphorus, and minor elements. Moisture contents of the new mixtures were maintained at 10 percent for the low exchange capacity series, and at 12 percent for the high series. Oats were grown for a period of 70 days. Table 2 gives the summary of the actual plan of the greenhouse experiments for the kaolin-sand mixtures.

III. FOX SANDY LOAM

No sand was added to the Fox sandy loam. The soil had a base exchange capacity of 9.8 m.e. per 100 grams, and was about 25 percent saturated with bases. The first series of experiments was run

TABLE 2—*Summary of the treatments of the greenhouse experiments on kaolin-sand mixtures*

Series	Treatments					Mean pH		Crops grown
	Exchange capacity, m.e./100 gm.	Base saturation, percent				Start	End	
		Ca	Mg	K	Total			
I	1	15	3	2	20	5.1	5.4	Rye: Sept. 20-Nov. 31, 1947
	1	30	6	4	40	5.8	6.1	
	1	45	9	6	60	6.5	6.6	
	1	60	12	8	80	6.8	6.9	
	2	15	3	2	20	5.2	5.4	Oats: Dec. 19, 1947-Feb. 26, 1948
	2	30	6	4	40	5.9	6.3	
	2	45	9	6	60	6.7	6.9	
	2	60	12	8	80	6.9	7.2	
II	1	30	15	15	60	6.2	6.4	
	1	35	15	15	65	6.3	6.5	
	*1	40	15	15	70	6.5	6.6	
	1	45	15	15	75	6.6	6.7	
	1	50	15	15	80	6.7	6.7	
	1	40	5	15	60	6.3	6.5	Rye: Sept. 20-Nov. 31, 1947
	1	40	10	15	65	6.3	6.5	
	*1	40	15	15	70	6.5	6.6	
	1	40	20	15	75	6.5	6.5	
	1	40	25	15	80	6.6	6.6	
	1	40	15	5	60	6.4	6.5	
	1	40	15	10	65	6.2	6.4	
	*1	40	15	15	70	6.5	6.6	
	1	40	15	20	75	6.3	6.4	
	1	40	15	25	80	6.5	6.3	

*Identical treatments, actually represented by the same jars in the experiment.

with five levels of total base saturation, i.e., 25, 50, 75, 100 and 150 percent, each having the same Ca:Mg:K ratio of 75:15:10. The second series of experiments consisted of five treatments with varying ratios between Ca:Mg:K but with a constant degree of base saturation of 50 percent. One of the treatments was actually a part of the first series as is noted in Table 3, which gives the summarized plan of the treatments.

Both series first were carried out in 4-gallon glazed earthenware jars, each filled with 20 kilograms of the soil. Three young peach seedlings were transplanted into each jar, only one being retained after three weeks. A moisture content of about 15 percent was maintained during the experiment. At the end of 166 days, the total length of the main shoots of peach seedlings was determined.

After the removal of peach seedlings, the soil in each jar was allowed to dry and was remixed. Without additional fertilizer treatment, 9500-gram portions of the soil from each jar were weighed into 2-gallon pots. Thus a total of eight 2-gallon pots could have been obtained from each quadruplicate of the same treatment in 4-gallon jars, but only six of them were actually used for further experimental purposes. Each group of six, 2-gallon pots, having the same treatment, were divided equally into two groups. One group was

TABLE 3—*Summary of the treatments of the greenhouse experiments on Fox sandy loam*

Series	Treatments					Mean pH		Crops grown
	Exchange capacity, m.e./100 gm.	Base saturation, percent						
		Ca	Mg	K	Total	Start	End	
I.....	9.8	18.7	3.9	1.9	24.5	6.0	6.1	In 4-gal. jars: Peach seedlings, Mar. 9-Aug. 21, 1947
	*9.8	37.5	7.5	5	50	6.2	6.0	
	9.8	56.25	11.25	7.5	75	6.4	6.3	In 2-gal. jars: Soybeans, Aug. 28-Oct. 23, 1947
	9.8	75	15	10	100	6.5	6.5	
	9.8	112.5	22.5	15	150	6.7	6.5	Proso (Millet), Oct. 23-Nov. 27, 1947
II.....	*9.8	37.5	7.5	5	50	6.2	6.0	
	9.8	40	5	5	50	6.2	6.0	Oats, Dec. 19, 1947-Feb. 26, 1948
	9.8	35	5	10	50	6.3	6.2	
	9.8	30	10	10	50	6.2	6.2	Tomatoes, Aug. 27, 1947-Jan. 29, 1948
	9.8	30	5	15	50	6.1	6.1	

*Treatments actually represented by the same jars.

used for growing soybeans, proso and oats in succession and the other for growing tomatoes. Soybeans and proso (millet) were grown in the period from Aug. 28 to Oct. 23, 1947 and from Oct. 23 to Nov. 27, 1947, respectively, with no artificial illumination in the greenhouse. Being short-day plants, all appeared dwarfed in vegetative growth and matured earlier than usual. Because of the limiting nature of the photoperiod to the growth of soybeans and proso, the results were not valid for direct interpretation. No measurement of their growth rate, therefore, was attempted during the experiment.

ANALYTICAL METHODS

Harvested plant materials including oats, rye, and leaves of tomato were air-dried and ground in a small Wiley Mill to pass through a 20-mesh sieve. One-gram portions of the oven-dried tissue were then wet-ashed at a moderate heat with a mixture composed of 4 milliliters of 70 percent $HClO_4$, 15 milliliters of concentrated HNO_3 and 4 milliliters of concentrated H_2SO_4(33). The extract finally was diluted with water to 25 milliliters. Aliquots of this extract were taken for the analysis of calcium, magnesium and potassium.

The determination of calcium was made volumetrically on the 5-milliliter aliquot as oxalate, following the procedure of standard A.O.A.C. micro-method (5). Magnesium was determined photocolorimetrically, using a 520-millimeter filter and 0.2 milliliter aliquots by the thiazol yellow method (29), which was essentially the same as the ordinary titan-yellow method (32). Potassium was determined on 1-milliliter aliquots by the cobaltinitrite method using Peech's technique (30).

All pH measurements of soil and clay-sand mixtures were made potentiometrically with a Macbeth alternating current pH-meter using glass electrodes with a soil:water ratio of about 1 to 2.

RESULTS

ACTUAL BASE STATUS OF THE TREATED COLLOIDS

In the previous sections, reference was made to the possibility that with the present method of preparing colloids, the exchange reactions between the exchangeable hydrogen ion of the electrodialyzed clays and cations of the introduced electrolytes was likely to be incomplete. In order to evaluate the actual status of the bases in the exchange materials, a series of laboratory experiments was carred out.

To 10-gram portions of H-bentonite in suspension, different amounts of the solutions of calcium acetate, magnesium nitrate and potassium sulfate were added according to the calculated ratios. The systems were then allowed to stand in the laboratory, with occasional shaking, for a period of at least 2 weeks. Analyses of calcium, magnesium and potassium were made on the filtrate. From them, the actual percentages of base saturation were calculated. Similar experiments, using 50-gram portions of materials, were also carried out with electrodialyzed kaolin and natural Fox sandy loam.

The results of these experiments indicate that some of the bases added to the colloids were not held on the colloidal surface. The portion of the bases that existed in the free form varied with the nature of colloid, the electrolyte, and the symmetry concentration of the electrolyte added. The higher efficiency of replacement for H-ions was observed in the lower symmetry concentration of electrolytes. It is not the purpose of this paper to involve a discussion of exchange reactions except to mention the fact that the results obtained are in general agreement with many others (12).

Figures 1, 2 and 3 show exchange isotherms of calcium, magnesium, and potassium with different types of soil colloids respectively. As no similar laboratory experiment was conducted for the treatments involved in the second experiment using the bentonite-sand mixture, the kaolin-sand mixture, or the Fox sandy loam, the actual base status of those treatments was not known precisely.

Inasmuch as the results of the present investigation, like many others along the same line, are likely to be qualitative in nature, the degrees of base saturation referred to hereafter in the tabulation of the results of greenhouse experiments will be the theoretical values indicated explicitly by the treatment according to calculation, rather than the actual values indicated implicitly by the treatment according to chemical analysis.

EFFECT OF TREATMENT ON SOIL REACTIONS

The results of the pH determinations made on the cultural media at the start and at the end of the experiment are presented in Tables

1, 2 and 3. The pH values of bentonite-sand mixtures were low, as can be seen from Table 1. Even with a total base saturation of 80 percent, the values were still around 5.0 at the start of the experiment. The results thus indicate a rather high buffer capacity of bentonite at low pH levels which is in general agreement with Mehlich's findings (24, 25).

There were general increases in the pH values of the bentonite-sand cultures after crops had been grown on them although the increases were slight where degrees of base saturation were low. On the other hand, noticeable pH increases were observed where the de-

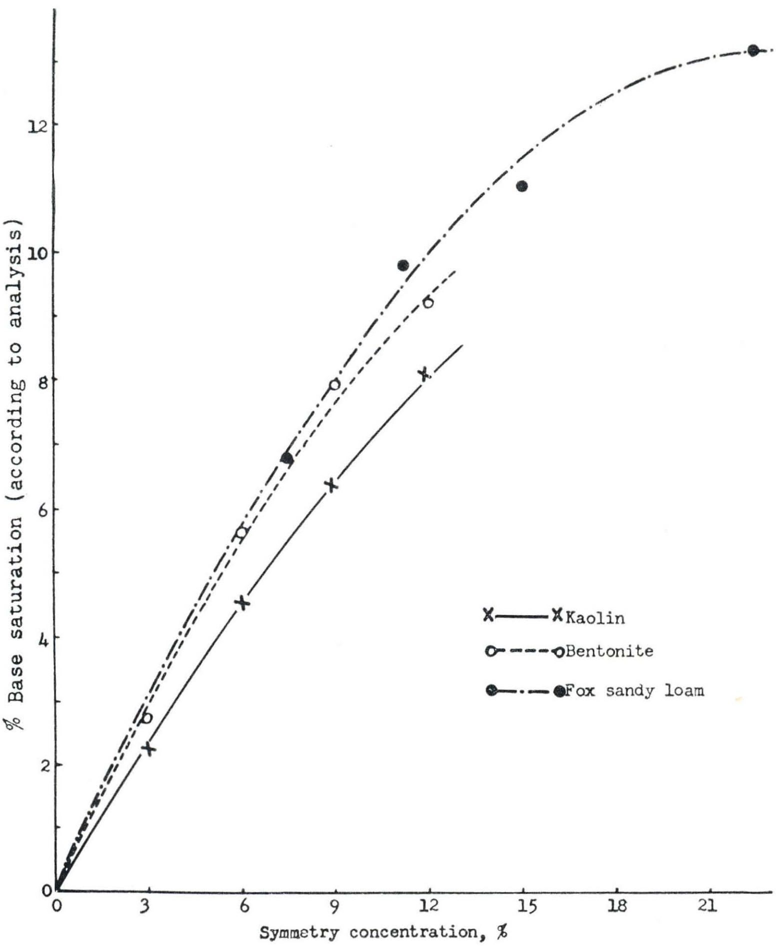

Fig. 1. The exchange isotherms of calcium in different types of soil colloids.

grees of base saturation were high. No effort was made to explore the reasons for these increases. However, it is suspected that, aside from the possible unequal absorption of NH_4-N and NO_3-N by plants, the decomposition of acetic acid, which is formed as a result of base exchange reactions between calcium acetate and acid colloid, might be one of the principal reasons.

