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The Exchangeable Bases of Two Missouri Soils in Relation to Composition of Four Pasture Species

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I. INTRODUCTION

The relationship between the chemical properties of soils and the composition of plants grown thereon forms one of the oldest topics of agricultural chemistry and one in which interest has been sustained over a full century. The volume of work published annually in this field is now very great. It may be subdivided into three parts, with some overlapping, as follows: (1) Plant yield and composition as related to the major nutrient elements, N, P, K, and Ca, supplied in the soil; (2) similar studies with regard to the minor elements; (3) vitamin content in relation to soil nutrient factors.

The scope of the present study was restricted to the cationic or basic nutrients. It involved addition to the soils of four elements, calcium, potassium, magnesium, and sodium, and determination in the plant material not only of these elements, but also of N, P, Mn, Sr, and in some cases of Si. The two soils chosen were the Putnam and the Lindley silt loams, and the four crops were bluegrass (Poa Pratensis L.), redtop (Agrostis Alba L.), sweet clover (Melilotus Alba), and Korean lespedeza (Lespedeza Stipulacae). This investigation followed, in natural sequence, a calcium and phosphorus study using the same two soils and the same four species, the results of which have been published in part by Albrecht and Smith (2, 3).*

The experiments were arranged so as to show, as far as possible, the broad general factors involved in the uptake of cationic nutrients by plants. The earlier studies by Albrecht and co-workers (1) using colloidal clay cultures with soybeans as the experimental crop, had shown that total nutrients as well as degree of saturation were important in the uptake by plants. The importance of calcium had been very strikingly shown by these studies; consequently in the present series calcium was given an especially important role. The effects of other nutrients such as potassium, magnesium, and sodium, were therefore determined at three levels in combination with three different levels of calcium saturation. The arrangement thus adopted gave six levels of total base saturation. In evaluating the results we can therefore proceed in two ways. The results of increasing amounts of one element when others are held constant can be determined; secondly, the changes caused by variations in the proportions of the nutrient cations at constant levels of base saturation can be investigated. Most of the previous work with soils has been concerned with

*Numerals refer to "References", Page 58.

comparisons of the former type. Van Itallie, whose work with soil will be considered in some detail below, showed the advantages of the latter type of comparison. This has also been extensively used by Albrecht and co-workers in clay culture studies.

On the analytical side an unusually wide range of constituent elements was covered by a combination of chemical and spectrographic methods. Our adoption of the Lundegardh method for the spectrographic analysis of solutions has greatly contributed to this end. The determination of strontium, seldom considered previously in plant composition studies, was so easy using the spectrograph that it was included throughout, and, as will be shown later, it has added much to the significance of the conclusions.

In the selection of the crops studied, regard was paid to the importance of pasture species in Missouri generally, and, in particular, in the areas of Putnam silt loam and the Lindley silt loam. These are important soil types of a relatively poor quality in the northeastern part of the state. Because of the difficulty of arranging an adequate control of the nutrient supply in the field, a greenhouse pot culture study was chosen. Field conditions were simulated to some extent by regular cutting at specific stages of growth. This practice had one considerable advantage from the point of view of interpretation. The grass or legume was cut before a major segregation of the chemical constituents to different parts could occur. Hence, if we may neglect the injury due to intermittent cutting, a fairly clear picture of the relationship between soil nutrient conditions and plant uptake should result.

II. THE BASIS OF COMPARISON IN PLANT COMPOSITION STUDIES

The effect of a fertilizer or other treatment upon a crop was for many years followed chiefly through the total yields of dry matter obtained. Chemical analyses of the crops were used in two ways. The percentages of the constituents as determined in the dry matter were taken as reflecting changes in the physiological mechanisms of the plants. On the other hand, total yields of specific elements were utilized chiefly in the balance-sheet type of experiment, such, for instance, as those of Lawes and Gilbert on nitrogen. To some extent this divergence of function has tended to disappear in recent years. Many authors now give both percentage compositions and total yields of individual elements. Few, however, have examined with sufficient care the question as to which provides the more appropriate comparison of the effects of the factors under experiment.

Consider a simple case, such as that of experiments carried out on a single crop at two nutrient levels of a single element, all other nutrient elements being constant and in sufficient amount. In general, both the percentages and the absolute amounts of all the different elements found will be changed. The absolute amount of a given element is the integral with respect to time of the appropriate rate processes which have gone on during the growth of the plant. This integral would include the change of root area and of mean root activity with time. If the outer nutrient media remained absolutely constant in composition during growth, and, if the crops were harvested at similar stages of growth, the integral or total amounts of a given element removed could be taken as a measure of the effect of varying the given element. There would be two kinds of such measures—direct and indirect, the former referring to the element added in variable amount, and the latter to all others determined by analysis in the plant.

The total amounts absorbed, being integral quantities, are dependent upon the shapes of the respective rate of absorption curves. It would thus be possible in a comparison to have curves of different shapes with the same area beneath them. The only way to get reliable results would appear to be to limit the growth to the earlier stages where differentiation of nutrient elements by translocation would be less marked than if the plants were grown to maturity. Experiments with pasture species in which the crops are harvested at a definite stage of growth, then allowed to grow again to the same stage, and so on, would seem to offer the best assurance that the rate of absorption curves would be similar.

It is often assumed that percentage composition, expressed on the basis of dry matter, bears a close relation to the physiological condition of the plant. For this reason differences in treatment have usually been compared through the percentages of the elements determined. More assumptions are here involved than is commonly realized. Consider the case of a plant growing in continuously renewed culture solutions. The nutrients pass from the outer solutions through the root membranes into the plant. With the lapse of time the root membranes change both in area and in activity per unit area. At the same time inside the plant there is an increase in total organic matter, total water and total inorganic elements. The percentage composition for a given element can only provide a proportionate measure of the rate of absorption of this element, when it is proportional to the product of the mean root area and the mean root activity. Expressing the matter another way, whereas the total quantity of a given element can be regarded as one multiple integral, the fractional or percentage composition is the ratio of two such integrals. These are, it is true, not entirely independent of one another, but it would indeed be presumptious to assert without experimental evidence that the same relationship exists between them under different treatments.

The experiments of Burd (5) which deal with the constituents removed from the soil by growing barley plants, show very clearly that increase in dry matter may show entirely different relationships to the total uptake of nitrogen, potassium, calcium, and magnesium depending upon the period in the growth of the plant. Under the conditions used, the barley plants lost considerable amounts of potassium and nitrogen between the ninth and eleventh weeks of growth, yet the total dry matter steadily increased. Of the five elements studied, only phosphorus maintained an approximately constant relationship to the total dry matter. During the first nine weeks of growth all five elements showed a linear increase with time, as did the dry matter. One may say therefore that it is only at certain stages of the life of the plant (notably the early stages) that a simple relationship between total dry matter and total nitrogen, potassium, calcium or magnesium can be demonstrated. Unfortunately, we have little detailed information of this kind for other crops, nor for crops grown under different nutrient conditions.

The most comprehensive investigations of composition in relation to stage of growth are those of Wilfarth, Römer and Wimmer (26) who made determinations of dry matter, starch, potassium, sodium, nitrogen, and phosphorus at three, four or five stages. Barley, wheat and potatoes were grown in the field. Barley and peas were also grown in the greenhouse in sand cultures using four different levels of potassium in the nutrient solutions. Potatoes were grown in the greenhouse using a peat-sand mixture. White mustard was grown as a greenhouse culture in soil with the addition of fertilizers, the potassium being used at two levels. These investigators clearly established a loss of nutrients back to the soil during the ripening of the grains. At the same time the total dry matter and total starch increased. This loss did not occur with potatoes.

James (18) has investigated the rate of uptake of potassium in potatoes grown in a soil-sand mixture and found the potassium content and the dry matter to be closely correlated. Knowles and Watkin (21) have given similar data for wheat grown in soil. Fonder (9) determined potassium and calcium in alfalfa grown in soil at different stages of growth. Lundegardh (22) finds a close correlation between the growth of wheat up to grain formation and potassium content. Four varieties of wheat were used in three different water culture solutions. In none of these cases were sufficient determinations made to trace the growth curves with precision and therefore our information regarding rates of uptake is very inadequate.

It would seem therefore that the effects of different nutrients upon plants cannot, in general, be represented by single numbers, whether they be total quantities of individual elements or percentages. Only rate of absorption-time curves or integral absorption-time curves such as those of Burd (5) are properly adequate. If, however, plants of a given species are to be compared only with respect to the early stages of growth under different treatments then total uptake may give a moderately reliable index. The use of percentages based on total dry matter can be justified for special purposes. Thus in attempting to compare one species with another, or in the use of plant materials as feeding stuffs, percentage compositions are used.

In the absence of measurements of root area, rates of uptake of nutrients have been computed per gram of dry matter. In the early stages of growth where practically all the plant participates in active metabolism the errors in such comparisons will evidently be much smaller than in the later stages.

As regards pasture species, there appear to be in water cultures no data whatever on rate of growth in relation to nutrient uptake, nor information on the composition of successive cuttings made at the same stage of growth. Comparisons of soil cultures and water cultures have seldom been made. Hunter (14) has made such a comparison for alfalfa but it is not possible to deduce growth and nutrient uptake curves from his data. Hunter, Toth, and Bear (15) have made a valuable contribution in a comparison of nutrient uptake in successive cuttings of alfalfa grown on soil-sand mixtures with a wide variation in the exchangeable Ca/K ratios.

The experiments herein discussed have been evaluated chiefly on the percentage basis. It has the advantage that comparisons between a single crop grown on two different soils and comparisons between four different crops can be made with moderate assurance.

III. THE PHYSICAL CHEMISTRY OF NUTRIENT UPTAKE

Our knowledge of the reactions undergone by the nutrient elements in their passage from the soil to the plant and in their diverse roles inside the plant is so fragmentary that we are nowhere in a position to apply quantitatively the principles of chemical kinetics. The broader thermodynamic principles which operate independently of mechanism may have restricted application. They will not, of course, enable us to distinguish between different possible mechanisms.

A. Thermodynamic Considerations

In order to consider the matter thermodynamically one begins by setting up a simplified system consisting of the outer nutrient medium, a membrane of some kind to represent the average function of the root and an inner solution, usually identified with the plant sap.

An adequate description of the external environment of the plant root would be afforded by the sum of the chemical potentials of all the molecules and ions in its neighborhood. We are as yet very far from realizing such a complete summation. The same is true of the situation within the plant root. We must realize also that this information can be adequate to our needs only under two possible sets of circumstances; namely (1) chemical equilibrium exists between the outer and inner environments of the root, or (2) a steady state is maintained between them. We have good reason to believe that the former condition is seldom realized and that it would be abnormal for the the growing plant. As regards the second possibility, namely the maintenance of a steady state, we can readily imagine some circumstances in which it would hold and others in which it would not. If it does not obtain, then chemical potentials are no longer sufficient and progress will depend upon the setting up of chemical potential—time relationships.

Before discussing the mechanisms which are available for the establishment of the chemical potentials inside and outside the root membrane we should consider somewhat more closely the implications of the terms "chemical equilibrium" and "steady state". A complete chemical equilibrium is said to exist between two systems when the chemical potentials of the molecular species in one system are respectively equal to those in the other. Restricting ourselves to dilute solutions of non-volatile solutes in water this would be equivalent to saying that their respective activities must be equal.

Three main types of steady state merit discussion. (1) In the first the solvent is at the same chemical potential and therefore the sum of the chemical potentials of the solutes is the same in both systems. For example, two isotonic solutions containing different salts have the same vapor pressure and when connected only through the vapor phase no change occurs. However, in a free diffusion experiment in the liquid phase the solutes will move so as to establish complete chemical equilibrium as defined above. Such steady states can thus be maintained by placing restrictions on the movement of certain constituents.

(2) In the second a constant difference is maintained between the chemical potential of the water in the one system and that in the other. This difference will be numerically equal to the difference in the sums of the chemical potentials of the solutes in the two systems. As in case 1 the solutes need not bear any quantitative relation to each other except through the sums of their chemical potentials. The maintenance of this type of condition, like that in case 1, would require restrictions placed on the free movement of the solutes. (3) The third kind of steady state is similar to the second in that a constant difference in the chemical potential of the water is maintained but now the same molecular and ionic species are found in both systems and for each a constant activity ratio between the two systems is maintained. Here there are no complete restrictions on movement.

It will be evident that steady states intermediate in character between (2) and (3) are possible. In these the restrictions would apply to certain constituents only. For instance, a porous membrane impermeable to large molecules might separate a solution containing both large and small molecules from one containing only small molecules.

More detailed discussion of possible steady states is not warranted at this time since we now realize that any which may be apparent between a living root and its chemical environment represent merely statistical averages. Recent work, such as that of Hoagland and Broyer (12) and Prevot and Steward (25), has emphasized the great importance of active or physiological absorption as compared with passive or purely physical absorption. A close connection has been established between physiological activity and uptake of nutrients. A single root system contains regions of varying physiological activity. The analysis of a root sap represents an average from all of these. However, because of its generality and freedom from mechanistic details the concept of a steady state should not be neglected. We can only learn more about it by utilizing activity measurements on as broad a scale as possible.

B. The Chemical Environment of the Plant Root

Although we are still far from being able to predict plant composition from a study of soil properties, some of the factors involved are now becoming clearer to us. In a continuously renewed culture solution the chemical environment a short distance from the absorbing root is maintained constant. There are three possible ways in which ions can enter the plant; (a) by free diffusion, (b) by chemical interaction, (c) by mechanical transport with water. This last is largely discounted though not entirely ruled out by experiments which have shown that water uptake and salt absorption are apparently independent of one another. Diffusion must be present in any case; if ions are removed by chemical interaction then the concentration gradient is changed so as to make the diffusion more effective. We are not yet in a position to evaluate the relative contributions of diffusion and chemical interaction. We can see something of the qualitative trends in particular cases by assuming that the root acts as a membrane. The properties of the root strongly suggest that to a predominant extent it acts as a negatively charged membrane.

The consequences of this are as follows: According to the Meyer and Sievers and Teorell theory of membrane permeability a negative charge acts to increase the apparent mobility of cations compared with anions. However, recent experiments using bromide as anion have shown a relatively easy passage for this ion. Thus the root membrane can have only a relatively small negative charge. But a rather porous membrane with a small charge would certainly not be capable of imposing a low mobility on sodium as compared with potassium. Hence although the qualitative effect as predicted would operate in the right direction, no ordinary porous membrane appears capable of accounting for the quantitative results. We may now consider chemical effects. A cationic exchange reaction may be expected between the membrane cations and those of the external solution. Here the lyotrope series will make itself apparent—potassium should enter by exchange more readily than sodium and so on. Again, although qualitatively this effect also operates in the right direction it does not seem capable, either alone or in combination with the diffusion effect, of explaining the enormous differences in uptake by plants between sodium and potassium. Some further chemical mechanism seems called for. It might perhaps be found in Overton's and Osterhout's hypothesis of a lipoid layer in which salts of different cations are soluble to different degrees. Much further work is required before this problem can be considered solved.

Passing now to the soil rather than to a culture solution as providing the external environment of the root, we have to consider an additional mechanism for the movement of ions to the root. This is contact exchange, beautifully demonstrated by Jenny and his coworkers in recent years (20). We shall suppose that hydrogen ions from the root surface exchange with cations attached to the clay or the humic matter. Two extreme cases present themselves.

If the steady rate of removal of cations from colloidal particles adjacent to the root is low compared with the rate of renewal of these cations from the bulk of the soil, then over any short interval of time the proportion in which the exchange for hydrogen occurs will be the same as is found for these cations in the soil by activity measurements. This is so because thermodynamically the measurement of activity is equivalent to the isothermal transfer of a minute proportion of the ions from the soil to a standard solution. Thus whenever a very small fraction of the exchangeable ions are removed by exchange against any cation they will be in the same proportion to each other, and this proportion will be the same as is given by activity measurements on the individual cations present.

On the other hand, if the rate of renewal from the bulk of the soil is low compared with that of uptake by the root, then a zone of unsaturation will extend outwards from the root. Within it the clay will be largely denuded of exchangeable cations. Their proportions as exchanged on to the root surface will thus approximate to those given by exchangeable base determinations, when all the cations are removed by the displacing solution.

Although this field of study is comparatively new, it is already apparent that the ionic proportions afforded by activity measurements may be widely different from those given by exchangeable base determinations. Figures were given in a previous paper (23) which showed that with certain dilute clay suspensions when the ratio of exchangeable calcium to exchangeable potassium was 1.5:1 (molar basis) the activity ratio was 0.15. Thus under these conditions calcium is dissociated from the clay to about one-tenth the extent of the potassium.

It would seem then, that the proportions of cations which arrive at the root surface will be enormously dependent upon the two rate processes considered above. These may be considered as external rate processes. Superimposed upon these are the reactions going on within the root.

We may consider from this point of view Jenny's and Ayers' experiments on the complementary ion principle in exchange reactions (19). Both their experimental results and their theoretical curves agree in the conclusion that the proportionate release of a particular ion is not affected by the nature of the complementary ion for an infinitesimal exchange. This is precisely equivalent to a measurement of the proportionate activity. At the other end of the range where 100 per cent exchange has been achieved they again find that the nature of complementary ion is immaterial, which, of course, means that here we measure the relative proportions of the total exchangeable bases. In between these two regions the nature of the complementary ion has a great influence on the loss by exchange of any particular cation.

Bray (4) has attempted to apply a reasoning somewhat similarly based, to the problem of determining available nutrients. He suggests that the exchange of only part of the exchangeable bases against hydrogen corresponds much more nearly to what actually occurs than would a complete exchange. He therefore takes the proportion of exchangeable cations which are released for a small exchange as affording a basis for the evaluation of the relative nutrient level. From what has been said above this is equivalent to fixing one point on the curves connecting the proportions of the cations released with the percentage of exchange. For smaller and smaller release by exchange these proportions will approach ever more closely those given by activity measurements. Since in the field the exchange is governed by rate processes which are likely to vary from one plant to another, and also with the rate of growth of the plant roots and their physiological activity it seems doubtful whether a single point chosen arbitrarily can have general validity.

IV. OUTLINE OF METHODS

A. Greenhouse Procedure

The crops were grown in earthenware jars on the bottom of which was placed a layer of gravel. Then 7000 (Putnam) or 6700 grams (Lindley) of soil (110° basis) were added to bring the level to within one inch of the top. The soils had been thoroughly mixed after being brought in from the field. The requisite quantities of carbonates or bicarbonates were added to each pot, along with a basal dressing of 38% superphosphate to all. Calcium and magnesium carbonates (CP grade) were added dry and thoroughly mixed with the soil in a churn. Sodium and potassium bicarbonates were added in solution in 1939-40 but as solids in 1940-41. Because of the bad structural condition caused at the surface by the solution treatment, subsequent mixing throughout the body of the soil was needed. Before the crops were sown, a period of at least two weeks was allowed for equilibrium to become established. During this period the soil was kept at the moisture equivalent.

The two grasses, bluegrass and redtop, and the sweet clover were sown in winter and grown until June or early July when the heat becomes excessive. Korean lespedeza needed special treatment. Because of its photo-sensitivity it can only be kept at the vegetative stage during long days. It was therefore sown later in the spring than the other crops and overhead lights were used to supplement natural daylight. All treatments were carried out in quintuplicate. In the two previous seasons similar studies had been made on the same four crops using chiefly lime and phosphate treatments. The standard errors of such experiments had been determined and found to be satisfactorily low and the five fold replication was found by experience to give sufficient dry matter for the analyses.

During growth, successive cuttings were made of the four crops, the weights being recorded separately. Details of the exact times and stages of growth are given in the tabulation of data in Appendix A.

B. Analytical Procedure

Duplicate samples of one gram were used for moisture determinations (70° C.) and subsequently for nitrogen by the Kjeldahl method (Murneek and Heinze's mixture as catalyst). Duplicate samples of 2.5 grams were used for the digestion with nitric and perchloric acids. In this way total silica remained as an insoluble residue which was filtered off, and washed. The filtrate and washings were made up to standard volume (250 cc.) and separate samples were taken from this for the determination of Ca and P. Part of the solution was then used for the spectrographic determination of Sr, Mg, Mn, K, and Na, using the Lundegardh technique under the conditions as described by Ells and Marshall (7). Some general observations on the precision with which the different elements were determined follow:

Silica.—The separation of the amorphous silicia of the plant material from the accompanying resistant mineral grains from soil and dust was attempted in some cases using the sodium carbonate-sodium hydroxide mixture as given in the A.O.A.C. method. The results were not very satisfactory. No reliable blank for the insoluble portion could be obtained even with a single crop so that the actual separation had to be carried out in each individual case. There was wide variation in the amount of the insoluble portion and it frequently exceeded the soluble silica in amount. We should expect that where the dust which contributes largely to the insoluble silica consists partly of reactive clay minerals the latter will make an appreciable contribution to the soluble silica. For this no correction can be applied. Further work on the determination of silica in plant composition studies is therefore needed. In the present study it is doubtful whether differences less than 0.2% can be used as a basis for valid discussion.

Calcium.—The use of a 50 cc. aliquot with the usual technique for the precipitation of calcium oxalate in acid solution was found preferable to the semi-micro method using 5 cc. in which the centrifuge is employed in place of filtration. Duplicate determinations were made on each solution; thus since duplicate digestions were the rule, each result given is the average of four determinations. The differences between separate digestions of the same forage sample rarely exceeded 0.05% Ca. Blanks were carried through with each crop analysed. They were small and consistent.

Phosphorus.—The colorimetric method used proved exceedingly reliable with proper attention to exact timing of the interval between addition of the reducing agent and the reading of the colorimeter. Reagent and digestion blanks were run in each series. Duplicate readings were made on each solution analysed. The differences between separate digestions of the same forage samples very rarely exceeded 0.01% P.

Nitrogen.—The Kjeldahl procedure is very reliable and no difficulty was experienced in obtaining agreement within 0.1% N, using separate digestions of the same forage sample.

Elements determined spectrographically.—Two spectra were obtained for each solution; thus as in the case of calcium and phosphorus, each result tabulated for K, Na, Sr, Mg, and Mn, is the mean of four determinations. However, the reading of line intensity in the microphotometer is affected by background variation as well as by variation in the excitation conditions for the particular element. For very low concentrations of sodium these background variations were comparable with the heights of the sodium maxima. This situation could have been remedied by the use of the D lines in place of the less sensitive ultraviolet line but sodium blanks also showed about the same order of variability, so that little would have been gained. It will be noted that in the tabulated results sodium is sometimes given simply as $<0.06\%$ Na, whereas in other cases actual figures below 0.06% are provided. The variable threshold for Na may be ascribed chiefly to background variation, which in some series was greater than in others. None of the other elements occurred close to the theshold value so that for K, Mg, Mn, and Sr, the accuracy remains reasonably consistent from one set to another. As between one digestion and another the following variations were rarely exceeded; for potassium 0.1% K, for magnesium 0.05% Mg, for manganese 0.005% Mn, for strontium 0.0005% Sr, and for sodium 0.05% Na.

V. THE EFFECT OF THE CATIONS ON THE EXCHANGEABLE BASE STATUS OF THE TWO SOILS

In order to allow for secondary effects which might arise after addition of the bases to the soils, samples were taken from the pots during the first growth period of the plants. Ten borings were made to the full depth of the pots, from each soil treatment. The exchange capacity and exchangeable bases were then determined by the neutral normal ammonium acetate method, the chemical method being used for calcium and the spectrographic method for the other bases. In this way such effects as the fixation of potassium could be quantitatively followed. Tables 1 and 2 give the results for the two soils.

It is evident that calcium remains in the exchangeable form since in both soils the recovery is over 90%. As regards magnesium, potassium, and sodium, the quantities displaced by ammonium acetate are considerably below the sum of the amounts in the untreated soil plus those added as carbonates or bicarbonates. This discrepancy may be partly due to early uptake of these nutrients by the growing plants which were already several inches in height when the samples were taken. However, a considerable measure of fixation in a non-exchangeable form may also have occurred. Potassium shows a greater discrepancy than sodium or magnesium, which would tend to support the idea that fixation has played an important part.

In order to provide information regarding the influence of the complementary ions upon the exchange of cations for hydrogen a limited set of soil samples was treated with hydrochloric acid equivalent to one-tenth of the exchange capacity. The idea that such limited exchange experiments give a better expression of the proportions of the cations available for plants than do the ordinary exchangeable base determinations, has been put forward by Bray (4). He has shown that Jenny's complementary ion principle (19) can be applied to the complex situation in an actual soil. The present study afforded a good opportunity to follow these exchange properties in relation to plant composition. Hence nine selected treatments from each soil were investigated. The results are given in Tables 3 and 4.

In interpreting the results it must be remembered that small amounts of water soluble constituents will strongly affect these figures. The total bases released in every case exceed the equivalents of acid used. The Lindley soil shows greater discrepancies than the Putnam. It is believed that the high figures obtained for the Lindley are affected by storage of the soil samples. Prior to these determinations they were kept in a laboratory in which acid fumes were sometimes produced. The pH figures after storage were markedly lower than was anticipated from the treatments, and for that reason they have been omitted from Table 2. Table 3 (Putnam) thus affords more clear

Table 1. Exchange properties of Putnam silt loam soil (1939-40 series). (Figures in parentheses refer to the appropriate exchangeable base as calculated from the amount in the untreated soil plus that added as a soil treatment. All results in milliequivalents per 100 grm. dry soil.)