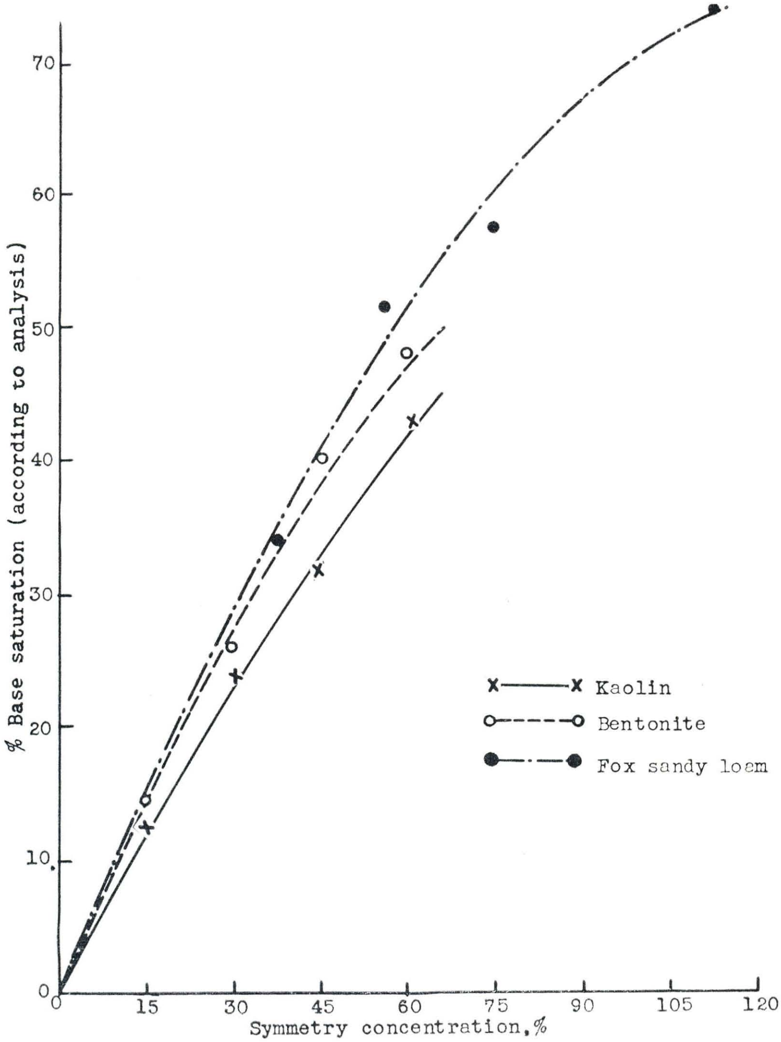

Fig. 2. The exchange isotherms of magnesium in different types of soil colloids.

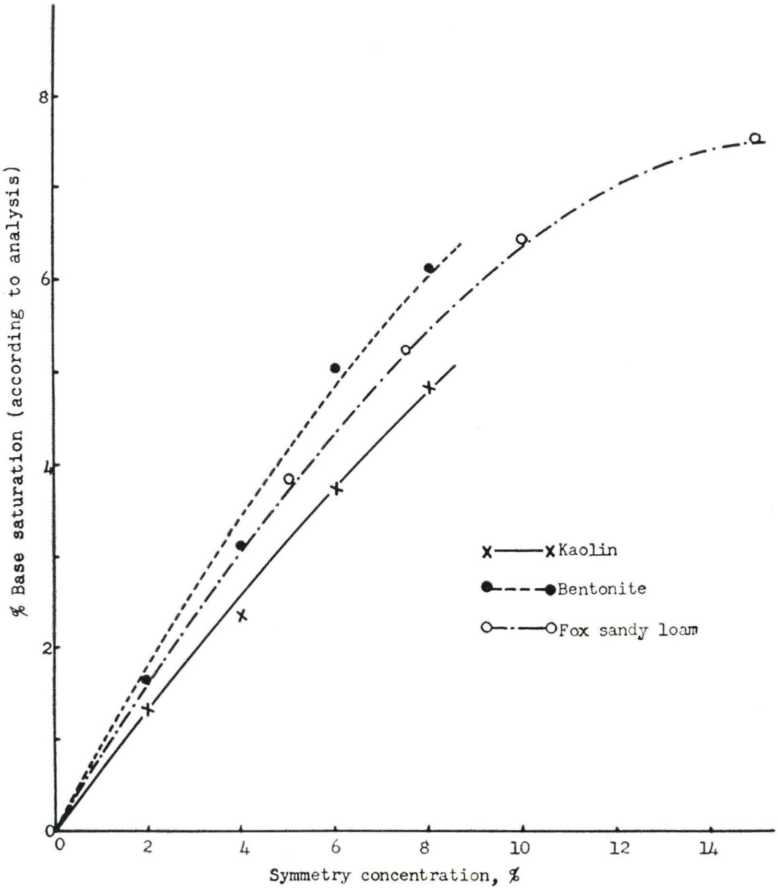

Fig. 3. The exchange isotherms of potassium in different types of soil colloids.

EFFECT OF DEGREE OF BASE SATURATION ON CROP YIELDS

I. Bentonite-sand Mixtures

The general growth of oats and rye as related to the total quantity of bases present in the bentonite-sand mixture is shown by the data in Table 4. These results show that as the supply of exchangeable bases was increased, with a constant base exchange capacity, the yields of the crop increased. The increased yields for the increasing percentages of base saturation arrange themselves in a nearly straight line relation, as can be noted from the actual photographs of the growth conditions of the plants (Figs. 4, 5, and 6).

TABLE 4—*Effect of different levels of exchangeable bases on yields of oats and rye plants in bentonite-sand mixtures*

Base saturation, percent	Exchange capacity, m.e./100 gm.							
	2		4		6		8	
	Yield in gm.*							
	Oats	Rye	Oats	Rye	Oats	Rye	Oats	Rye
20	.53	1.58	.55	1.93	.55	1.86	.54	1.83
40	1.13	2.43	.86	2.80	.85	2.48	.77	2.40
60	1.85	3.39	1.09	3.80	1.04	3.12	1.07	3.03
80	2.59	4.24	1.30	5.70	1.18	3.58	....	....

*Values represent average dry weights of the above-ground portions from three replicate pot cultures.

The four levels of degree of base saturation, which represent a variation in both the supply of exchangeable bases and the hydrogen-ion concentration—the two variables which are reciprocally related—show that the growth of both oats and rye improved with a decreasing hydrogen-ion concentration and an increasing base saturation. Which of these two variables is the more significant factor is not evident in the yield data presented. However, the fact that both oats and rye are acid-tolerant crops is well known. According to Weir (39), oats

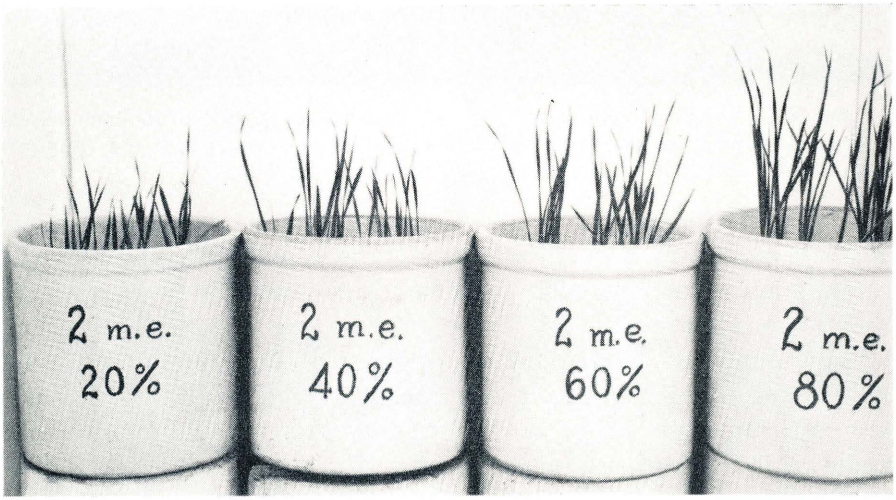

Fig. 4. Growth of 17-day-old oats as related to degree of base saturation of the bentonite-sand mixture with a base exchange capacity of 2 m.e. per 100 grams of the mixture. (Increasing saturation from left to right.)

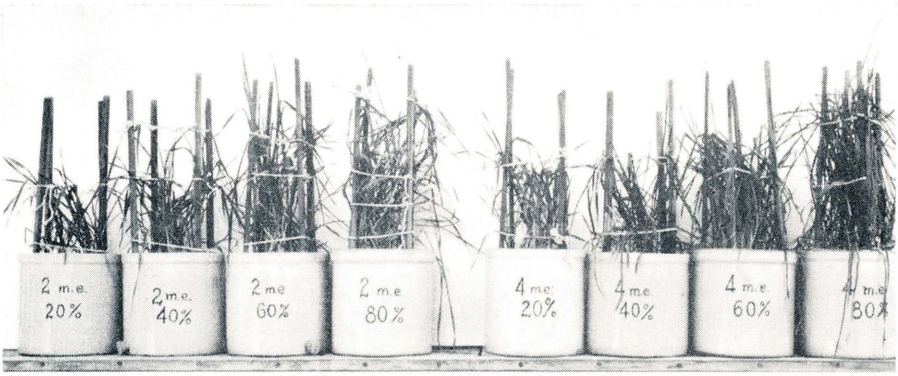

Fig. 5. Growth of rye at the end of 2 months as related to degree of base saturation of the bentonite-sand mixture with exchange capacity of 2 m.e. (left four jars) and 4 m.e. (right four jars) per 100 grams.

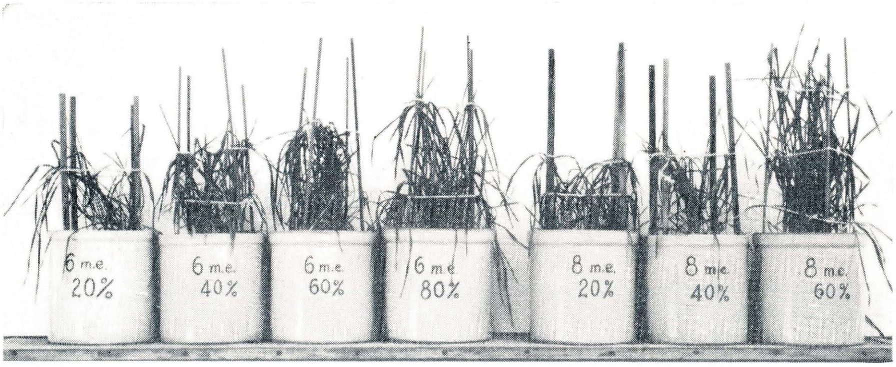

Fig. 6. Growth of rye at the end of 2 months as related to degree of base saturation of the bentonite-sand mixture with exchange capacity of 6 m.e. (left four jars) and 8 m.e. (right three jars) per 100 grams.

and rye may grow normally in strongly acid soil with pH 4.8. The compilation of soil reaction preferences of plants by Spurway (35) shows oats and rye will tolerate a pH 4.5 without possibility of serious injury. Analyses of plant materials, as will be presented in later sections, also give indications that the total amount of available bases is a more important factor in affecting the difference in growth than a variation in hydrogen-ion concentration.

The data in Table 4 also show that at 20 percent of base saturation, oats and rye yields were approximately the same, regardless of the exchange capacity of the media. A similar situation is observed at 40 and 60 percent base saturation levels, except in the yields of oats from the 2 m.e. base exchange capacity jars, which were higher than the rest at corresponding base saturation levels. Photographs showing these facts are presented in Figs. 7 and 8.

With the design of this experiment, it is possible to make a further comparison between treatments. Out of the 15 different treatments listed in Table 4, there were actually eight different levels of total bases contained in the cultural media, viz., 0.4, 0.8, 1.2, 1.6, 2.4, 3.2, 3.6 and 4.8 m.e. bases per 100 grams of medium. Except for the levels

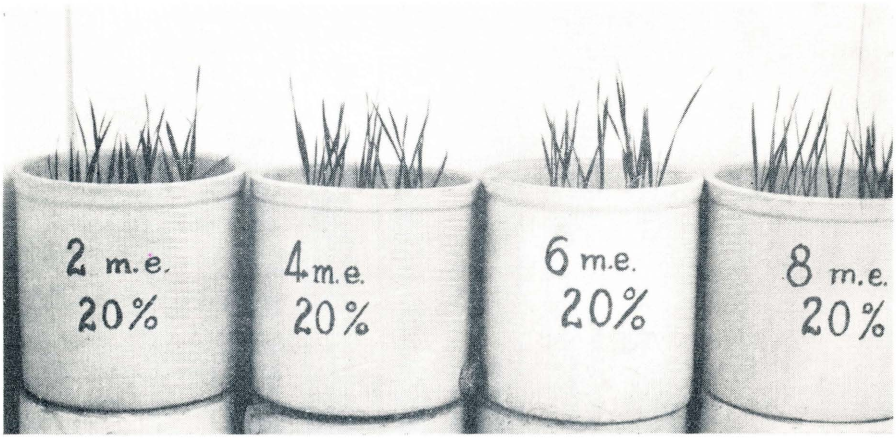

Fig. 7. Seventeen-day-old oats showing, with the same low degree of base saturation, no effect on the growth by varying the base-exchange capacity of the bentonite-sand mixture.

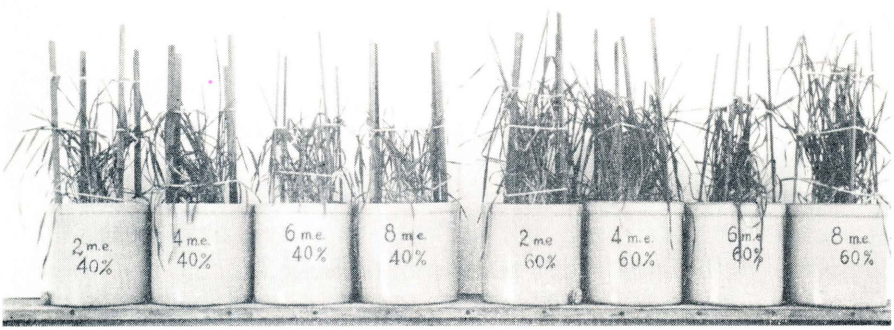

Fig. 8. Rye crops at the end of 2 months, showing no significant difference of the growth by varying the base exchange capacity of the bentonite-sand mixture.

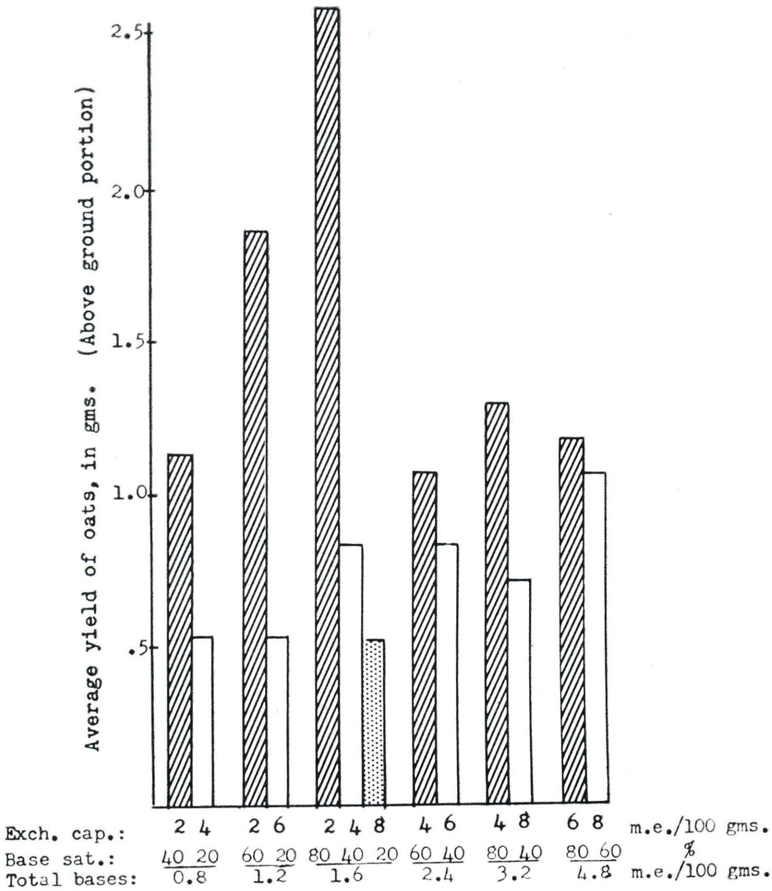

Fig. 9. Effect of degree of base saturation on yield of oats planted in bentonite-sand mixtures.

0.4 and 3.6 m.e., each level was made up, in more than one way, by varying the levels of the base exchange capacity, and the degrees of saturation. Thus, for instance, treatments made up by either of 2 m.e. exchange capacity, 80 percent saturation, or 4 m.e. exchange capacity, 40 percent saturation, or 8 m.e. exchange capacity, 20 percent saturation, all gave the same absolute amount of bases, i.e., 1.6 m.e. per 100 grams of the bentonite-sand mixture. However, crop yields have been affected differently by these treatments. In all cases, with the same absolute amount of bases present in the media, the highest percentage

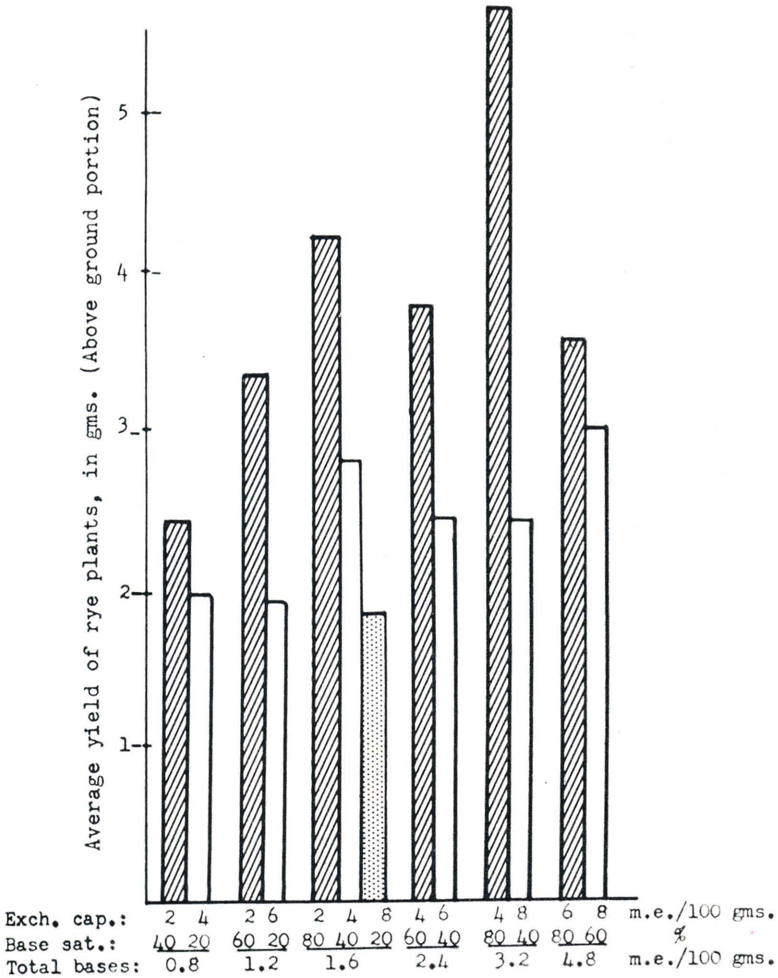

Fig. 10. Effect of degree of base saturation on yield of rye plants in bentonite-sand mixtures.

of saturation gave the best yields of oats and rye. Furthermore, the greater the difference of degree of saturation, the greater the difference in yields. These facts, shown by the graphs in Figs. 9 and 10, and by the photographs in Figs. 11 and 12, suggest that the growth of both oats and rye crops is more directly related to percentage saturation than to total amount of bases.

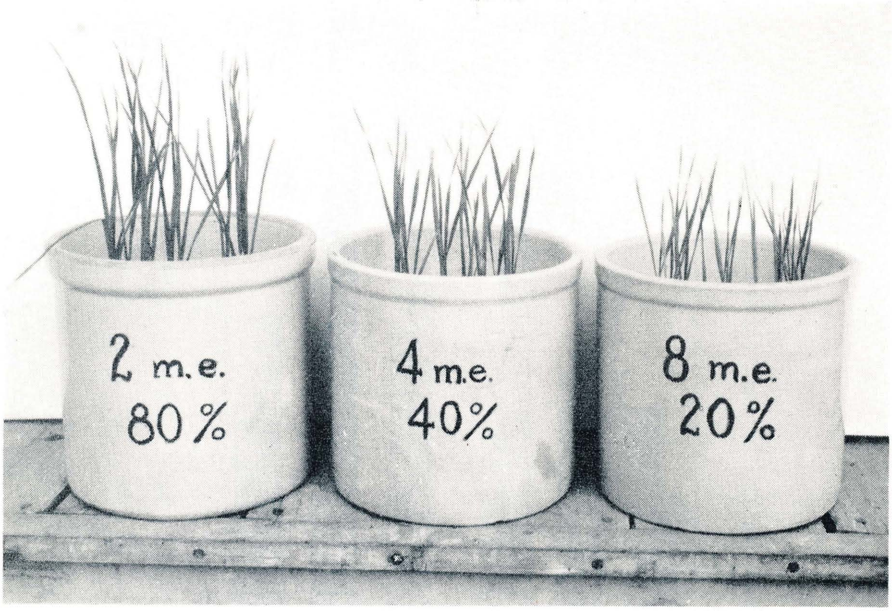

Fig. 11. Seventeen-day-old oats showing the growth condition is more directly related to percentage saturation than to total amount of bases in bentonite-sand mixtures. All three jars contained 1.6 m.e. of bases per 100 grams of media.