Soil treatment	Ca	Mg	K	Na	Mn	Sr	Exch. Cap.	pH
1. Basal	7.58	2.32	.20	.39	.072	.032	14.2	5.16
2. Basal 1/2Ca	12.39(12.53)	1.93	.20	.38	.016	.029	14.5	6.48
3. Basal 1Ca	16.85(17.48)	1.98	.25	.44	.012	.029	14.6	7.27
4. Basal 1/4K	7.53	2.02	1.42(2.67)	.38	.016	.029	13.1	5.76
5. Basal 1/2K	7.51	2.07	3.59(5.15)	.36	.017	.031	13.6	6.42
6. Basal 1/4Mg	7.77	3.92(4.79)	.21	.23	.014	.028	14.4	5.77
7. Basal 1/2Mg	7.58	5.39(7.17)	.21	.24	.009	.026	14.2	6.52
8. Basal 1/4Na	7.65	1.73	.24	2.28(2.86)	.016	.025	14.3	6.15
9. Basal 1/2Na	7.73	1.62	.19	4.14(5.34)	.015	.029	14.7	6.73
10. Basal 1/2Ca 1/4K	12.53(12.53)	2.18	1.64(2.67)	.28	.013	.031	14.3	7.04
11. Basal 1/2Ca 1/2K	12.67(12.53)	1.92	3.43(5.15)	.27	.014	.026	13.6	7.35
12. Basal 1Ca 1/4K	16.42(17.48)	1.87	1.39(2.67)	.29	.012	.028	14.3	7.48
13. Basal 1/2Ca 1/4Mg	12.36(12.53)	3.29(4.79)	.15	.22	.010	.025	---	7.46
14. Basal 1/2Ca 1/2Mg	12.56(12.53)	6.05(7.17)	.27	.25	.012	.028	---	7.19
15. Basal 1Ca 1/4 Mg	16.37(17.48)	3.40(4.79)	.15	.22	.009	.027	---	7.38
16. Basal 1Ca 1/4Na	12.49(12.53)	1.87	.19	2.58(2.86)	.007	.027	---	7.19
17. Basal 1/2Ca 1/2Na	12.26(12.53)	1.60	.19	4.27(5.34)	.011	.024	13.7	7.70
18. Basal 1Ca 1/4Na	17.07(17.48)	1.33	.17	2.04(2.86)	.012	.024	13.7	7.69
19. Basal 1/2Ca 1/4 Mg 1/4K	13.32(12.53)	2.65(4.79)	1.28(2.67)	.22	.008	.024	12.9	7.35
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	12.57(12.53)	3.13(4.79)	1.42(2.67)	2.13(2.86)	.016	.026	13.3	7.76

Table 2. Exchange properties of Lindley silt loam soil (1940-41). (Figures in parentheses refer to the appropriate exchangeable base as calculated from the amount in the untreated soil plus that added as a soil treatment. All results in milliequivalents per 100 grm. dry soil).

Soil Treatment	Ca	Mg.	K	Na	Mn	Sr	Exch. Cap.
1. Basal	6.30	1.14	.17	.21	.32	.013	10.82
2. Basal 1/2Ca	7.88(8.30)	1.18	.15	.17	.18	.015	10.86
3. Basal 1Ca	9.17(10.3)	1.22	.15	.19	.16	.013	10.86
4. Basal 1/4K	6.30	1.40	.72(1.17)	.28	.21	.014	10.44
5. Basal 1/2K	5.98	1.16	1.21(2.17)	.22	.15	.013	10.12
6. Basal 1/4Mg	6.51	2.01(2.14)	.19	.17	.19	.012	10.91
7. Basal 1/2Mg	5.88	2.61(3.14)	.14	.13	.14	.011	10.90
8. Basal 1/4Na	6.13	1.34	.17	1.14(1.21)	.19	.014	11.06
9. Basal 1/2Na	5.99	1.21	.21	2.19(2.21)	.14	.015	10.95
10. Basal 1/2Ca 1/4K	7.51(8.30)	1.17	.51(1.17)	----	.13	.015	10.26
11. Basal 1/2Ca 1/2K	7.71(8.30)	1.34	1.20(2.17)	----	.10	.015	10.19
12. Basal 1Ca 1/4K	8.60(10.3)	1.18	.57(1.17)	.20	.09	.012	10.56
13. Basal 1/2Ca 1/4Mg	7.92(8.30)	2.51(2.14)	.30	----	.10	.012	10.95
14. Basal 1/2Ca 1/2Mg	7.71(8.30)	3.58 (3.14)	.26	----	.09	.013	11.00
15. Basal 1Ca 1/4Mg	9.41(10.3)	2.31(2.14)	.23	.20	.09	.011	11.23
16. Basal 1/2Ca 1/4Na	7.89(8.30)	1.13	.19	1.41(1.21)	.13	.013	11.22
17. Basal 1/2Ca 1/2Na	7.55(8.30)	1.15	.21	2.07(2.21)	.10	.013	10.89
18. Basal 1Ca 1/4Na	9.71(10.3)	.92	.14	1.20(1.21)	.07	.013	11.32
19. Basal 1/2Ca 1/4K 1/4Mg	8.10(8.30)	2.31(2.14)	.50(1.17)	.32	.09	.014	10.81
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	8.09(8.30)	2.36(2.14)	.46(1.17)	1.04(1.21)	.12	.013	11.18
21. No treatment	6.21	1.30	.18	.21	.21	.011	10.96

cut examples of the operation of the complementary ion principle than does Table 4 (Lindley).

It will be seen that the sodium treatments are very effective in reducing the percentages of calcium, magnesium, and strontium liberated. This is exactly what one would predict using the complementary ion principle. The addition of the readily replaceable ion sodium ensures that in the reaction with hydrogen ions the sodium will

TABLE 3. BASES RELEASED FROM PUTNAM SOIL BY HYDROCHLORIC ACID. (HCL= 1.42 m.e. per 100 grm EXCHANGE CAPACITY 14.2 m.e. per 100 grm.

Treatment	Calcium m.e.	Calcium %	Magnesium m.e.	Magnesium %	Potassium m.e.	Potassium %	Sodium m.e.	Sodium %	Manganese m.e.	Manganese %	Strontium m.e.	Strontium %
1. Basal	1.18	15.6	.32	13.9	.032	16	.146	37	.095	132	.0034	10.6
2. Basal 1/2Ca	1.51	12.3	.27	14.1	.021	11	.096	25	.034	212	.0025	9.6
4. Basal 1/4K	1.07	14.2	.27	13.5	.356	25	.143	38	.040	250	.0025	8.6
6. Basal 1/4Mg	1.07	13.7	.55	14.1	.023	11	.113	49	.038	272	.0024	8.6
8. Basal 1/4Na	0.34	4.5	.08	4.5	.019	8	1.34	59	.011	69	.0005	2.0
10. Basal 1/2Ca 1/4K	1.30	10.4	.23	10.5	.287	18	.132	47	.011	85	.0020	6.5
13. Basal 1/2Ca 1/4Mg	1.27	10.3	.48	14.7	.033	22	.120	55	.011	110	.0020	8.0
16. Basal 1/2Ca 1/4Na	0.67	5.4	.13	7.0	.034	18	1.55	60	.006	86	.0010	3.7
19. Basal 1/2Ca 1/4K 1/4Mg	2.20	16.5	.52	19.5	.346	27	.180	82	.004	50	.0026	10.8

(Total bases released vary from 1.78-3.25 m.e. per 100 grm.)

TABLE 4. BASES RELEASED FROM LINDLEY SOIL BY HYDROCHLORIC ACID. (HCl = 1.05 m.e. per 100 gm Exchange capacity 10.5 m.e. per 100 grms.)

Treatment	Calcium m.e.	Calcium %	Magnesium m.e.	Magnesium %	Potassium m.e.	Potassium %	Sodium m.e.	Sodium %	Manganese m.e.	Manganese %	Strontium m.e.	Strontium %
1. Basal	1.18	18.7	.38	33	.024	14	.107	50	.132	41	.0018	14
2. Basal 1/2Ca	1.19	15.1	.32	27	.022	15	.121	73	.060	33	.0017	11
4. Basal 1/4K	1.05	16.7	.39	28	.153	21	.137	49	.085	41	.0018	13
6. Basal 1/4Mg	1.05	16.2	.61	30	.019	10	.119	69	.083	45	.0017	14
8. Basal 1/4Na	0.54	8.9	.18	13	.023	13	.926	81	.036	19	.0011	10
10. Basal 1/2Ca 1/4K	1.12	14.9	.26	22	.121	24	.147	--	.042	31	.0016	11
13. Basal 1/2Ca 1/2Mg	0.93	11.7	.61	24	.028	9	.081	--	.046	44	.0014	12
16. Basal 1/2Ca 1/4Na	0.63	8.0	.16	14	.024	13	1.11	79	.024	19	.0007	5
19. Basal 1/2Ca 1/4K 1/4Mg	1.19	14.7	.68	29	.124	25	.187	59	.037	41	.0016	12

(Total bases released vary from 1.69-2.23 m.e. per 100 grm.)

partially monopolize the exchange; hence much smaller proportions of the divalent ions are brought into solution. Potassium, however, does not show this effect to any extent in Tables 3 and 4. There are several possible reasons for this. It must be remembered that each result represents only a single point on an exchange curve which runs from 100% for each element for complete displacement down to percentages around 1-10 for infinitely small displacements. The latter correspond to measurements of the fraction active based on the use of membrane electrodes. The curves probably fall at different rates, and in some cases they may cross one another. The agreement in the effects of the calcium, magnesium, and potassium treatments may therefore only hold for this particular proportion of hydrochloric acid used. The fact that these soils fix potassium may perhaps also be reflected in a lower degree of replacability of the exchangeable potassium present.

In both tables the calcium and strontium results follow the same trends, the strontium percentages being consistently the lower. This would be expected since strontium is, in general, less easy to displace than calcium.

The element manganese diverges in its behavior when compared with magnesium, calcium, and strontium. The acid treatment liberates some manganese which was not set free by ammonium acetate and several percentages above 100 are to be found in Table 3. The chief factor concerned seems to be the final pH of the soil-acid mixture. The two soils differ markedly in their manganese reserves. The Putnam soil has only a small amount of exchangeable manganese, but acid treatments bring much larger quantities into solution. The Lindley soil contains almost ten times as much exchangeable manganese but only small additional quantities are brought into solution by acid. Thus in Table 4 the depressing effect of the complementary ion sodium upon the manganese can be seen in spite of the pH factor.

The exchange complex and nutrient removal by crops

Before proceeding to a detailed discussion of plant composition some mention should be made of the total nutrients removed in relation to

TABLE 5. TOTAL EXCHANGEABLE BASE CONTENT OF SOIL AND BASES REMOVED BY CROPS. (Expressed in grams per treatment of five pots.)

			Ca		Mg		K		Na		Sr	
Soil	Treatment	Crop	Soil	Crop	Soil	Crop	Soil	Crop	Soil	Crop	Soil	Crop
Putnam	1. Basal	Bluegrass	52.8	.79	9.8	.76	2.75	1.83	3.2	.04	.49	.0043
		Redtop	52.8	1.05	9.8	.69	2.75	2.08	3.2	.10	.49	.0053
		Sweet Clover	52.8	.62	9.8	.23	2.75	.50	3.2	.01	.49	.0031
		Korean lespedeza	52.8	.86	9.8	.15	2.75	.84	3.2	Trace	.49	.0036
Lindley	1. Basal	Bluegrass	42.2	.38	4.7	.30	2.2	1.68	1.6	Trace	.19	.0013
		Redtop	42.2	.65	4.7	.46	2.2	2.06	1.6	.06	.19	.0024
		Sweet Clover	42.2	.57	4.7	.32	2.2	.85	1.6	.03	.19	.0018
		Korean lespedeza	42.2	.51	4.7	.15	2.2	.77	1.6	Trace	.19	.0030

the supplies of exchangeable bases present. It is not necessary to give these figures for all treatments. The basal treatment shows the most extensive cases of denudation of the soil and serves well for general orientation later. In Table 5 the major cations concerned are tabulated as totals in grams for the five pots comprising the basal treatment. For strontium and calcium the proportion removed does not exceed 2%, for magnesium 10%, and for sodium 4%. The potassium lost to the crop in some cases approaches 100% of that found in the exchangeable form in the soils. However, most of the soil treatments lower the total potassium removed by the crop. Nevertheless it will not be possible to assume that the removal of the potassium causes only a small change in the exchangeable potassium status of the soil.

VI. THE CATIONS AS THEY AFFECT ONE ANOTHER IN THE PLANT

Most of the experiments which deal with exchangeable bases in relation to plant composition have been carried out somewhat as follows: For instance, with potassium and calcium as variables, experiments have been set up by using increasing amounts of potassium at a constant calcium level and vice versa. In such experiments with actual soils the total exchangeable base level has rarely been held constant, but Albrecht and co-workers (1) have paid close attention to this in clay-sand cultures. The work of Van Itallie (17) on ryegrass grown on an acid Dutch soil to which various amounts of bases were added, showed very clearly the great advantages of setting up series with constant levels of exchangeable bases. These advantages show themselves very strikingly where elements other than those added are being investigated. Thus in our present study the effect of different cations upon the strontium content of the crops can be properly deduced only from series in which the exchangeable strontium bears a constant relation to the total exchangeable bases.