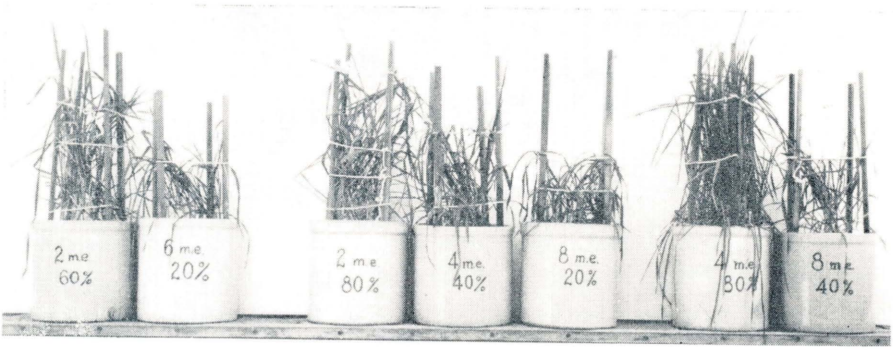

Fig. 12. Rye crops at the end of 2 months, showing that the growth condition is more directly related to percentage saturation than to total amount of bases in bentonite-sand mixtures. The two jars on the left contained 1.2 m.e. bases, the three in the middle contained 1.6 m.e. bases, and the two on the right contained 3.2 m.e. bases per 100 grams of media.

II. Kaolin-sand Mixture

Yields of oats and rye showing the effect of varying levels of bases in the kaolin-sand mixtures are given in Table 5. The increase of percentage saturation of the kaolin-sand mixtures in this experiment did not seem to have the same effects on the yields of oats and rye as it had produced in the bentonite-sand mixtures. There were some increases in the yields as the degree of base saturation increased from 20 to 40 percent at both levels of exchange capacity. But on the percentage basis the amount of increase was slight as compared with the percentage increases of yields in the case of bentonite-sand mixtures. The yields of rye were about the same at the corresponding levels of base saturation regardless of the exchange capacity, although the yields of oats were a little higher on the 2 m.e. exchange capacity series after the mixture had been diluted with sand.

These facts suggest that a sufficient supply of available bases was supplied in the low-saturation levels, and/or that some other factors besides the base status of the media were limiting the growth of the plants. It is evident from the data in Table 2 that the pH of the media is not sufficiently low to limit the growth of oats and rye. But it was noticed during the experiment that kaolin-sand mixtures exhibited poor physical properties. As water evaporated from the mixture, a very hard crust formed on the surface as if it had been subjected to pressure. Furthermore, cavities developed under the surface crust which might have caused damage to the roots of the crops. All these indications lead one to suspect that the base status of the kaolin-sand mixture is not the only factor affecting the growth of oats and rye. However, the general similarity of the results between the yields of rye grown on the original kaolin-sand mixtures and the yields of oats grown on the diluted kaolin-sand mixtures indicate that the growth of oats and rye is more closely related to the base status than to the physical properties of the media. It was observed that a 20 percent saturation of bases in kaolin-sand mixtures provided a sufficient supply of available bases for fair growth of oats and rye, and a 40 percent saturation supplied enough available bases for maximum growth of plants under the limitation of other factors existing in the experiment.

A comparison of treatments between 1 m.e. and 2 m.e. exchange capacity series reveals that with the same total supply of 0.4 m.e. bases per 100 grams of the mixture, the 40 percent saturation of the 1 m.e. exchange capacity jars gave greater yields of oats and rye than

TABLE 5—*Effect of different levels of exchangeable bases on yields of oats and rye plants in kaolin-sand mixtures*

Base saturation percent	Exchange capacity, m.e. 100 gm.			
	1		2	
	Yield in gm.*			
	Oats	Rye	Oats	Rye
20	4.83	3.01	5.06	3.23
40	5.77	3.90	6.82	3.81
60	5.50	3.81	6.72	4.14
80	6.03	3.72	6.35	3.98

*Values represent average dry weights of the above-ground portions from three replicate pot cultures.

the 20 percent saturation of the 2 m.e. exchange capacity jars (Table 5). On the other hand, no improvement of yields of the 80 percent saturation of the 1 m.e. exchange capacity jars over those of the 40 percent of the 2 m.e. exchange capacity jars was obtained, although they all contained 0.8 m.e. total bases per 100 grams mixture. These results again suggest that the growth of both oats and rye crops is more directly related to percentage saturation than to total amount of bases and that a 40 percent saturation of bases in kaolin-sand mixture is probably all that is needed for the growth of oats and rye under the experimental condition.

III. FOX SANDY LOAM

The general growth condition of peach seedlings as affected by the degree of base saturation is shown in Fig. 13. The average total length of the shoots of peach seedlings after 5 months of growth in the treated soil was 29.1, 41.5, 25.7, 22.3, and 23.7 centimeters for the 25 percent (untreated), 50 percent, 75 percent, 100 percent and 150 percent saturated soils respectively.

As can be seen in Fig. 13, the growth of the peach seedlings in general was not very good. The best growth was at the 50 percent saturation level. Peach seedlings grown in the soil with the treatments to give more than 75 percent saturation of bases appeared very poor in growth, with only few leaves remaining on the top, and, of the four replications, two failed to survive at the 150 percent saturation level, and one at the 100 percent saturation level. During the early stages of the experiment, it was discovered that some of the peach seedlings

Fig. 13. Growth of peach seedlings as influenced by the degree of base saturation of Fox sandy loam. Treatments from left to right are: No. 1—untreated natural soil (about 25-percent saturation), No. 2—50-percent saturation, No. 3—75-percent saturation, No. 4—100-percent saturation, No. 5—150-percent saturation.

developed abnormalities in growth. Their leaves became curled and and seedlings began to branch out with numerous small leaves. According to Tukey and Carlson (37, 38) it is probable that this dwarfing effect is the result of incomplete "after-ripening" of the peach seeds prior to planting. Although all the abnormal peach seedlings were

TABLE 6—*Yields of tomato and oats crops as affected by the degree of base saturation of Fox sandy loam*

Base saturation				Tomato plant			Oats
Ca	Mg	K	Total	Weight fruit*	Weight plant*	Height of main stalk*	Weight straw*
percent	percent	percent	percent	gm.	gm.	cm.	gm.
18.7	3.9	1.9	24.5	582	32.1	105	4.5
37.5	7.5	5	50	593	36.1	118	5.7
56.25	11.25	7.5	75	692	50.2	150	5.5
75	15	10	100	670	44.2	123	5.8
112.5	22.5	15	150	653	42.7	115	5.5

*Values representing averages from three replicated pot cultures.

finally replaced by normal ones during the experiment, the general unsuccessful growth did not yield dependable information as to the effect of degree of saturation on the growth of the peach.

Because of the unfavorable photo-period, as has been mentioned before, the growth of soybean and proso millet crops following the peach also was not satisfactory. Consequently, no measurement of their response to the soil treatments has been made available for the discussion.

In Table 6 are presented the results of the experiment on tomato and oats crops with the same treatments. A comparison of the height of the tomato plants, as affected by the various treatments, can be made by referring to Fig. 14. Differences in the yields of fruit and plants and also in the length of the main stalk were marked between the 50 and 75 percent saturation levels. Above 75 percent saturation levels, there were slight decreases in the yield of fruit and plant materials, accompanied by more marked decreases in the length of the main stalk.

The yield data of the oats show the same general trend, as related to the base status of the soil, as did the tomatoes except that the difference in yields is noticeable only between 25 percent (untreated) and 50 percent saturation levels. All these facts suggest that the growth of tomato and oats increases as the degree of base saturation of the soil increases but only up to a certain saturation level. For the present soil containing dominantly illitic type of mineral colloid along with some organic colloids, this limiting level seems to be about 50 percent

Fig. 14. Growth of tomato plants at 90 days as influenced by the degree of base saturation of Fox sandy loam. Treatments from left to right are: No. 1—untreated natural soil (about 25-percent saturation), No. 2—50-percent, No. 3—75-percent, No. 4—100-percent, and No. 5—150-percent base saturated.

saturation for the oats and 75 percent for the tomato plant. The higher critical saturation level for tomato plants as compared with that for oats has the support of the well recognized fact that in general tomatoes demand soils of higher fertility than do oats.

EFFECT OF DEGREE OF BASE SATURATION ON THE MINERAL CONTENT OF PLANTS

I. BENTONITE-SAND MIXTURES

The results of the chemical analyses of the above-ground portions of oats and rye are summarized in Table 7. Among the three mineral constituents, the greatest variation occurred in K. Figures 14 to 20 show graphically the Ca, Mg and K contents of the oats and rye and the relationships between the base status of the bentonite-sand mixture and the mineral composition of the crops.

TABLE 7—*Mineral content of the oven-dry tissues of oats and rye as influenced by base status of bentonite-sand mixtures*

Base saturation, percent	Base exchange capacity, m.e./100 gm. mixture											
	2			4			6			8		
	M.e./100 gm. dry tissue											
	Ca	Mg	K	Ca	Mg	K	Ca	Mg	K	Ca	Mg	K
	Oats											
20......	18.2	3.1	13.2	14.8	8.0	10.8	19.2	5.4	10.3	22.0	4.6	12.7
40......	28.0	9.3	23.9	31.3	11.5	17.8	40.2	8.5	14.0	41.3	7.4	16.1
60......	32.1	20.9	37.5	33.2	19.1	36.5	38.5	13.2	30.7	42.8	18.1	29.5
80......	32.3	22.6	52.3	34.5	22.0	44.7	40.2	20.3	36.0	......	......	......
	Rye											
20......	11.1	3.0	11.7	11.9	7.2	21.0	18.5	7.0	9.2	15.2	8.1	21.5
40......	21.6	12.9	13.7	29.5	15.0	20.1	29.9	14.3	12.7	34.0	23.4	23.5
60......	29.8	20.2	41.1	34.0	16.5	37.3	32.6	23.3	25.8	35.2	26.5	49.2
80......	31.6	23.1	52.0	32.8	22.8	45.5	32.3	24.0	40.4	......	......	......

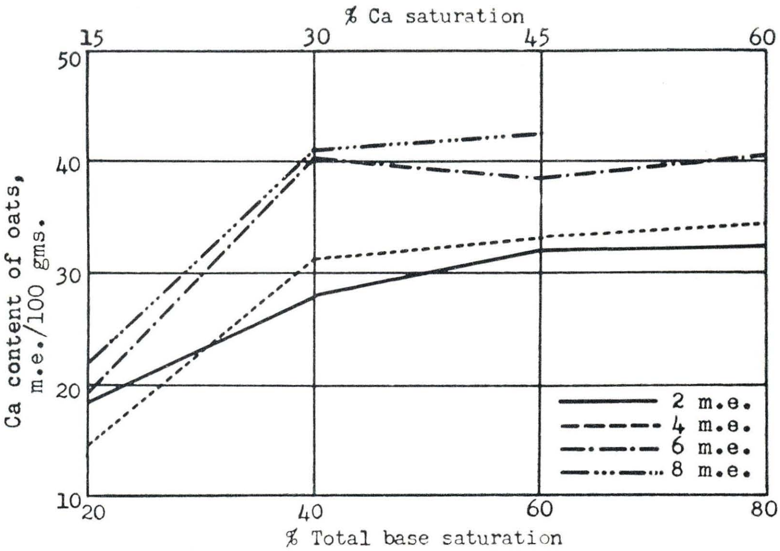

Fig. 15. The effect of degree of base saturation on the Ca content of oats in bentonite-sand mixtures.

From Figs. 15 and 16, it can be seen that the Ca content of both oats and rye increased markedly from 15 to 30 percent Ca saturation levels (or from 20- to 40-percent saturation of total bases), but showed only a little increase from 30- to 45-percent Ca saturation levels (or from 40- to 60-percent saturation of total bases). Beyond that, there was practically no increase in Ca content. This situation is similar in all cases, regardless of the exchange capacity of the media. The results indicate that for a bentonite-sand mixture, a 15-percent saturation of Ca will not supply enough available Ca to meet the re-

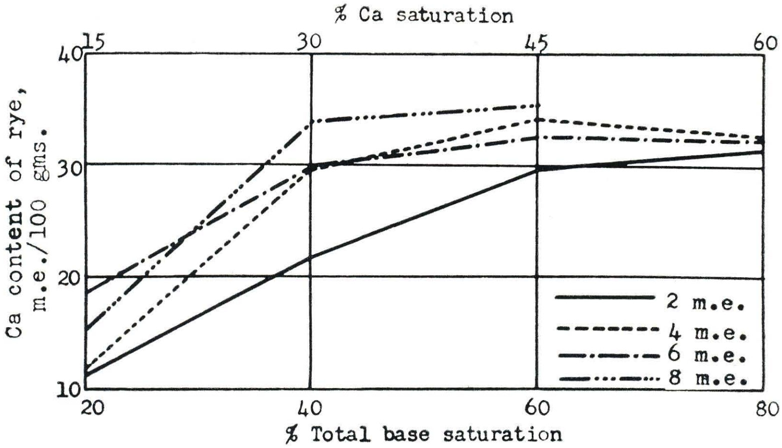

Fig. 16. The effect of degree of base saturation on the Ca content of rye in bentonite-sand mixtures.

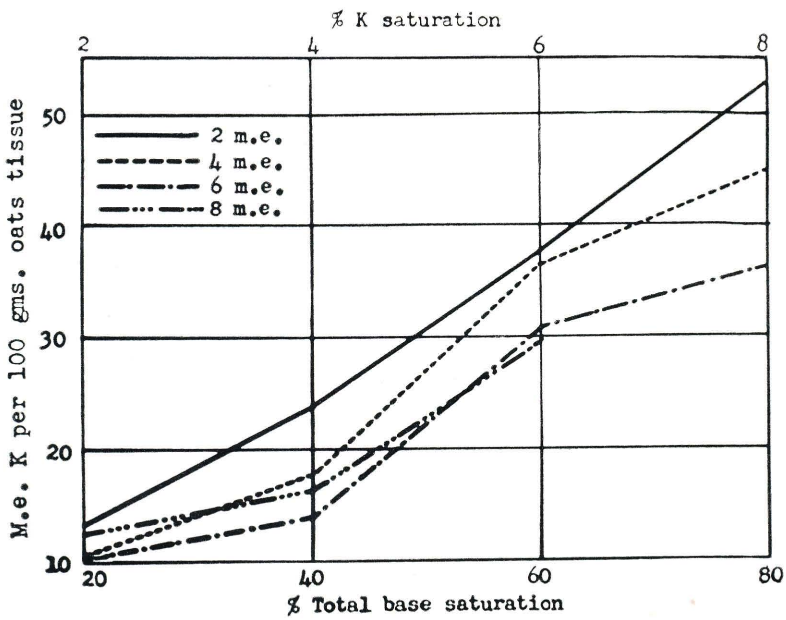

Fig. 17. The effect of degree of base saturation on the K content of oats in bentonite-sand mixtures.

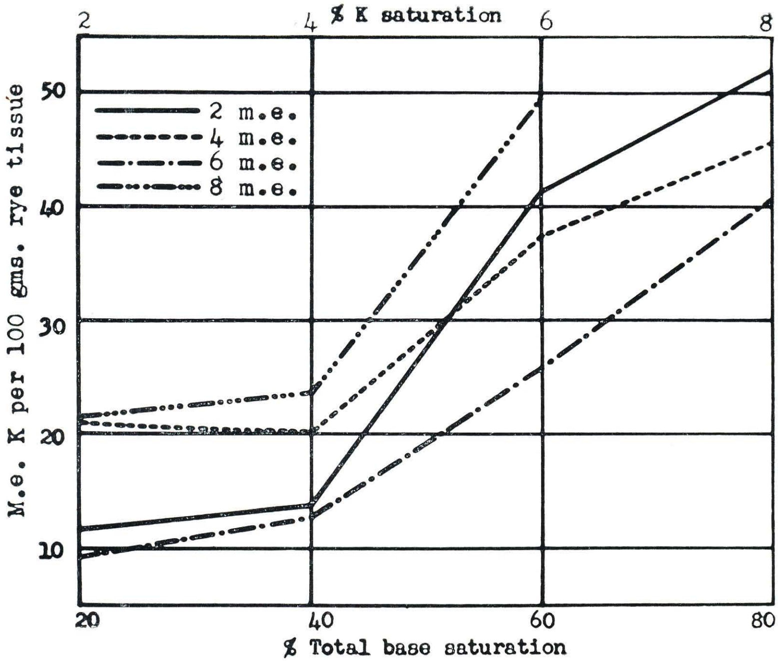

Fig. 18. The ffect of degree of base saturation on the K content of rye in bentonite-sand mixtures.

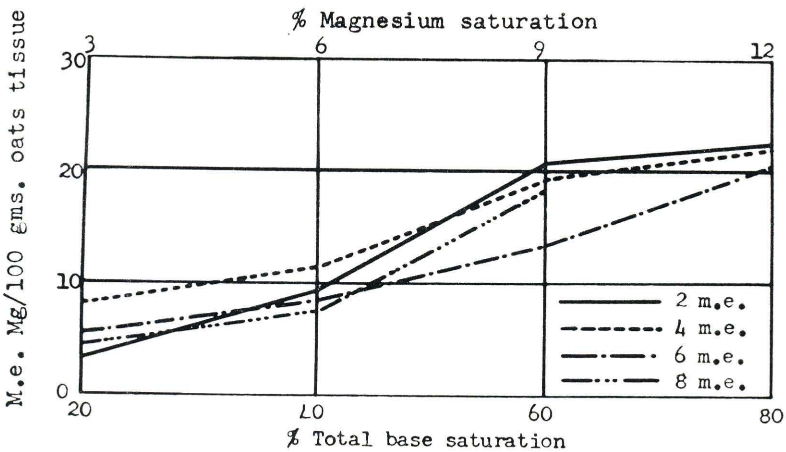

Fig. 19. The effect of degree of base saturation on the Mg content of oats in bentonite-sand mixtures.

quirement of oats and rye. In order to afford an ample supply of readily available Ca from the exchange complex, the saturation level of Ca for a montmorillonitic clay has to be at least above 30 percent, or better 45 percent, of the exchange capacity.

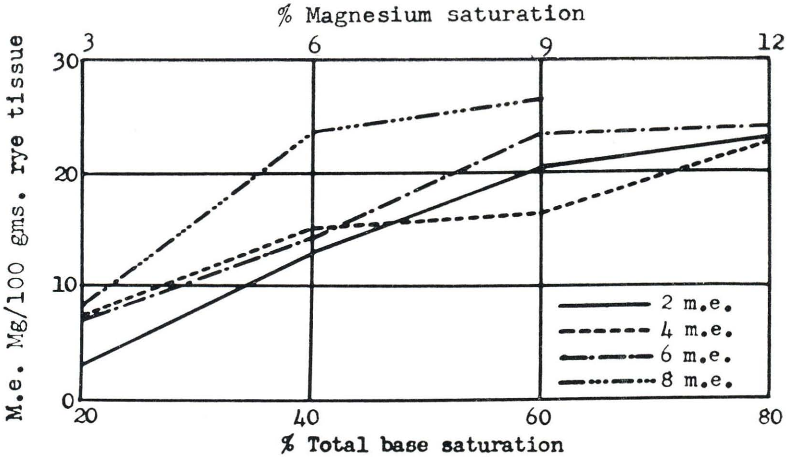

Fig. 20. The effect of degree of base saturation on the Mg content of rye in bentonite-sand mixtures.

With respect to the potassium curves shown in Figs. 17 and 18, it is observed, in general, that the curves rise slowly at the beginning and then rather steadily throughout the remaining range of the curves. Considering the usually great error involved in the method of determining potassium, it is believed that the potassium content of the plants in question was probably not significantly affected by the base status of the medium until it reached a K-saturation level of about 4 percent of the total exchange capacity. A considerable increase of K availability to the plants from a 4 percent to a 6 percent K-saturation level was evident from the curves. As the K-saturation level increased from 6 to 8 percent, the K-content of the plants increased still further, indicating a maximum availability of K had not yet been reached.

The Mg-curves (Figs. 19 and 20) also show general increases in the Mg content of the plant tissue as the saturation level of Mg in the medium increased. The trend is more or less like that of K rather than Ca, but the variation is within a smaller range.

In comparing the yields with the mineral composition of the oats and rye, it is suggested that the marked increase of Ca availability at the 40-percent level of total base saturation is probably the main reason for the increase of the yields at that level. Furthermore, the increase of yields beyond the 40-percent level seems to coincide with the continuous rise of the K and Mg curves. These facts indicate that the differences in the growth of oats and rye are more closely related to the degree of base saturation, through its combined effects on the availability of different cations, rather than the pH values as such.