The treatments we have used can be grouped into six series according to the total exchangeable bases present. Within each series slight variation occurs owing to fixation effects. Thus the magnitude of the total exchangeable bases within each series will follow the order Ca > Mg = Na > K. The significance of this variation, however, is probably small, since we know that potassium which has become nonexchangeable by fixation is to some extent available for plant growth. The grouping of the series according to the total bases added would therefore seem to be satisfactory. We then have the following arrangement.

Zero level	1(Basal), 21 (no treatment, 1940-41 only).
¼ level	4(Basal, ¼K), 6(Basal, ¼Mg), 8(Basal, ¼Na).
½ level	2(Basal, ½Ca), 5(Basal, ½K), 7(Basal, ½Mg), 9(Basal, ½Na).
¾ level	10(Basal, ½Ca, ¼K), 13(Basal, ½Ca, ¼Mg), 16(Basal ½Ca, ¼Na).
1 level	3(Basal, 1Ca), 11(Basal, ½Ca, ¼K), 14(Basal, ½Ca, ½Mg), 17(Basal, ½Ca, ½Na), 19 (Basal, ½Ca, ¼Mg, ¼K).
1¼ level	12(Basal, 1Ca, ¼K), 15(Basal, 1 Ca, ¼Mg), 18(Basal, 1Ca, ¼Na), 21(Basal, ½Ca, ¼K, ¼Mg, ¼Na).

In view of the fact that we are frequently concerned with comparisons between four different crops grown on two different soils the percentage composition figures will be used.

In comparing the 1939-40 results on the Putnam soil with those of 1940-41 on the Lindley it must be remembered that the former comprised relatively heavier applications of bases. The total exchangeable bases of the Putnam amounted to 10.6 m. e.; the bases added at the 1 level were 9.9 m. e., an increase of 93%. The Lindley contained 8.1 m. e. exchangeable bases originally, the bases added at the 1 level amounted to 4.0 m. e. on increase of only 48%. We should therefore expect that the relative effects of the additions would be the more marked in crops grown on the Putnam soil.

The cations will be considered individually in the order Sr, Ca, Mg, Mn, K, Na. Strontium is examined first because under the conditions of the experiment only a very small proportion of it is present either in the soil or in the plant. We can thus follow very clearly the effect of other ions on strontium without concerning ourselves with the effect of strontium on the other cations. It is not known to be an essential element in plant growth and we therefore do not need to consider special mechanisms for its utilization within the plant.

Strontium.—(a) *Variation with total exchangeable base level.* No experiments were set up in which the proportions of exchangeable bases remained the same whilst the total amount varied. However, we can select from the various treatments used a limited number in which calcium and magnesium additions were made. This can be done because exchangeable calcium and magnesium show a great preponderance over sodium and potassium in the original soils. The data are assembled in Table 6.

TABLE 6. STRONTIUM PERCENTAGES IN FOUR CROPS GROWN AT DIFFERENT EXCHANGEABLE BASE LEVELS.

	Putnam 1939-40				Lindley 1940-41			
Treatment	Bluegrass	Redtop	Sweet clover	Korean lespedeza	Bluegrass	Redtop	Sweet clover	Korean lespedeza
Basal	.0040	.0049	.0086	.0063	.0019	.0028	.0052	.0030
Basal 1/4Mg	.0034	.0054	.0083	.0063	.0017	.0033	.0059	.0036
Basal 1/2Ca	.0034	.0058	.0074	.0048	.0023	.0027	.0054	.0035
Basal 1/2Mg	.0037	.0060	.0070	.0059	.0019	.0034	.0051	.0032
Basal 1/2Ca 1/4Mg	.0031	.0051	.0061	.0034	.0023	.0029	.0056	.0036
Basal 1/2Ca 1/2Mg	.0028	.0045	.0053	.0029	.0023	.0028	.0055	.0032
Basal 1Ca	.0029	.0058	.0062	.0040	.0016	.0027	.0052	.0032
Basal 1Ca 1/4Mg	.0029	.0049	.0048	.0032	.0022	.0029	.0049	.0033

On the Lindley soil the strontium remains approximately constant for each crop whereas on the Putnam the bluegrass, sweet clover, and Korean lespedeza show a fairly definite decrease with increasing additions of base. Redtop shows irregular fluctuations. The calcium and magnesium treatments give very similar results throughout.

Considering the fact that the strontium percentages of the crops grown on the Lindley soil are small and that the treatments given to this soil are less in amount than for the Putnam we may conclude that there is some significant decrease in the strontium with increase in calcium or magnesium. We should therefore expect a decrease in the strontium with increase in the total level of exchangeable bases. It would be nothing more than what might be called a dilution effect.

(*b*) *Comparison at the same exchangeable base* levels. Taken as a whole, the evidence from Table 6 would indicate that calcium and magnesium treatments cause only minor changes in the strontium percentages. Certainly there is nothing suggesting large specific differences in the effects of the two ions. In making comparisons of other treatments it will be convenient to take the calcium or magnesium treatment as the standard for each level of exchangeable bases added. The effect of sodium or potassium can be expressed then in terms of the percentage increase or decrease in the strontium. Since at all five levels of additions we have a magnesium, or magnesium plus calcium treatment this will be used in each case as the standard. In Table 7 we have first potassium, then sodium and finally calcium (at two levels only).

TABLE 7. PERCENTAGE INCREASE OR DECREASE IN SR CONTENT COMPARED WITH STANDARD

		Putnam 1939-40				Lindley 1940-41			
Standard treatment	Other treatment	Blue-grass	Red-top	Sweet clover	Korean lespe-deza	Blue-grass	Red-top	Sweet clover	Korean lespe-deza
Basal 1/4Mg									
Basal 1/4Mg	Basal 1/4K	-21	-59	-42	-14	-24	-24	-32	-11
Basal 1/2Ca 1/4Mg	Basal 1/2Ca 1/4K	0	-45	-34	15	-30	-52	- 9	11
Basal 1Ca 1/4Mg	Basal 1Ca 1/4K	-17	-51	-29	---	- 5	-38	-16	18
Basal 1/2Ca 1/2Mg	Basal 1/2Ca 1/4Mg 1/4K	-39	-38	-34	14	-26	-21	-13	61
Basal 1/2Mg	Basal 1/2K	-41	-57	-31	-44	-11	-29	-18	-22
Basal 1/2Ca 1/2Mg	Basal 1/2Ca 1/2K	6	-56	-30	--7	-48	-57	-20	19
	Mean	-18	-51	-33	- 6	-24	-37	-18	20
Basal 1/4Mg	Basal 1/4Na	-26	-39	-14	2	- 6	-15	- 5	-19
Basal 1/2Ca 1/4Mg	Basal 1/2Ca 1/4Na	-19	-33	-25	12	-30	-38	16	36
Basal 1Ca 1/4Mg	Basal 1Ca 1/4Na	-34	-38	- 8	41	-32	-31	24	64
Basal 1/2Mg	Basal 1/2Na	-46	-58	-13	- 8	26	-59	9	15
Basal 1/2Ca 1/2Mg	Basal 1/2Ca 1/2Na	-46	-58	- 4	10	-52	-46	11	59
	Mean	-34	-45	-13	-11	19	-38	11	31
Basal 1/2Mg	Basal 1/2Ca	- 8	- 4	6	-19	21	-21	- 5	9
Basal 1/2Ca 1/2Mg	Basal 1Ca	3	29	17	38	-30	- 3	- 5	0
	Mean	- 2	12	12	10	- 5	-12	- 5	5

Very considerable variations in the figures for each crop are to be expected since these percentages involve small differences in Sr content and each is affected by the errors of two determinations. Taking the mean values for each crop, several features are nevertheless clearly apparent in the table.

Bluegrass.—Potassium treatments are not consistently different from sodium treatments in their depressing effects upon strontium, which amount to 18-34%.

Redtop.—Potassium treatments are not significantly different from sodium treatments in their depressing effects upon strontium which amount to 37-51%.

Sweet clover.—Potassium treatments appear to cause a greater depression than sodium treatments. On the Lindley soil the sodium treatment caused a small rise in the Sr content as compared with magnesium treatments as standard.

Korean lespedeza.—The sodium treatments caused a significant rise in the Sr content. On the Lindley soil the potassium treatment gives a smaller rise than the sodium treatment whilst on the Putnam a small depression is caused by the potassium treatments.

In comparing the effects of K and Na treatments on the four crops we see that redtop clearly shows the greatest depressions by Na and K on both soils, bluegrass and sweet clover show smaller effects, whilst with lespedeza there is a distinct tendency for a rise in Sr content over that of the Mg treatment to occur.

(*c*) *Comparison of early and late cuttings.* A tabulation of the data for bluegrass (1939-40), redtop (1939-40) and Korean lespedeza (1940-41) shows no definite trend towards an increase or decrease in the Sr content with the advancing season. The features discussed in paragraph (*b*) above are shown both by the early and the late cuttings (Table 8).

TABLE 8. STRONTIUM PERCENTAGES OF EARLY AND LATE CROPS

	1939-40				1940-41	
	Bluegrass		Redtop		Korean lespedeza	
Treatment	Early	Late	Early	Late	Early	Late
1. Basal	.0043	.0036	.0053	.0045	.0033	.0029
4. Basal 1/4K	.0037	.0017	.0025	.0020	.0039	.0029
6. Basal 1/4Mg	.0032	.0036	.0051	.0057	.0034	.0036
8. Basal 1/4Na	.0025	.0025	.0031	.0035	.0039	.0026
2. Basal 1/2Ca	.0038	.0029	.0056	.0059	.0034	.0035
5. Basal 1/2K	.0023	.0020	.0020	.0030	.0038	.0039
7. Basal 1/2Mg	.0038	.0035	.0056	.0063	.0039	.0029
9. Basal 1/2Na	.0017	.0022	.0023	.0027	.0034	.0038
10. Basal 1/2Ca 1/4K	.0040	.0022	.0025	.0029	.0036	.0042
13. Basal 1/2Ca 1/4Mg	.0034	.0028	.0056	.0048	.0026	.0040
16. Basal 1/2Ca 1/4Na	.0023	.0026	.0035	.0033	.0044	.0050
3. Basal 1Ca	.0027	.0031	.0052	.0046	.0033	.0032
11. Basal 1/2Ca 1/2K	.0044	.0015	.0020	.0019	.0030	.0038
14. Basal 1/2Ca 1/2Mg	.0031	.0025	.0055	.0036	.0026	.0034
17. Basal 1/2Ca 1/2Na	.0016	.0014	.0018	.0019	.0045	.0052
19. Basal 1/2Ca 1/4K 1/4Mg	.0018	.0015	.0028	.0028	.0053	.0052
12. Basal 1Ca 1/4K	.0029	.0018	.0031	.0018	.0025	.0043
15. Basal 1Ca 1/4Mg	.0030	.0028	.0057	.0040	.0040	.0031
18. Basal 1Ca 1/4Na	.0017	.0020	.0022	.0033	.0052	.0054
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.0018	.0022	.0024	.0025	.0051	.0050

(*d*) *Discussion.* The strontium determinations here presented afford some guidance in regard to the relative importance of different possible mechanisms by which this element has passed from the soil into the plants. Since we are concerned firstly with the release of exchangeable strontium from the soil, we shall take up the analytical results in the light of the complementary ion principle. Tables 3 and 4 on the release of bases by hydrochloric acid have already amply demonstrated this principle. Much less strontium was liberated from the sodium treated than from the potassium treated soils when each reacted with a limited quantity of acid. According to this mechanism of replacement by hydrogen, the soil solution from the Na-treated soil should contain considerably less strontium than that from the K-treated soil. Plants which take their nutrients from such solutions might be expected to show strontium contents lower for Na treatments than for K treatments. Table 7 does not bear out this conclusion. For sweet clover and lespedeza the effect seems to be the other way, and only in the case of bluegrass grown on the Putnam soil is the result in accordance with these suppositions. The Korean lespedeza is noteworthy for the fact that neither potassium nor sodium treatment depresses the strontium consistently; indeed on the Lindley soil there is an increase.

There is, however, another approach which will be considered. This is to observe whether the variations in strontium content within the plant are related in any way to variations in other constituents, particularly Ca or Mg. That the four plants under consideration differ so widely in respect to strontium is a favorable circumstance in this inquiry.