TABLE 8—*Mineral content of the oven-dry tissues of oats and rye as influenced by the base status of kaolin-sand mixtures*

Base saturation, percent	Base exchange capacity, m.e./100 gm. mixture					
	1			2		
	m.e./100 gm. dry tissue					
	Ca	Mg	K	Ca	Mg	K
	Oats					
20	38.1	10.1	5.5	45.0	13.3	10.1
40	37.3	18.2	17.1	43.1	19.2	18.5
60	39.1	16.2	18.5	42.2	21.1	21.3
80	37.8	17.3	23.0	39.2	19.8	22.8
	Rye					
20	31.1	9.1	2.5	28.2	12.5	8.5
40	30.8	10.2	13.5	31.9	15.8	12.4
60	29.2	14.0	18.7	30.5	17.3	19.6
80	29.9	15.7	19.3	34.8	16.2	18.0

Furthermore, the data reveal that the mineral content of the plants, like the yields, was more directly related to the percentage saturation than to the total amount of bases present in the montmorillonitic clay.

II. KAOLIN-SAND MIXTURE

The effect of the variations in the level of base saturation upon the mineral content of the plants in kaolin-sand mixture is given in Table 8 and Figs. 21, 22, and 23. There was no significant increase in the calcium content of the plants as the saturation level increased. This

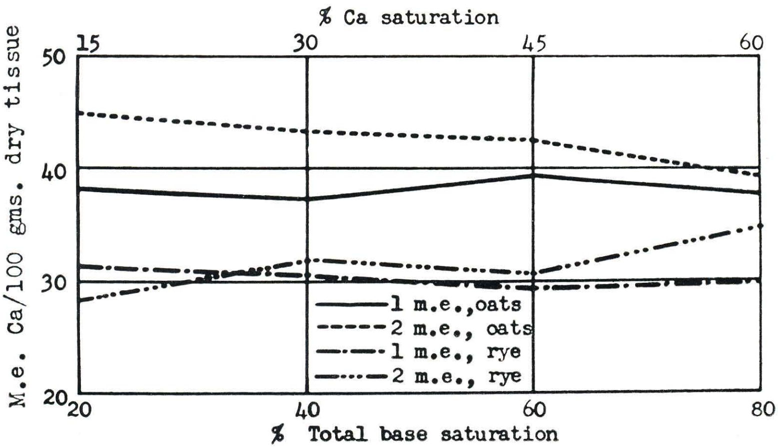

Fig. 21. The effect of degree of base saturation on the Ca content of the plants in kaolin-sand mixtures.

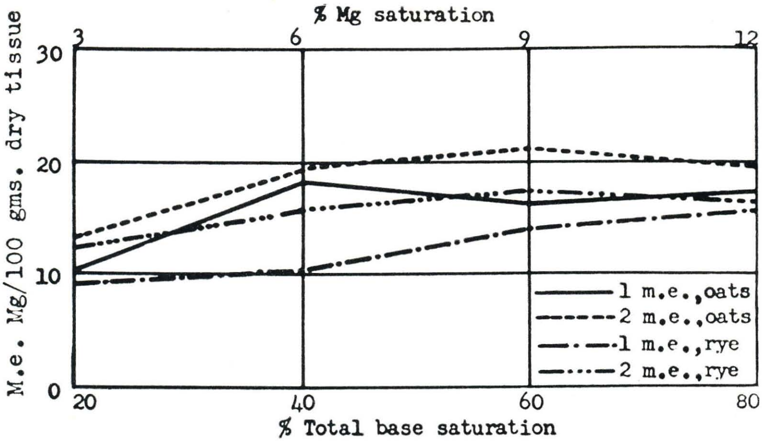

Fig. 22. The effect of degree of base saturation on the Mg content of the plants in kaolin-sand mixtures.

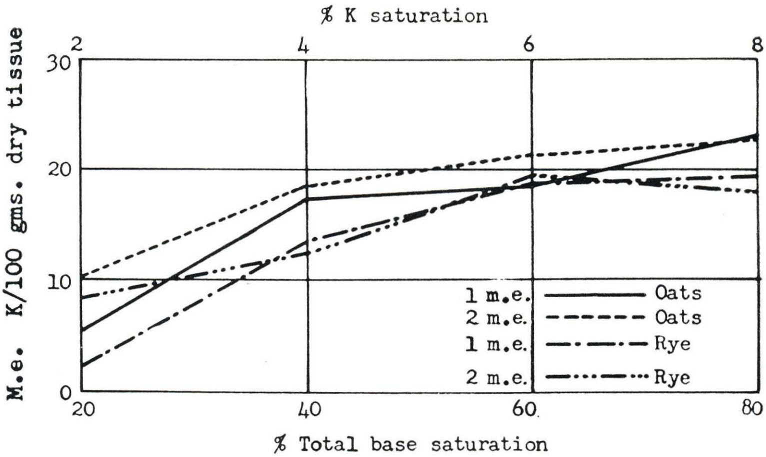

Fig. 23. The effect of degree of base saturation on the K content of the plants in kaolin-sand mixtures.

indicates that a 15-percent level of Ca saturation supplies enough available calcium for the nutritional requirement of oats and rye.

The potassium curves show that there was a general increase in the potassium content of the plants as the level of K saturation in the kaolinitic colloid increased from 2, through 4 to 6 percent of the total base exchange capacity. However, no significant increase was noticed above the 6-percent saturation level. The Mg situation was much the same as the K. Therefore, it is believed that a sufficient supply of K and Mg had been reached at the level corresponding to 60-percent saturation of total bases.

III. FOX SANDY LOAM

The results of the chemical analyses of tomato leaves and oats grown on Fox sandy loam are shown in Table 9 and in Figs. 24, 25 and 26. There were appreciable increases in the Ca content of plants when the level of total base saturation was increased from about 50 to 75 percent of the total exchange capacity (Fig. 24). However, above that level, the increase in the Ca content of the plants was overshadowed

TABLE 9—*Effect of degree of base saturation on the composition of oats and tomato plants grown on Fox sandy loam*

Base saturation,* percent	Tomato leaves			Oats		
	Mineral content, m.e./100 gm.					
	Ca	Mg	K	Ca	Mg	K
24.5	34.1	22.4	13.5	28.1	16.2	18.5
50	35.4	22.3	16.0	20.3	19.4	21.2
75	63.6	21.4	16.9	40.4	17.1	25.6
100	65.2	32.5	21.1	45.3	22.3	43.8
150	59.3	35.6	26.9	45.9	20.4	40.8

*Ratios of Ca:Mg:K are shown in Table 3.

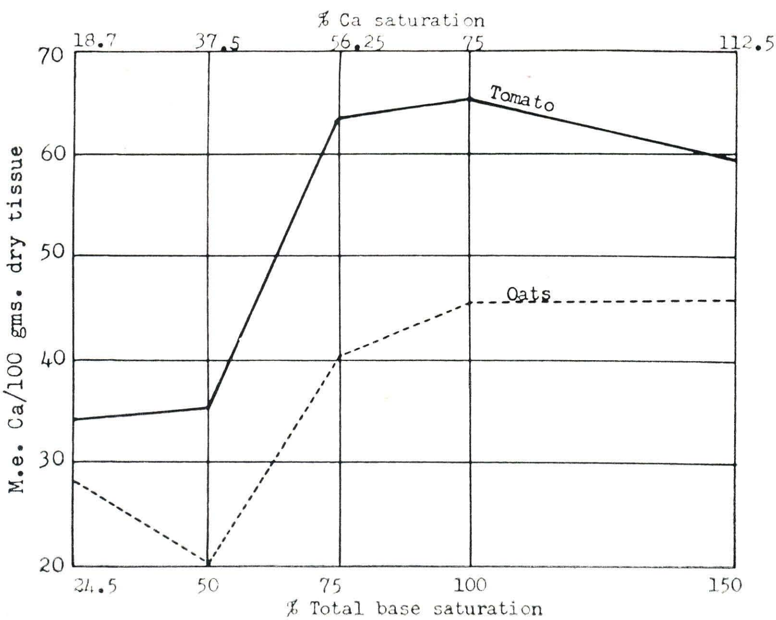

Fig. 24. The effect of the degree of base saturation on the Ca content of tomato and oats plants in Fox sandy loam.

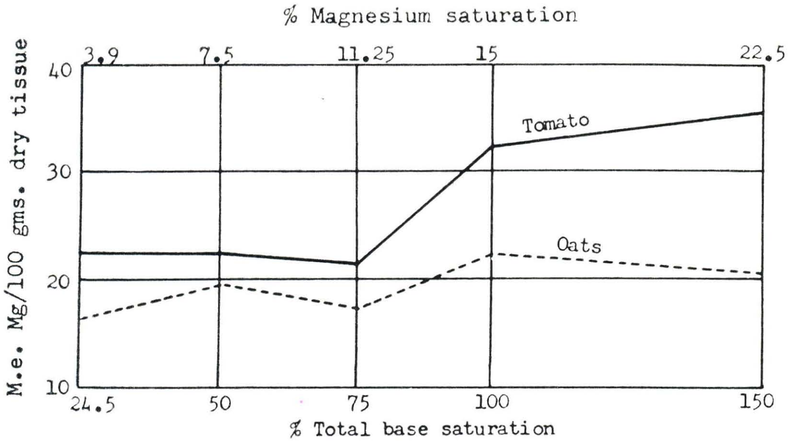

Fig. 25. The effect of the degree of base saturation on the Mg content of tomato and oats plants in Fox sandy loam.

by the rapid increase in K content (Fig. 26). The Mg curves (Fig. 25) were not as regular as the Ca and K curves. In general, the Ca curves coincided fairly well with the yield data.

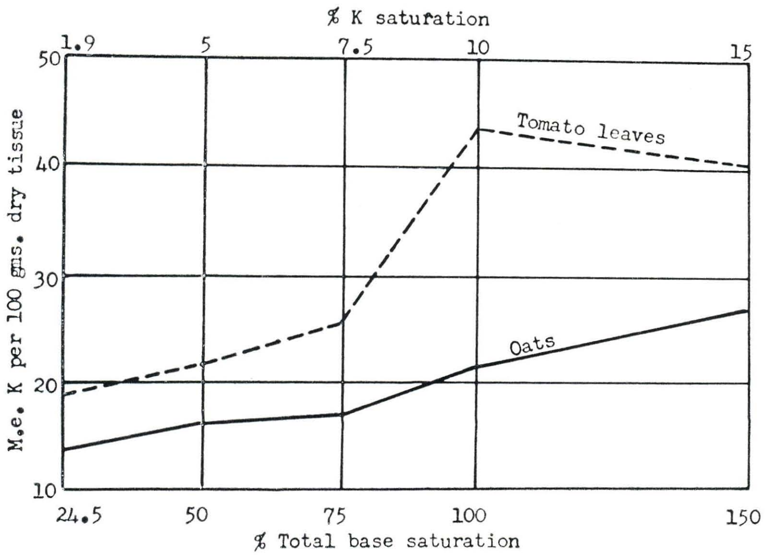

Fig. 26. The effect of degree of base saturation on the K content of tomato and oats plants in Fox sandy loam.