It would seem therefore that other mechanisms enter into the overall picture. This is not surprising since the complementary ion principle only applies to the primary release from the exchange complex into the soil solution. If ions should pass directly from the colloidal particles of the soil to the plant roots by contact exchange then we should not expect to find marked complementary ion effects although they might still be detected in cases where the plant root, treated as a colloidal system, showed different energies of absorption for various ions than the soil colloids.

The complementary ion effect, as noted earlier, varies greatly in its magnitude depending upon the percentage release. When this is very small the proportion of strontium released should be a measure of the strontium ion activity, a quantity which is likely to show little variation with the nature of the accompanying ions. Turning back to Table 5 we see that the total Sr removal by the crops in the basal treatment does not exceed 1.6% of that provided in the soil in the exchangeable form. We might therefore suppose that the effect of varying the proportions of exchangeable bases should be small. The difficulty is that the four crops behave differently, which was clearly brought out in paragraph (*b*).

TABLE 9. STRONTIUM DATA ON TOTAL CROPS. (a) PERCENTAGE SR.

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley	Korean Lespedeza Putnam	Korean Lespedeza Lindley
21. No Treatment	-----	.0018	-----	.0035	-----	-----		.0050
1. Basal	.0040	.0019	.0049	.0028	.0086	.0052	.0063	.0030
4. Basal 1/4K	.0027	.0013	.0022	.0025	.0048	.0040	.0054	.0032
6. Basal 1/4Mg	.0034	.0017	.0054	.0033	.0083	.0059	.0063	.0036
8. Basal 1/4Na	.0025	.0016	.0033	.0028	.0071	.0056	.0064	.0029
2. Basal 1/2Ca	.0034	.0023	.0058	.0027	.0074	.0054	.0048	.0035
5. Basal 1/2K	.0022	.0013	.0026	.0024	.0048	.0047	.0033	.0039
7. Basal 1/2Mg	.0037	.0020	.0060	.0034	.0070	.0057	.0059	.0032
9. Basal 1/2Na	.0020	.0010	.0025	.0014	.0061	.0062	.0054	.0037
10. Basal 1/2Ca 1/4K	.0031	.0016	.0028	.0018	.0039	.0051	.0039	.0040
13. Basal 1/2Ca 1/4Mg	.0031	.0023	.0051	.0029	.0061	.0056	.0034	.0036
16. Basal 1/2Ca 1/4Na	.0025	.0016	.0034	.0018	.0046	.0065	.0038	.0049
3. Basal 1Ca	.0029	.0016	.0058	.0027	.0062	.0052	.0040	.0032
11. Basal 1/2Ca 1/2K	.0030	.0012	.0020	.0012	.0037	.0044	.0027	.0038
14. Basal 1/2Ca 1/2Mg	.0028	.0023	.0045	.0028	.0053	.0055	.0029	.0032
17. Basal 1/2Ca 1/2Na	.0015	.0011	.0019	.0015	.0051	.0061	.0032	.0051
19. Basal 1/2Ca 1/4K 1/4Mg	.0017	.0017	.0028	.0022	.0035	.0048	.0033	.0052
12. Basal 1Ca 1/4K	.0024	.0021	.0023	.0018	.0034	.0041	-----	.0039
15. Basal 1Ca 1/4Mg	.0029	.0022	.0047	.0029	.0048	.0049	.0032	.0033
18. Basal 1Ca 1/4Na	.0019	.0015	.0029	.0020	.0044	.0061	.0045	.0054
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.0020	.0017	.0025	.0024	.0039	.0055	.0038	.0050

TABLE 9. STRONTIUM DATA ON TOTAL CROPS. (b) TOTAL YIELDS IN GRAMS.

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley	Korean lespedeza Putnam	Korean lespedeza Lindley
21. No treatment	-----	.0003	-----	.0011	-----	-----	-----	.0015
1. Basal	.0043	.0013	.0053	.0024	.0031	.0018	.0036	.0014
4. Basal 1/4K	.0026	.0010	.0024	.0023	.0032	.0018	.0034	.0019
6. Basal 1/4Mg	.0034	.0013	.0054	.0028	.0046	.0025	.0042	.0022
8. Basal 1/4Na	.0024	.0012	.0031	.0025	.0049	.0020	.0040	.0015
2. Basal 1/2Ca	.0027	.0016	.0055	.0023	.0050	.0022	.0031	.0021
5. Basal 1/2K	.0018	.0010	.0028	.0022	.0043	.0023	.0015	.0027
7. Basal 1/2Mg	.0033	.0016	.0057	.0029	.0049	.0022	.0042	.0023
9. Basal 1/2Na	.0015	.0007	.0023	.0012	.0044	.0023	.0025	.0022
10. Basal 1/2Ca 1/4K	.0025	.0008	.0031	.0018	.0038	.0026	.0029	.0029
13. Basal 1/2Ca 1/4Mg	.0030	.0017	.0048	.0026	.0046	.0024	.0025	.0024
16. Basal 1/2Ca 1/4Na	.0020	.0013	.0031	.0017	.0044	.0031	.0025	.0033
3. Basal 1Ca	.0026	.0013	.0061	.0023	.0051	.0024	.0026	.0023
11. Basal 1/2Ca 1/2K	.0023	.0010	.0021	.0011	.0039	.0024	.0018	.0029
14. Basal 1/2Ca 1/2Mg	.0028	.0017	.0043	.0025	.0046	.0024	.0021	.0022
17. Basal 1/2Ca 1/2Na	.0010	.0008	.0016	.0014	.0064	.0026	.0019	.0032
19. Basal 1/2Ca 1/4K 1/4Mg	.0013	.0014	.0035	.0021	.0038	.0028	.0020	.0035
12. Basal 1Ca 1/4K	.0022	.0017	.0027	.0017	.0042	.0022	-----	.0028
15. Basal 1Ca 1/4Mg	.0030	.0015	.0045	.0026	.0046	.0026	.0023	.0021
18. Basal 1Ca 1/4Na	.0014	.0011	.0029	.0018	.0055	.0030	.0028	.0037
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.0020	.0013	.0028	.0023	.0057	.0031	.0011	.0035

As regards variations in the proportions and total amounts of the exchangeable bases of the soil, the suggestion has been made by Van Itallie (17) that these can be directly related to the plant content by means of a series of quotients set up as follows: The plant composition with respect to a single cation is assumed to be proportional to the amount exchangeable in the soil divided by the sum of the products of the quantities of the other exchangeable ions multiplied each by a specific factor. For instance, for strontium we should have:

$$\mathrm{Sr}_{\text{plant}} = \frac{\mathrm{Sr}}{a\mathrm{Ca} + b\mathrm{Mg} + c\mathrm{K} + d\mathrm{Na} + e\mathrm{Sr}}$$

and since Sr is very small in comparison with the others, eSr will also be small and can be neglected. The question is whether a consistent set of factors a, b, c, d, etc., can be found for each crop. This relationship is precisely similar to that used by Bray (4) in predicting the amounts of cations displaced from the soil by electrolytes which he used on the complementary ion principle. Van Itallie's expression thus stands or falls according as to whether the complementary ion relationships are dominant or not. In his own experiments with rye grass with one exeception this appeared to be the case. In the present experiments only the 1939-40 bluegrass series appear to follow all the trends predicted by the complementary ion principle alone.

We have seen in comparing the effects of potassium and sodium upon strontium content that only in one case out of eight did sodium cause greater depression than potassium. Van Itallie did not estimate Sr but his calcium figures indicate that potassium caused a greater depression than sodium. He ascribes this to the fact that in the plant the sum of the cations (expressed as milliequivalents per 100 gm. dry matter) is relatively constant. Hence one element replaces another almost equivalent for equivalent. The element which varies most widely, namely potassium, would therefore by its increase cause an automatic depression in the others. This, however, is equivalent to saying that the complementary ion principle is not the only one affecting nutrient content. Factors operating inside the plant must also be considered. Van Itallie's assertion that the total cation content is approximately constant, will be examined later.

Calcium. (*a*) *Variation with total exchangeable base level.* The only comparisons in which this matter can be tested are the basal treatment and the two levels of magnesium. This is somewhat unsatisfactory since specific effects of magnesium upon calcium might also enter into the picture. Tabulation of the results shows small and irregular variations (Table 10).

(*b*) *Comparisons at the same exchangeable base levels.* The data will be tabulated in the same way as was done for strontium, the magnesium or magnesium plus calcium treatment being used as the standard at each level (Table 11). We thus have a comparison of sodium and potassium treatments for the four crops and the two soils.

Bluegrass. Potassium and sodium treatments depress the calcium to about the same extent, from 14 to 28%.

Redtop. On the Putnam soil potassium depressed the calcium rather more than did the sodium. On the Lindley there was no significant difference.

TABLE 10. EFFECTS OF CALCIUM AND MAGNESIUM ADDITIONS ON CALCIUM CONTENT OF CROPS

	CROP AND SOIL							
	Bluegrass		Redtop		Sweet clover		Korean lespedeza	
Treatment	Putnam	Lindley	Putnam	Lindley	Putnam	Lindley	Putnam	Lindley
1. Basal	.71	.56	.97	.77	1.73	1.61	1.49	1.11
2. Basal 1/2Ca	.92	.58	1.25	.87	2.94	1.88	1.70	1.24
3. Basal 1Ca	1.11	.62	1.43	.90	3.19	1.95	1.81	1.32
6. Basal 1/4Mg	.66	.47	.94	.80	2.17	1.45	1.45	1.18
7. Basal 1/2Mg	.64	.43	.86	.82	1.85	1.82	1.44	1.07
13. Basal 1/2Ca 1/4Mg	.82	.59	1.14	.96	2.50	1.96	1.40	1.26
14. Basal 1/2Ca 1/2Mg	.79	.53	1.05	1.04	2.31	2.05	1.68	1.31
15. Basal 1Ca 1/4Mg	.87	.65	1.22	.86	2.60	2.15	1.33	1.47

TABLE 11. PERCENTAGE INCREASE OR DECREASE IN CA CONTENT COMPARED WITH STANDARD

		Putnam 1939-40				Lindley 1940-41			
Standard treatment	Other treatment	Blue-grass	Red-top	Sweet clover	Korean lespe-deza	Blue-grass	Red-top	Sweet clover	Korean lespe-deza
Basal 1/4Mg	Basal 1/4K	-32	-41	-38	-12	- 2	-16	- 8	- 4
Basal 1/2Ca 1/4Mg	Basal 1/2Ca 1/4K	-26	-37	-31	- 7	-19	-25	-14	2
Basal 1Ca 1/4Mg	Basal 1Ca 1/4K	-13	- 6	-33	---	-29	0	-27	- 8
Basal 1/2Ca 1/2Mg	Basal 1/2Ca 1/4Mg 1/4K	-32	-14	14	-20	-13	-27	-31	31
Basal 1/2Mg	Basal 1/2K	-36	-37	-34	-27	4	-26	-22	0
Basal 1/2Ca 1/2Mg	Basal 1/2Ca 1/2K	-29	- 5	-32	-16	-23	-27	-26	- 8
	Mean	-28	-23	-25	-18	-14	-20	-21	2
Basal 1/4Mg	Basal 1/4Na	-26	-28	-16	0	- 6	- 5	10	- 1
Basal 1/2Ca 1/4Mg	Basal 1/2Ca 1/4Na	-12	-25	-21	4	-22	-17	-19	8
Basal 1Ca 1/4Mg	Basal 1Ca 1/4Na	-11	0	- 9	21	-32	- 6	-16	27
Basal 1/2Mg	Basal 1/2Na	-41	-22	-16	-17	- 9	-32	- 4	13
Basal 1/2Ca 1/2Mg	Basal 1/2Ca 1/2Na	-30	-11	- 4	2	-15	-38	-13	30
	Mean	-24	-14	-13	2	-17	-20	- 8	15

Sweet clover. On both soils potassium treatments caused greater depressions of the calcium than did sodium treatments.

Korean lespedeza. On the Putnam soil potassium caused a depression of the calcium whilst sodium gave a slight rise. On the Lindley potassium gave a small rise and sodium a clearly significant rise.

On comparing the four crops we find the depressions somewhat similar in magnitude for bluegrass, redtop and sweet clover. The depression for this last crop with sodium treatment on the Lindley soil was significantly lower than the others. Korean lespedeza is very significantly different from the others, potassium on the Putnam soil giving a depression, sodium on the Putnam an insignificant rise, potassium on the Lindley an insignificant rise and sodium on the Lindley a clear cut rise in calcium.

As regards a comparison of the two soils, with one exception the Lindley gives smaller depressions than the Putnam. Where increases occurred, these were greater for the Lindley.

A comparison of Table 11 with Table 7 shows that strontium and calcium are affected in a similar way by potassium and sodium throughout the four crops and the two soils under investigation. This will be gone into more fully when the data for magnesium have been examined.

(c) *Comparison of early and late cuttings* (Table 12). In rather striking contrast to the case of strontium, the calcium percentages are significantly different for the early and late cuttings. In nineteen treatments out of twenty bluegrass shows a higher calcium percentage in the late cuttings than in the early cuttings. This is true also for redtop in eighteen cases out of twenty. The lespedeza is opposite in this regard. In all twenty treatments the late cuttings are lower in calcium than the early cuttings.

TABLE 12. CALCIUM PERCENTAGES OF EARLY AND LATE CROPS,

	1939-40				1940-41	
	Bluegrass		Redtop		Korean lespedeza	
Treatment	Early	Late	Early	Late	Early	Late
11. Basal	.70	.72	.94	1.02	1.28	1.04
4. Basal 1/4K	.46	.44	.55	.55	1.33	1.06
6. Basal 1/4Mg	.60	.71	.85	1.03	1.32	1.13
8. Basal 1/4Na	.44	.54	.63	.73	1.33	1.11
2. Basal 1/2Ca	.89	.94	1.16	1.32	1.44	1.16
5. Basal 1/2K	.40	.41	.56	.53	1.34	.98
7. Basal 1/2Mg	.58	.69	.79	.92	1.46	1.13
9. Basal 1/2Na	.32	.43	.73	.62	1.38	1.16
10. Basal 1/2Ca 1/4K	.60	.61	.64	.76	1.50	1.21
13. Basal 1/2Ca 1/4Mg	.80	.83	1.10	1.18	1.39	1.22
16. Basal 1/2Ca 1/4Na	.60	.84	.84	.88	1.93	1.21
3. Basal 1Ca	1.04	1.18	1.28	1.55	1.55	1.26
11. Basal 1/2Ca 1/2K	.50	.61	.73	1.15	1.35	1.16
14. Basal 1/2Ca 1/2Mg	.75	.83	.93	1.15	1.36	1.29
17. Basal 1/2Ca 1/2Na	.48	.62	.64	1.08	1.95	1.65
19. Basal 1/2Ca 1/4K 1/4Mg	.51	.57	.78	.97	1.79	1.69
12. Basal 1Ca 1/4K	.70	.81	.86	1.31	1.52	1.29
15. Basal 1Ca 1/4Mg	.84	.89	1.15	1.27	1.95	1.31
18. Basal 1Ca 1/4Na	.67	.89	.92	1.39	2.08	1.81
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.40	.57	.56	.98	1.80	1.59

(d) *Effects of calcium and magnesium additions.* In comparing the four crops in their direct response to calcium we may utilize treatments 1, 2, and 3, bearing in mind that in such comparisons we are concerned with changing proportions of exchangeable cations as well as increasing amounts of calcium. The data are assembled in Table 10. The Lindley soil gives lower calcium percentages than the Putnam and since the additions were considerably smaller the increases are also less. The variability in calcium content is greatest

TABLE 13. CALCIUM DATA ON TOTAL CROPS; (a) PERCENTAGE CA.

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley	Korean lespedeza Putnam	Korean lespedeza Lindley
21. No treatment	---	.38	---	.60	---	---	---	1.44
1. Basal	.71	.56	.97	.77	1.73	1.61	1.49	1.11
4. Basal 1/4K	.45	.46	.55	.67	1.35	1.34	1.27	1.13
6. Basal 1/4Mg	.66	.47	.94	.80	2.17	1.45	1.45	1.18
8. Basal 1/4Na	.49	.44	.68	.76	1.82	1.60	1.45	1.17
2. Basal 1/2Ca	.92	.58	1.25	.87	2.94	1.88	1.70	1.24
5. Basal 1/2 K	.41	.45	.54	.61	1.23	1.42	.90	1.07
7. Basal 1/2Mg	.64	.43	.86	.82	1.85	1.82	1.44	1.07
9. Basal 1/2Na	.38	.39	.67	.56	1.59	1.74	1.19	1.21
10. Basal 1/2Ca 1/4K	.61	.48	.72	.72	1.72	1.69	1.30	1.28
13. Basal 1/2Ca 1/4Mg	.82	.59	1.14	.96	1.50	1.96	1.40	1.26
16. Basal 1/2Ca 1/4Na	.72	.46	.86	.80	1.98	1.58	1.46	1.36
3. Basal 1Ca	1.11	.62	1.43	.90	3.19	1.95	1.81	1.32
11. Basal 1/2Ca 1/2K	.56	.41	1.00	.76	1.58	1.52	1.41	1.21
14. Basal 1/2Ca 1/2Mg	.79	.53	1.05	1.04	2.31	2.05	1.68	1.31
17. Basal 1/2 ca								
17. Basal 1/2Ca 1/2Na	.55	.45	.93	.64	2.23	1.78	1.72	1.70
19. Basal 1/2Ca 1/4K 1/4Mg	.54	.46	.90	.76	2.63	1.42	1.34	1.71
12. Basal 1Ca 1/4K	.76	.46	1.14	.86	1.74	1.56	---	1.35
15. Basal 1Ca 1/4Mg	.87	.65	1.22	.86	2.60	2.15	1.33	1.47
18. Basal 1Ca 1/4Na	.78	.43	1.22	.81	2.36	1.81	1.61	1.87
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.49	.37	.82	.49	1.39	1.46	1.39	1.64

TABLE 13. CALCIUM DATA ON TOTAL CROPS. (b) TOTAL YIELDS IN GRAMS OF CA.

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley	Korean lespedeza Putnam	Korean lespedeza Lindley
21. No treatment	---	.052	---	.19	---	---	---	.44
1. Basal	.79	.38	1.05	.65	.62	.57	.86	.51
4. Basal 1/4K	.47	.35	.60	.61	.88	.61	.79	.69
6. Basal 1/4Mg	.66	.37	.94	.68	1.19	.60	.96	.73
8. Basal 1/4Na	.47	.33	.63	.68	1.25	.58	.91	.61
2. Basal 1/2Ca	.77	.40	1.18	.74	2.00	.75	1.11	.76
5. Basal 1/2K	.34	.36	.59	.57	1.11	.71	.41	.74
7. Basal 1/2Mg	.59	.36	.82	.71	1.29	.71	1.03	.77
9. Basal 1/2Na	.29	.27	.63	.50	1.16	.64	.54	.72
10. Basal 1/2Ca 1/4K	.54	.39	.79	.71	1.66	.85	.97	.91
13. Basal 1/2Ca 1/4Mg	.80	.43	1.07	.85	1.89	.84	1.04	.83
16. Basal 1/2Ca 1/4Na	.60	.36	.78	.74	1.91	.76	.95	.92
3. Basal 1Ca	.98	.49	1.49	.77	2.65	.88	1.17	.94
11. Basal 1/2Ca 1/2K	.54	.35	1.06	.71	1.68	.81	.94	.93
14. Basal 1/2Ca 1/2Mg	.82	.40	1.01	.92	2.01	.91	1.20	.89
17. Basal 1/2Ca 1/2Na	.37	.31	.80	.59	2.80	.76	1.01	1.05
19. Basal 1/2Ca 1/4K 1/4Mg	.44	.38	1.13	.71	2.84	.83	.80	1.14
12. Basal 1Ca 1/4K	.78	.38	1.35	.81	2.13	.83		.99
15. Basal 1Ca 1/4Mg	.91	.46	1.16	.76	2.42	1.12	.96	.91
18. Basal 1Ca 1/4Na	.62	.32	1.22	.73	2.93	.89	.99	1.28
20. Basal 1/2Ca 1/4K 1/4Mg. 1/4Na	.49	.29	.94	.46	2.03	.81	.41	1.14

for sweet clover, less for bluegrass and redtop and relatively small for Korean lespedeza. The calcium percentages follow the order sweet clover > Korean lespedeza > redtop > bluegrass.

The effect of magnesium additions upon the calcium content can also be seen from Table 10. As would be expected, the Putnam soil shows the most distinct effects. The bluegrass and redtop show a small lowering of the calcium with magnesium additions, the sweet clover and lespedeza are somewhat irregular in their behavior.

Magnesium. (*a*) *Variation with total exchangeable base level.* No exact test of this can be made in the absence of other variables, but the calcium treatments afford some guidance (Table 14). In six cases out of eight the magnesium falls slightly in passing from the basal treatment to the Basal, 1Ca treatment. Strong specific effects of Ca upon Mg do not appear to be present.

TABLE 14. EFFECTS OF MAGNESIUM AND CALCIUM UPON THE MAGNESIUM CONTENT OF THE CROPS

Treatment	Bluegrass		Redtop		Sweet clover		Korean lespedeza	
	Putnam	Lindley	Putnam	Lindley	Putnam	Lindley	Putnam	Lindley
1. Basal	.70	.44	.64	.55	.65	.91	.26	.32
6. Basal 1/4Mg	.65	.54	.78	.66	1.38	1.02	.33	.34
7. Basal 1/2Mg	.71	.71	.89	.80	2.13	.96	.34	.38
2. Basal 1/2Ca	.41	.46	.65	.55	.58	.79	.29	.28
3. Basal 1Ca	.44	.48	.56	.49	.58	.80	.32	.24
13. Basal 1/2Ca 1/4Mg	.75	.72	.61	.60	.61	.82	.33	.28
14. Basal 1/2Ca 1/2Mg	.78	.80	.71	.57	.74	.86	.34	.37
15. Basal 1Ca 1/4Mg	.63	.70	.67	.58	.62	.77	.44	.34

(*b*) *Comparisons at the same exchangeable base levels.* In discussing magnesium in the same fashion as was done for strontium and calcium, it will be necessary to take a different standard from the magnesium treatment which was previously employed. We shall utilize calcium treatments and also potassium treatments. In order to get a comparison with strontium these same standards have been used and the relevant strontium figures are inserted in the second part of Table 15.

Bluegrass. Potassium treatments cause a significant depression in the magnesium but the sodium gives an insignificant rise.

Redtop. Potassium treatments depress the magnesium and sodium treatments give a smaller depression.

Sweet clover. Potassium treatments depress the magnesium considerably more than do the sodium treatments.

Korean lespedeza. Potassium on the Putnam depresses the magnesium considerably whilst sodium gives an insignificant depression.

TABLE 15.

(a) PERCENTAGE ENCREASE OR DECREASE IN MG CONTENT COMPARED WITH STANDARD

Standard treatment	Other treatment	Putnam 1939-40 Blue-grass	Red-top	Sweet clover	Korean lespe-deza	Lindley 1940-41 Blue-grass	Red-top	Sweet clover	Korean lespe-deza
Basal 1/2Ca	Basal 1/2K	-29	-57	-40	-41	-39	-25	-24	-18
Basal 1Ca	Basal 1/2Ca 1/2K	-34	-52	-47	-44	-35	-43	-27	-13
	Mean	-32	-54	-44	-42	-37	-34	-25	-16
Basal 1/2Ca	Basal 1/2Na	17	-43	-21	14	2	-29	-16	- 4
Basal 1Ca	Basal 1/2Ca 1/2Na	-11	-32	-22	-19	6	2	-15	70
	Mean	3	-38	-22	- 3	4	-13	-16	33
Basal 1/2K	Basal 1/4Na	23	53	19	28	85	83	45	30
Basal 1/2Ca 1/4K	Basal 1/2Ca 1/4Na	44	31	23	24	96	75	36	37
Basal 1Ca 1/4K	Basal 1Ca 1/4Na	10	77	41	----	85	53	17	100
	Mean	22	54	28	26	89	70	33	56

(b) PERCENTAGE INCREASE OR DECREASE IN SR CONTENT COMPARED WITH STANDARD (FOR COMPARISON WITH (a) ABOVE)

Standard treatment	Other treatment	Putnam 1939-40 Blue-grass	Red-top	Sweet clover	Korean lespe-deza	Lindley 1940-41 Blue-grass	Red-top	Sweet clover	Korean lespe-deza
Basal 1/2Ca	Basal 1/2K	-35	-55	-35	-31	-26	-11	-13	11
Basal 1Ca	Basal 1/2Ca 1/2K	3	-65	-40	-32	-25	-56	-15	19
	Mean	-16	-60	-37	-32	-25	-33	-14	15
Basal 1/2Ca	Basal 1/2Na	-41	-57	-18	12	4	-48	15	6
Basal 1Ca	Basal 1/2Ca 1/2Na	-48	-67	-18	-20	-31	-44	17	59
	Mean	-45	-62	-18	- 4	-14	-46	16	33
Basal 1/4K	Basal 1/4Na	- 7	50	48	19	23	12	40	- 9
Basal 1/2Ca 1/4K	Basal 1/2Ca 1/4Na	-19	21	18	- 3	0	29	27	22
Basal 1Ca 1/4K	Basal 1Ca 1/4Na	-21	26	29	---	-29	11	49	39
	Mean	-16	32	32	8	- 2	17	37	17

On the Lindley, potassium depresses the magnesium but sodium enhances it.

When the potassium is taken as standard the corresponding sodium treatments give consistently higher magnesium contents for all four crops on both soils.