EFFECT OF COMPLEMENTARY IONS ON THE GROWTH AND MINERAL COMPOSITION OF PLANTS

I. BENTONITE- AND KAOLIN-SAND MIXTURES

The yields and composition of rye in the bentonite- and kaolin-sand mixtures are given in Table 10. The 15 treatments listed in the table can be divided into three groups according to the design of the experiment. The first five treatments gave the same degree of Mg and K saturation, but varied in the degree of Ca saturation or its concomitant, the degree of hydrogen saturation. In the second five treatments, the degree of Mg saturation varied and lastly in the third group of treatments, the degree of K saturation varied. The yield data of the plants showed little differences within the groups or among the three groups. Only the last group of five treatments showed consistently increasing yields as the degree of potassium saturation increased.

The graphs shown in Figs. 27, 28 and 29 show the effect of degree of saturation of the complementary ions on the mineral nutrition of plants. From Fig. 27, it can be noted that with an increase in the Ca ions on the clay particle there was a gradual decrease in the Mg and an increase in the K content of rye. More K was also absorbed by rye when complementary hydrogen ions were increasingly replaced by the magnesium ions on the colloidal particles (Fig. 27). The results agree with the findings reported by Peech and Bradfield (31).

TABLE 10—*Effect of complementary ions on yields and composition of rye in bentonite- and kaolin-sand mixtures*

Percent saturation				Yield, gm.		M.e./100 gm. dry tissue					
						Bentonite			Kaolin		
Ca	Mg	K	H	Ben-tonite	Kaolin	Ca	Mg	K	Ca	Mg	K
30	15	15	40	3.53	3.05	13.3	11.5	24.8	24.5	13.6	22.5
35	15	15	35	3.25	3.38	18.1	10.8	23.8	28.3	12.8	22.8
40	15	15	30	3.53	3.04	24.4	8.7	27.5	26.8	12.1	26.4
45	15	15	25	3.06	3.48	28.6	9.2	29.0	25.6	12.2	25.1
50	15	15	20	3.18	3.23	26.8	8.5	29.7	29.7	11.4	28.4
40	5	15	40	3.01	3.05	25.5	8.4	27.2	29.3	8.9	22.4
40	10	15	35	3.91	3.36	26.1	10.2	28.0	26.8	9.6	24.2
40	15	15	30	3.53	3.04	24.4	8.7	27.5	26.8	12.1	26.4
40	20	15	25	3.99	3.33	21.5	9.6	30.4	24.4	11.5	27.6
40	25	15	20	3.38	3.31	20.5	15.3	31.7	23.5	14.6	26.9
40	15	5	40	3.20	3.00	29.3	10.7	16.5	27.6	14.4	11.7
40	15	10	35	3.07	3.22	28.0	10.3	24.1	26.2	12.5	29.4
40	15	15	30	3.53	3.37	24.4	8.7	27.5	26.8	12.1	26.4
40	15	20	25	4.09	3.48	23.2	8.0	34.4	21.0	11.3	31.7
40	15	25	20	3.91	3.53	22.7	8.3	37.8	20.5	10.8	28.5

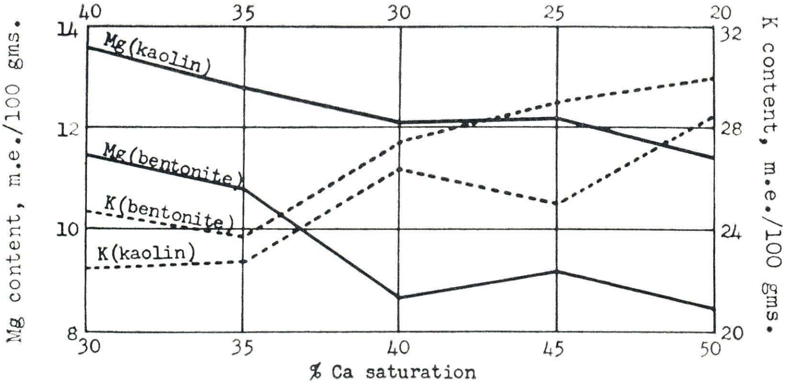

Fig. 27. The effect of the degree of Ca saturation on the Mg and K contents of rye.

The Ca content of the plants was decreased by increasing the Mg-saturation, or by decreasing its concomitant, the H-saturation (Fig. 28). It also is observed, that as complementary ions to exchangeable Ca and Mg, increasing increments of K-ions resulted in less absorption of Ca and Mg by the plant (Fig. 29). In other words, the increase of the degree of H-ion saturation as compared with K-ion saturation is in general a helpful factor in mobilizing Ca and Mg ions into plants.

Figure 30 shows the Ca, Mg and K contents of rye as influenced directly by the degree of saturation of Ca, Mg, and K respectively.

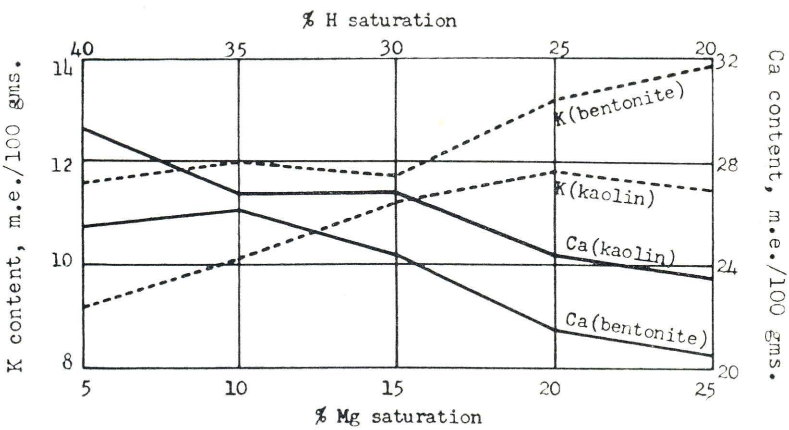

Fig. 28. The effect of the degree of Mg saturation on the Ca and K contents of rye.

The results are in general agreement with those mentioned previously. Some deviations might be due to the differences in the ratio between the three major exchangeable cations.

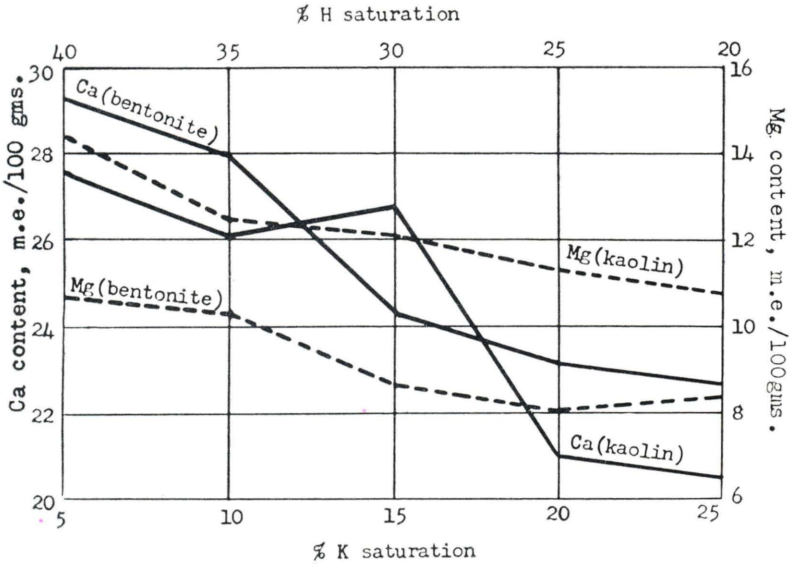

Fig. 29. The effect of the degree of K saturation on the Ca and Mg contents of rye.

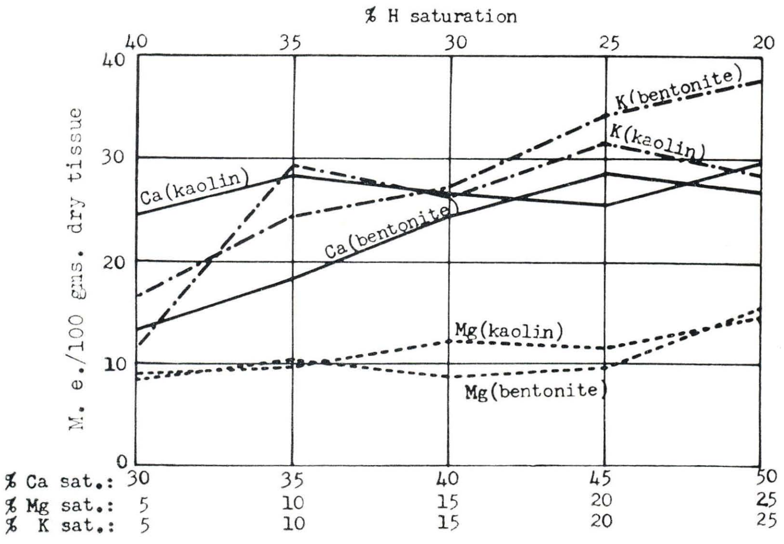

Fig. 30. The Ca, Mg and K contents of rye as influenced directly by the degree of saturation of the respective cations.

II. Fox Sandy Loam

The yields and mineral composition of tomato and oat plants grown in Fox sandy loam are presented in Table 11. Figure 31 shows the actual growth condition of tomato plants at the end of 90 days. The maximum yield of tomato fruits was obtained when the soil was at the level of 35 percent saturation with Ca, 5 percent with Mg and 10 percent with K (i.e. a ratio 7:1:2). The yield data of the tomato plants, however, did not coincide with those of the fruits. No significant difference in the yields of oats was observed.

It was found that with the same degree of K saturation, the replacement of a part of the Mg by Ca as complementary ions, increased the potassium content of the plants. Aside from that, the results are not available for further interpretation because of the design of the experiment.

EFFECT OF THE NATURE OF CLAYS ON THE AVAILABILITY OF EXCHANGEABLE CATIONS

Since most of the relationships between the nature of clay minerals and the effects of degree of base saturation on the growth and mineral composition of plants have already been mentioned in the previous sections, only a few remarks need to be added here to complete the picture. As indicated in Table 1, rye was grown on the bentonite- and

TABLE 11—*Effect of complementary ions on yields and composition of oats and tomato plants grown on Fox sandy loam*

Percent saturation				Yield, gm.*		Composition, m.e./100 gm. dry tissue					
						Tomato leaves			Oats		
Ca	Mg	K	H	Tomato	Oats	Ca	Mg	K	Ca	Mg	K
37.5	7.5	5	50	36.1 593	5.7	35.4	22.3	16.0	20.3	19.4	21.2
40	5	5	50	41.6 597	5.9	58.2	20.1	20.4	25.4	17.3	22.5
35	5	10	50	33.3 678	5.5	42.3	18.4	31.5	22.1	16.2	42.7
30	10	10	50	29.4 618	6.0	35.6	24.4	29.1	26.2	21.4	39.7
30	5	15	50	34.9 608	5.2	37.4	22.6	32.4	20.0	15.1	40.4

*Averages of the triplicate replications. Two values are given for the yields of tomato. The upper values represent the dry weight of plant materials and the lower values the fresh weight of fruits.