Using the calcium treatment as standard it is seen that the depressions in magnesium produced by the potassium treatments are not so widely different for the four crops. In the sodium treatments we find that redtop and sweet clover show depressions but bluegrass and lespedeza give small changes or increases.

(c) *Comparison of early and late cuttings* (Table 16). In fourteen out of twenty cases for bluegrass and sixteen out of twenty for redtop the early cuttings are higher in magnesium than the late cuttings. Lespedeza is quite uniform in this regard. In all twenty cases the magnesium content is higher for the early than for the late cuttings.

(d) *Effects of magnesium and calcium additions.* Table 14 seems to display some irregularities not readily accounted for. The lespedeza is consistent in showing only small increases in Mg content with magnesium additions to the soil. Redtop shows somewhat greater increases and bluegrass and sweet clover are erratic. The percentage of magnesium in the lespedeza is markedly below that in the other

TABLE 16. MAGNESIUM PERCENTAGES OF EARLY AND LATE CROPS,

	1929-40				1940-41	
	Bluegrass		Redtop		Korean lespedeza	
Treatment	Early	Late	Early	Late	Early	Late
1. Basal	.84	.55	.64	.63	.41	.28
4. Basal 1/4K	.41	.28	.39	.26	.34	.19
6. Basal 1/4Mg	.73	.57	.81	.77	.41	.31
8. Basal 1/4Na	.46	.40	.51	.48	.45	.25
2. Basal 1/2Ca	.41	.41	.63	.66	.38	.24
5. Basal 1/2K	.31	.27	.36	.21	.32	.20
7. Basal 1/2Mg	.76	.65	.89	.89	.52	.33
9. Basal 1/2Na	.48	.48	.39	.37	.36	.24
10. Basal 1/2Ca 1/4K	.30	.38	.40	.24	.32	.21
13. Basal 1/2Ca 1/4Mg	.70	.79	.62	.60	.35	.25
16. Basal 1/2Ca 1/4Na	.55	.42	.32	.40	.48	.29
3. Basal 1Ca	.40	.48	.61	.54	.37	.20
11. Basal 1/2Ca 1/2K	.32	.25	.33	.23	.30	.18
14. Basal 1/2Ca 1/2Mg	.71	.85	.65	.75	.51	.32
17. Basal 1/2Ca 1/2Na	.34	.44	.29	.43	.43	.41
19. Basal 1/2Ca 1/4K 1/4Mg	.38	.25	.50	.30	.49	.44
12. Basal 1Ca 1/4K	.62	.21	.34	.22	.30	.21
15. Basal 1Ca 1/4Mg	.66	.59	.69	.65	.61	.25
18. Basal 1Ca 1/4Na	.39	.52	.35	.51	.55	.40
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.44	.34	.50	.31	.46	.36

three crops, the order being sweet clover>redtop>bluegrass>Korean lespedeza.

The effect of calcium additions is small in most cases and both increases and decreases are present, the latter predominating.

Discussion of strontium, calcium, and magnesium

(*a*) *Mutual effects.* The evidence of Tables 6, 10, and 14 would seem to preclude large specific effects. The dilution caused by additions of calcium or magnesium which might be expected to lower the strontium content is not always discernable and on the average it is less than might be expected from the quantities involved. The same is true of the calcium percentages when magnesium is added and of the magnesium when calcium is added. These facts suggest a considerable degree of independence in the uptake of the three divalent cations.

(*b*) *Effects of monovalent ions.* By comparing Tables 7 and 11 we can get some idea of the relative effects of potassium and sodium additions to the soil upon the strontium and calcium contents of the plant. It is seen that there is a very close similarity. In general sodium produces a smaller depression of the divalent ion than does potassium, or in case there is a rise, a larger rise. Redtop shows the smallest difference in the effects of K and Na, bluegrass is somewhat similar, sweet clover gives large differences whilst lespedeza shows definite increases with the sodium treatment. It is interesting to see

TABLE 17. MAGNESIUM DATA ON TOTAL CROPS; (a) PERCENTAGE MG;

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley	Korean lespedeza Putnam	Korean lespedeza Lindley
21. No treatment		.27		.35				.45
1. Basal	.70	.44	.64	.55	.65	.91	.26	.32
4. Basal 1/4K	.35	.27	.32	.29	.42	.56	.18	.23
6. Basal 1/4Mg	.65	.54	.78	.66	1.38	1.02	.33	.34
8. Basal 1/4Na	.43	.50	.49	.53	.50	.81	.23	.30
2. Basal 1/2Ca	.41	.46	.65	.55	.58	.79	.29	.28
5. Basal 1/2K	.29	.28	.28	.41	.35	.60	.17	.23
7. Basal 1/2Mg	.71	.71	.89	.80	2.13	.96	.34	.38
9. Basal 1/2Na	.48	.47	.37	.39	.46	.66	.33	.27
10. Basal 1/2Ca 1/4K	.34	.30	.29	.32	.35	.56	.21	.24
13. Basal 1/2Ca 1/4Mg	.75	.72	.61	.60	.61	.82	.33	.28
16. Basal 1/2Ca 1/4Na	.49	.59	.38	.56	.43	.76	.26	.33
3. Basal 1Ca	.44	.48	.56	.49	.58	.80	.32	.24
11. Basal 1/2Ca 1/2K	.29	.31	.27	.28	.31	.58	.18	.21
14. Basal 1/2Ca 1/2Mg	.78	.80	.71	.57	.74	.86	.34	.37
17. Basal 1/2Ca 1/2Na	.39	.51	.38	.50	.45	.68	.26	.41
19. Basal 1/2Ca 1/4K 1/4Mg	.32	.38	.37	.42	.40	.50	.21	.45
12. Basal 1Ca 1/4K	.42	.27	.26	.30	.32	.54	---	.23
15. Basal 1Ca 1/4Mg	.63	.70	.67	.58	.62	.77	.44	.34
18. Basal 1Ca 1/4Na	.46	.50	.46	.46	.45	.63	.27	.46
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.39	.32	.38	.36	.33	.50	.22	.38

TABLE 17. MAGNESIUM DATA ON TOTAL CROPS, (b) TOTAL YIELDS IN GRAMS OF MG.

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley	Korean lespedeza Putnam	Korean lespedeza Lindley
21. No treatment		.04		.11				.14
1. Basal	.76	.30	.69	.46	.23	.32	.15	.15
4. Basal 1/4K	.35	.21	.35	.26	.28	.26	.11	.14
6. Basal 1/4Mg	.64	.36	.78	.56	.76	.43	.22	.21
8. Basal 1/4Na	.40	.38	.45	.47	.34	.29	.14	.16
2. Basal 1/2Ca	.34	.31	.61	.47	.40	.32	.19	.17
5. Basal 1/2K	.24	.22	.30	.38	.32	.30	.08	.16
7. Basal 1/2Mg	.64	.59	.85	.69	1.49	.37	.24	.27
9. Basal 1/2Na	.36	.33	.35	.35	.33	.24	.15	.16
10. Basal 1/2Ca 1/4K	.31	.24	.32	.31	.34	.28	.16	.17
13. Basal 1/2Ca 1/4Mg	.73	.53	.57	.53	.46	.35	.13	.18
16. Basal 1/2Ca 1/4Na	.37	.47	.34	.51	.42	.36	.17	.22
3. Basal 1Ca	.39	.38	.59	.42	.48	.36	.21	.17
11. Basal 1/2Ca 1/2K	.25	.27	.29	.26	.33	.31	.12	.16
14. Basal 1/2Ca 1/2Mg	.81	.60	.68	.50	.64	.38	.24	.25
17. Basal 1/2Ca 1/2Na	.26	.35	.33	.46	.57	.29	.15	.26
19. Basal 1/2Ca 1/4K 1/4Mg	.25	.31	.47	.39	.43	.29	.13	.30
12. Basal 1Ca 1/4K	.36	.22	.31	.28	.39	.29	---	.17
15. Basal 1Ca 1/4Mg	.63	.49	.64	.52	.60	.40	.32	.21
18. Basal 1Ca 1/4Na	.36	.37	.46	.41	.56	.31	.16	.31
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.37	.25	.43	.34	.51	.28	.07	.27

how some of the apparent irregularities in the strontium results again show themselves with calcium.

The comparison of magnesium with strontium can be made by using Table 15. Here we have fewer comparisons than were possible for strontium and calcium and in order to achieve the maximum reliability two sets of comparisons are made. In the first the calcium treatments are taken as standard and the potassium and sodium treatments are compared with these. In the second, the potassium treatments are chosen as standards and the corresponding sodium treatments are compared with them. In the comparison of magnesium and strontium as they are affected by potassium and sodium addition to the soil we see the same general regularities as were found in the calcium-strontium comparison. Sodium gives smaller depressions than potassium, lespedeza shows increases in some cases. The magnitude of the depressions produced by potassium are about the same for magnesium as for strontium. Sodium seems to produce somewhat smaller effects on the magnesium than on the strontium.

Another way of considering the results is to group the experiments according to the ions added instead of the exchangeable base level. This is the usual method adopted but it has been avoided here so far because, as mentioned above, when we increase the amount of one ion we not only change the proportions of the exchangeable bases but also the exchangeable base level itself. In certain cases, however, we need the usual method to supplement the conclusions already drawn. The apparent increases in strontium, calcium, and magnesium caused by sodium and sometimes by potassium treatments in the case of the Korean lespedeza need further examination. These apparent increases were, of course, based on the magnesium or calcium treatment at the same base level as standard. We shall now use the basal treatment

TABLE 18. PERCENTAGES OF STRONTIUM, CALCIUM AND MAGNESIUM IN KOREAN LESPEDEZA UNDER POTASSIUM-CALCIUM AND SODIUM-CALCIUM TREATMENTS.

Treatment	Strontium		Calcium		Magnesium	
	Putnam	Lindley	Putnam	Lindley	Putnam	Lindley
1. Basal	.0063	.0030	1.49	1.11	.26	.32
4. Basal 1/4K	.0054	.0032	1.27	1.13	.18	.23
5. Basal 1/2K	.0033	.0039	.90	1.07	.17	.23
2. Basal 1/2Ca	.0048	.0035	1.70	1.24	.29	.28
10. Basal 1/2Ca 1/4K	.0039	.0040	1.30	1.28	.21	.24
11. Basal 1/2Ca 1/2K	.0027	.0038	1.41	1.21	.18	.21
3. Basal 1Ca	.0040	.0032	1.81	1.32	.32	.24
12. Basal 1Ca 1/4K	-----	.0039	----	1.35	----	.23
1. Basal	.0063	.0030	1.49	1.11	.26	.32
8. Basal 1/4Na	.0064	.0029	1.45	1.17	.23	.30
9. Basal 1/2Na	.0054	.0037	1.19	1.21	.33	.27
2. Basal 1/2Ca	.0048	.0035	1.70	1.24	.29	.28
16. Basal 1/2Ca 1/4Na	.0038	.0049	1.46	1.36	.26	.33
17. Basal 1/2Ca 1/2Na	.0032	.0051	1.72	1.70	.26	.41
3. Basal 1Ca	.0040	.0032	1.81	1.32	.32	.24
18. Basal 1Ca 1/4Na	.0045	.0054	1.61	1.87	.27	.46

as standard and examine the lespedeza figures for these three ions. The actual percentages are given in Table 18, where we have first the potassium-calcium series, second the sodium-calcium series.

The regularities are much more evident on the lespedeza grown on the Putnam soil than on the crop grown on the Lindley. The crop grown on the Putnam soil seems to show the dilution effect with increasing additions of calcium, a specific reduction with increasing additions of potassium and a much smaller reduction for sodium. On the Lindley soil there are several cases of percentages higher than those of the basal treatment and other peculiarities are present which cannot now be explained.

We may also discuss at this point the relation of plant composition to the proportions of exchangeable bases in the soil. In most cases we find on comparing the Putnam and Lindley that the relative amounts in the crops follow those present in the exchangeable form in the soil. Thus the crops on the Lindley contain less strontium and less calcium than those grown on the Putnam. With magnesium, however, this is not always the case. The Lindley soil contains about half as much exchangeable magnesium as the Putnam, yet the lespedeza and sweet clover show higher Mg contents when grown on the Lindley, bluegrass is about the same for the two soils, and only redtop shows slightly higher magnesium percentages when grown on the Putnam soil.

The relationship of calcium and strontium in plant nutrition has been very fully discussed by Collander (6), who grew twenty different species of plants upon several different nutrient solutions of different ionic compositions. He came to the conclusion that calcium and strontium are scarcely differentiated by the absorbing mechanism of the plant. Thus their ratio in plants tended to be the same as those in the culture solutions used. The same was true also of potassium, rubidium and caesium. On the other hand, calcium and magnesium, and potassium and sodium were much less closely related in regard to uptake by plants. The present experiments were not designed to throw light specifically on this point, and no direct comparison with Collander's results is possible until we know more about the actual activities of calcium and strontium ions in the soil. However, on comparing the ratio exchangeable Ca/exchangeable Sr for the soils with the ratio Ca/Sr in the crops we find the latter to be distinctly greater. This, however, may reflect the fact that calcium is more easily displaced from the soil than strontium as well as any small differences in uptake due to the plants themselves.