Fig. 31. The growth of tomato plants in Fox sandy loam at the end of 90 days. Treatments involve variations in the degree of saturation of Ca, Mg and K.

No. 2—Saturation of Ca, 37.5%; Mg, 7.5%; K, 5%.
No. 6—Saturation of Ca, 40 %; Mg, 5 %; K, 5%.
No. 7—Saturation of Ca, 35 %; Mg, 5 %; K, 10%.
No. 8—Saturation of Ca, 30 %; Mg, 10 %; K, 10%.
No. 9—Saturation of Ca, 30 %; Mg, 5 %; K, 15%.

kaolin-sand mixtures at the same period during the experiment. As a result, data are available for making direct comparisons between the effect of the degree of base saturation of montmorillonitic clays and that of kaolinitic clays on the growth and mineral composition of the plants. In referring to the data in tables 4 and 5, it is observed that the yields of rye were all higher in kaolinitic than in montmorillonitic media when the base saturation was below 60 percent of the total exchange capacity of 2 m.e. per 100 grams. Furthermore, a comparison of the data in tables 7 and 8 reveals that the Ca and Mg content of the rye grown in kaolin-sand mixture was higher than that grown in bentonite-sand mixture when both were at the levels below 60 percent of base saturation.

DISCUSSION

Perhaps the most outstanding thing demonstrated by this investigation is the marked influence of the nature of the soil colloid upon crop response to increasing degrees of base saturation. Yields from montmorillonitic colloid increased with each increment of base saturation reaching a maximum at 80 percent saturation, the highest experimental level. Growth in kaolinitic colloid increased as the degree of base saturation was increased from 20 to 40 percent but there was no increase beyond the 40 percent level. The illitic (hydrous mica) colloid gave results which were intermediate between the other two. Mehlich and Colwell (26), working with soil containing montmorillonitic and kaolinitic type of colloids, have found similar results.

The data, pertaining to the mineral composition of the plants, show that only within a certain range of base saturation is the mineral composition of plants a function of the degree of base saturation. The ranges of Ca, Mg and K are all higher in montmorillonite than in kaolinite colloids. This fact suggests that with a given degree of base saturation, more exchangeable cations are available to plants in kaolinitic colloid than in montmorillonitic colloid. Exchangeable Ca and K held by illitic colloid seem to be even less available than those held by montmorillonitic colloids at the same degree of base saturation.

From the structural consideration, Marshall and Krindill (23) classified montmorillonite, beidellite, nontronite, saponite, and attapulgite as colloidal electrolytes, whereas the clays of the illite and kaolin groups are non-electrolytes. Using the potentiometric titration method and conductance measurement, Marshall (22) and his coworkers (23) recently concluded that for the three cations, Na^+, K^+, and NH_4^+, the ionization of the clay "salts" follows the order: kaolinite > montmorillonite > beidellite > illite, whereas the apparent strengths of the clay "acids" as judged by their dissociation of H^+ are in the order montmorillonite > beidellite > illite > kaolinite. Adopting Marshall's idea of cationic activity (21) in explaining the relative uptake of exchangeable bases by plants, it can be seen that the results of the present investigation coincide with the results found by Marshall and his coworkers in their laboratory studies.

From the viewpoint of practical agriculture, it is of interest to note that in order to increase the Ca uptake by growing plants higher saturation levels of Ca and K are needed for illitic clay than for montmorillonitic clay. In the case of kaolinite, the Ca uptake by plants was as great at low as at high degrees of Ca saturation and increasing amounts of K at the lower degrees of K saturation resulted in a slight but gradual increase in the uptake of K by plants. Hence on kaolinitic soils only a relatively small amount of lime would be necessary to react with a small percentage of the exchangeable hydrogen in order to give a good crop response, while on montmorillonitic and illitic soils, much larger quantities would be needed to give higher levels of Ca saturation for improving the Ca nutrition of plants. The fact that illite, according to Grim (13), is one of the main constituents of the glacial materials of the United States, might partly explain the need of heavy liming in some of Michigan soils.

The advantage of localized application of fertilizers, particularly in montmorillonitic and illitic soils, is clearly indicated by the results. Greater uptake of exchangeable bases and better growth of plants were obtained when the degree of base saturation was relatively high.

Of great importance also in soil-plant relationships are the effects of complementary ions on the uptake of exchangeable bases by plants. The results of this investigation indicate that neutralizing an acid soil with Ca or Mg should render exchangeable K more available. This serves as another reason for the general superiority of Ca-clay over H-clay. However, excess application of K fertilizers to an acid soil may prove to be undesirable, because as complementary ions, K tends to inhibit the uptake of Ca by plants.

Turning to the theoretical aspects, let us now review briefly some of the theories which have been offered to explain the difference in availability of various exchangeable bases. Explanations given by Horner (16), attributed the difference to the relative energy of adsorption of different exchangeable bases on the surface of clay particles. However, no numerical value or exactly relative order of energy of adsorption was given by Horner. Jenny (17), in his equation illustrating the quantitative relationship between the interchanging cations and the complementary ions, used oscillation volume as a measure of adsorbability. The greater the oscillation volume, the smaller the adsorbability and consequently the greater the availability of the ion to the plant. Later, Jenny and Ayres (18) were able to evaluate the ratio of oscillation volumes of some of the exchangeable ions.

Recently Marshall employed various methods for the measurement of cationic activity of the exchangeable bases, and used the term "cationic activity" almost synonymously as "ionic dissociation" or "availability". Cooper and his coworkers (9) have repeatedly proposed and presented evidence for the theory that the intensity of removal of cations from soil colloidal complexes is largely a function of the normal electrode potentials of the element concerned. Most of the theories proposed by various workers are, in reality, essentially the same but with different terminology.

No satisfactory explanation has yet been advanced for the difference in the availability of exchangeable bases on different types of clay minerals. Theoretically, the physico-chemical behavior of the surface of a colloidal particle is a function of both the geometrical and electrical properties of this surface. From the geometrical viewpoint, the surface may be of the convex, plane or concave type. These differences in geometric shape of colloidal particles will result in different distribution of electrostatic attractive force on the surface of the colloidal particle. Duclaux (3) has calculated the distribution of ions around a spherical particle (convex field) of opposite charge. Winterkorn (40) made studies on the surface behavior of platy-shaped clays (planar surface). An analysis of the equations for the convex field shows that the ionic concentration is very high close to the surface and falls off rapidly with increasing distance. This decrease becomes more rapid with increasing charge of the ions. In the case of the planar surface the concentration stays practically constant with increasing distance from the surface. For clays of different shape, these facts may account for a part of the different availability of exchangeable bases on different colloidal clays. But since the three colloids used in this experiment are all platy in shape, this factor of the shape of clay minerals does not actually exist in the present case.

According to Hendricks (15), there are two forces which exercise the attraction of exchangeable cations on the surface of colloidal crystals. One is the Couloumb's force due to electrostatic attraction and the other is the Van der Waal's force. Van der Waal's force varies primarily with the nature of the ions (or molecules) which come upon the surface of a clay mineral as adsorbed particle, while Couloumb's force varies with the nature of the ions, the crystal structure of the mineral and the distance between the crystal surface and the seat of isomorphous replacement within the crystal lattice. For certain structural reasons (14), isomorphous substitution within the crystal lattice of kaolinite is believed to be absent. The exchangeable bases are held on the surface of kaolinite mostly through the direct replacement, by cations, of H in OH groups of the lattice surface (20). But in montmorillonite, a 2:1 type clay mineral, due to its structural characteristics, seats of replacement are offered to the cations. The difference in the forces of attraction thus created may account for at least a part of the difference in the availability of exchangeable bases on the surface of montmorillonitic and kaolinitic types of clay minerals.

SUMMARY AND CONCLUSIONS

This investigation was undertaken to attain by means of pot cultures a better understanding of the significance of the degree of base saturation in relation to the growth and mineral composition of certain crops.

Two relatively pure mineral colloids, bentonite and kaolin, and a Fox sandy loam containing illite were used for the studies. Bentonite and kaolin were first electro-dialyzed and then mixed with different amounts of pure quartz sand to give varying levels of base exchange capacity. Treatments were made to all three cultural media for varying degrees of base saturation and also, in a separate experiment, for varying ratios between one of the three major exchangeable cations and exchangeable hydrogen. Oats and rye were grown in succession in montmorillonitic and kaolinitic media, while peaches, soybeans, proso (millett), tomatoes and oats were grown in the Fox sandy loam. Dry weights and contents of certain mineral constituents of oats, rye and tomatoes were determined.

Yield data from the montmorillonitic media showed nearly linear relationship between the degree of base saturation and the growth of the plants. In the kaolinitic media the increase in yields was only noticeable from the first increment of bases; effects above 40 percent total base saturation being insignificant. The results from illitic soil were intermediate between those mentioned above, i.e. the highest yields of tomatoes were obtained at the 75 percent saturation level.

The yield data further indicate that the growth of plants was more closely related to the degree of base saturation than to the total supply of exchangeable bases. With the same amount of bases and at the levels below 60 percent base saturation, the yields of rye grown in the kaolinitic colloid were higher than those grown in the montmorillonitic colloid.

In the montmorillonitic media, the increase of Ca uptake by the plants from the first increment of Ca was pronounced with only little effects above 30 percent Ca saturation (or 40 percent level of total base saturation). The K content of the plants was increased appreciably at only the higher levels of base saturation, while significant increases in the Mg content of the plants occurred at lower levels (i.e. below 60 percent base saturation level).

In the kaolinitic media no appreciable change in Ca and Mg content of the plants was noticed. This is an interesting contrast to the results obtained with the montmorillonitic media. However, there were definite increases in K content of plants, with increasing increments of K at the lower levels of saturation.

The higher contents of Ca and Mg in the plants were found in kaolinitic media rather than in the montmorillonitic media, provided the total base saturation level was under 60 percent of the exchange capacity. On the other hand, the K content of the plants from montmorillonitic media was invariably higher than that from the kaolinitic media.

In the illitic soil the most marked increase in Ca content in plants occurred when the degree of base saturation was increased from the 50- to the 75-percent level. Beyond that point, no appreciable increase was noticed. As the degree of base saturation of illitic soil increased, the K and Mg percentages in the plants increased also.

The effect of complementary ions on the availability of the exchangeable bases was indicated by the mineral composition of the rye grown in montmorillonitic and kaolinitic media receiving the same treatments. The results all show that referring to H-ion as standard, the Ca-ion and Mg-ion tended to increase the availability of exchangeable K, while the K-ion exhibited the reverse effect on exchangeable Ca and Mg. The well recognized fact that Ca and Mg ions have a mutual repressive effect was also observed in the experiment.

The study also discusses, from the theoretical point of view some of the factors involved in determining the availability of exchangeable bases.

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