Manganese. The most cursory inspection of the maganese figures shows that here specific effects such as those of potassium or sodium are subordinate to other factors, the most important of which appears to be the pH of the soil (3). In all the crops the control or the basal treatment gave much higher manganese percentages than did any other treatment. In a considerable number of cases the potassium

TABLE 19. MEAN MANGANESE PERCENTAGES AT VARIOUS EXCHANGEABLE BASE LEVELS

Level of addition	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley	Korean lespedeza Putnam	Korean lespedeza Lindley
Basal	.022	.040	.060	.090	.025	.035	.015	.051
Basal 1/4	.012	.022	.022	.063	.014	.017	.007	.025
Basal 1/2	.011	.021	.017	.052	.007	.015	.006	.018
Basal 3/4	.011	.022	.014	.038	.006	.013	.006	.018
Basal 1	.011	.018	.017	.030	.005	.011	.006	.015
Basal 1 1/4	.011	.016	.016	.025	.006	.010	.007	.013

and sodium treatments give lower manganese percentages than the corresponding calcium or magnesium treatments, but the differences are rather small and one has the impression that the pH factor overshadows all others. In Table 19 the mean percentages at the various levels of exchangeable bases are given.

On the Putnam soil from the ½ level onwards the manganese figures are practically constant for all crops. The pH for the ½ additions lies in the range 6.4-6.7, whereas at the ¼ level it is 5.8-6.2. The plants grown on the Lindley soil show significant decreases in manganese through the whole series of base additions. It must be remembered that these additions were less than for the Putnam and that the exchange capacity was underestimated in arriving at the quantities of base to be added. Unfortunately no reliable pH measurements on the treated Lindley soils are available owing to uptake of acid fumes

TABLE 20. MANGANESE PERCENTAGES OF EARLY AND LATE CROPS

Treatment	Bluegrass Early	Bluegrass Late	Redtop Early	Redtop Late	Korean lespedeza Early	Korean lespedeza Late
1. Basal	.021	.023	.058	.062	.060	.048
4. Basal 1/4K	.010	.015	.017	.024	.030	.028
6. Basal 1/4Mg	.010	.015	.019	.027	.028	.025
8. Basal 1/4Na	.013	.008	.018	.024	.026	.018
2. Basal 1/2Ca	.009	.015	.012	.021	.034	.028
5. Basal 1/2K	.012	.012	.012	.016	.019	.017
7. Basal 1/2Mg	.011	.012	.013	.021	.018	.011
9. Basal 1/2Na	.010	.008	.015	.020	.012	.013
10. Basal 1/2Ca 1/4K	.010	.010	.014	.016	.025	.020
13. Basal 1/2Ca 1/4Mg	.011	.013	.011	.015	.017	.017
16. Basal 1/2Ca 1/4Na	.009	.012	.013	.015	.013	.014
3. Basal 1Ca	.012	.011	.017	.018	.026	.020
11. Basal 1/2Ca 1/2K	.008	.013	.013	.016	.015	.015
14. Basal 1/2Ca 1/2Mg	.017	.011	.013	.020	.011	.012
17. Basa' 1/2Ca 1/2Na	.012	.010	.016	.020	.006	.014
19. Basal 1/2Ca 1/4K 1/4Mg	.009	.009	.014	.013	.012	.016
12. Basal 1Ca 1/4K	.009	.011	.013	.014	.016	.014
15. Basal 1Ca 1/4Mg	.011	.009	.014	.017	.013	.014
18. Basal 1Ca 1/4Na	.013	.011	.015	.017	.012	.012
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.014	.014	.017	.017	.009	.012

TABLE 21. (a) MANGANESE PERCENTAGES ON TOTAL CROPS

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley	Korean lespedeza Putnam	Korean lespedeza Lindley
21. No treatment	---	.042	---	.093	---	---	---	.070
1. Basal	.022	.040	.060	.090	.025	.035	.015	.051
4. Basal 1/4K	.012	.023	.020	.060	.017	.017	.006	.029
6. Basal 1/4Mg	.013	.018	.023	.069	.011	.018	.007	.026
8. Basal 1/4Na	.010	.026	.022	.060	.010	.015	.007	.020
2. Basal 1/2Ca	.012	.026	.017	.069	.008	.019	.006	.030
5. Basal 1/2K	.012	.017	.014	.047	.006	.014	.006	.017
7. Basal 1/2Mg	.011	.019	.018	.051	.007	.012	.007	.013
9. Basal 1/2Na	.009	.024	.018	.039	.008	.015	.006	.013
10. Basal 1/2Ca 1/4K	.010	.021	.016	.039	.007	.012	.007	.021
13. Basal 1/2Ca 1/4Mg	.012	.021	.014	.041	.005	.018	.005	.017
16. Basal 1/2Ca 1/2Na	.011	.023	.013	.035	.006	.010	.005	.014
3. Basal 1Ca	.011	.021	.017	.049	.007	.013	.006	.021
11. Basal 1/2Ca 1/2K	.011	.017	.015	.029	.005	.011	.006	.015
14. Basal 1/2Ca 1/2Mg	.014	.018	.018	.026	.006	.011	.006	.012
17. Basal 1/2Ca 1/2Na	.011	.018	.019	.024	.008	.009	.008	.013
19. Basal 1/2Ca 1/4K 1/4Mg	.009	.017	.014	.023	.005	.011	.005	.015
12. Basal 1Ca 1/4K	.010	.018	.014	.028	.005	.010	---	.015
15. Basal 1Ca 1/4Mg	.010	.016	.016	.026	.008	.010	.008	.014
18. Basal 1Ca 1/4Na	.012	.017	.015	.025	.007	.010	.006	.012
20. Basal 1/2Ca 1/4Na 1/4Mg 1/4Na	.014	.015	.017	.022	.005	.009	.007	.012

TABLE 21. (b) MANGANESE CONTENT IN GRAMS OF TOTAL CROPS.

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley	Korean lespedeza Putnam	Korean lespedeza Lindley
21. No treatment	---	.006	---	.029	---	---	---	.021
1. Basal	.024	.027	.064	.075	.009	.012	.009	.024
4. Basal 1/4K	.013	.017	.022	.054	.011	.008	.004	.017
6. Basal 1/4Mg	.013	.014	.023	.058	.006	.008	.005	.016
8. Basal 1/4Na	.009	.020	.020	.054	.007	.005	.005	.011
2. Basal 1/2Ca	.011	.018	.016	.059	.005	.008	.004	.018
5. Basal 1/2K	.010	.018	.015	.044	.005	.007	.003	.012
7. Basal 1/2Mg	.010	.016	.017	.044	.005	.005	.005	.009
9. Basal 1/2Na	.006	.017	.017	.034	.006	.006	.003	.008
10. Basal 1/2Ca 1/4K	.009	.017	.017	.038	.006	.006	.005	.015
13. Basal 1/2Ca 1/4Mg	.012	.015	.013	.036	.003	.008	.004	.011
16. Basal 1/2Ca 1/4Na	.009	.018	.012	.032	.004	.005	.003	.009
3. Basal 1Ca	.010	.017	.018	.042	.006	.006	.004	.015
11. Basal 1/2Ca 1/2K	.011	.015	.016	.027	.005	.006	.004	.011
14. Basal 1/2Ca 1/2Mg	.013	.013	.017	.023	.006	.005	.004	.008
17. Basal 1/2Ca 1/2Na	.007	.012	.016	.022	.010	.004	.005	.008
19. Basal 1Ca 1/4K 1/4Mg	.007	.014	.017	.021	.005	.006	.003	.010
12. Basal 1Ca 1/4K	.011	.015	.016	.026	.005	.005	---	.011
15. Basal 1Ca 1/4Mg	.010	.011	.015	.023	.007	.005	.005	.009
18. Basal 1Ca 1/4Na	.009	.013	.015	.022	.008	.005	.004	.008
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.013	.012	.019	.021	.007	.005	.002	.008

by the soil samples during storage. We should expect, however, a more gradual change in pH than in the case of the Putnam, and this would account for the progressive lowering of manganese content with rising base level.

The subordinate role played by the specific lowering of the manganese content, by potassium or sodium treatments is especially significant in view of the data presented previously in Table 4. It was shown clearly on the Lindley soil that the complementary ion principle operated in the release of manganese from the exchangeable form by acid. In consequence, the soils treated with sodium gave up much less exchangeable manganese than those treated with calcium, magnesium, or potassium. In the crops, on the other hand, the sodium treatments have produced little change in manganese content.

The order of the four crops in respect of manganese content is different on the two soils, and it changes to some extent also with the base level (Table 21). Redtop, however, always gave higher manganese percentages than the other three crops. In all cases the Lindley soil gave higher manganese percentages that did the Putnam, which is in accord with the relative amounts of exchangeable manganese.

Tabulation of the figures for early and late crops of bluegrass and redtop and Korean lespedeza shows that in all cases the differences are small (Table 20). The late redtop appears to be rather consistently higher in manganese than the early crop. The bluegrass and lespedeza show slight changes in both directions with no distinct trend.

Potassium. (*a*) *Effects of calcium and magnesium.* The specific effects of these ions are included along with the effect of increasing the total exchangeable bases in Table 22.

TABLE 22. POTASSIUM PERCENTAGES IN FOUR CROPS IN RELATION TO CALCIUM AND MAGNESIUM ADDITIONS TO TWO SOILS

	Putnam 1939-40				Lindley 1940-41			
Treatment	Blue-grass	Red-top	Sweet clover	Korean lespedeza	Blue-grass	Red-top	Sweet clover	Korean lespedeza
1. Basal	1.71	1.93	1.40	1.45	2.45	2.45	2.40	1.67
6. Basal 1/4Mg	1.58	1.83	1.48	1.43	2.22	2.37	2.33	1.62
2. Basal 1/2Ca	1.68	1.89	1.13	1.22	2.52	2.46	2.31	1.64
7. Basal 1/2Mg	1.64	1.95	1.31	1.53	2.19	2.52	2.23	1.61
13. Basal 1/2Ca 1/4Mg	1.69	1.92	1.01	1.16	2.25	2.36	2.29	1.49
14. Basal 1/2Ca 1/2Mg	1.64	1.64	0.92	1.12	2.28	2.18	2.15	1.50
3. Basal 1Ca	1.68	1.81	1.28	1.25	2.31	2.51	2.31	1.61
15. Basal 1Ca 1/4Mg	1.63	1.53	0.89	1.16	2.41	2.37	1.98	1.52

The variations in potassium are relatively small except that in the case of the sweet clover the calcium plus magnesium treatments cause a distinct fall. A tendency for the potassium content to fall slightly as the total bases rise is discernable in the others but no specific effects of calcium or magnesium are consistently shown by all four crops.

(*b*) *Effect of sodium.* We can get some idea of the specific effect of sodium by comparing the potassium percentages for the sodium treatment with those of the corresponding magnesium treatments. In Table 23 the percentage increase or decrease from the magnesium treatment has been tabulated for all the crops. In most cases there is a distinct increase in potassium due to the sodium treatment. On the Lindley soil the increases are less marked than on the Putnam except for the lespedeza. In many instances the increases are sufficiently great to bring the potassium percentages above those of the plants grown with the basal treatment only.

TABLE 23. PERCENTAGE CHANGE IN POTASSIUM CONTENT COMPARED WITH STANDARD.

Standard treatment	Other treatment	Blue-grass	Red-top	Sweet clover	Korean lespe-deza	Blue-grass	Red-top	Sweet clover	Korean lespe-deza
Basal 1/4Mg	Basal 1/4Na	30	16	32	21	10	8	1	12
Basal 1/2Ca 1/4Mg	Basal 1/2Ca 1/4Na	18	-20	20	27	5	-1	-2	20
Basal 1Ca 1/2Mg	Basal 1Ca 1/4Na	26	- 1	42	22	- 6	-2	4	54
Basal 1/2Mg	Basal 1/2Na	22	41	57	14	11	-2	-1	9
Basal 1/2Ca 1/2Mg	Basal 1/2Ca 1/2Na	21	- 6	29	28	7	8	0	78
	Mean	23	6	36	22	5	2	1	35

This effect is the converse of what one would predict for the release of ions from the soil using the complementary ion principle. Since potassium is more strongly held than sodium, addition of the latter would cause a smaller release of potassium in a subsequent partial exchange. Neither do these results suggest that sodium can have partially replaced potassium in the plant, as has sometimes been claimed. Of course, experiments of this kind are vastly different from those carried out in culture solutions. We are here dealing with comparisons between treatments both of which involve very low potassium ion activities in the soil.

It might perhaps be suggested that the sodium bicarbonate (analytical reagent quality) used as the soil treatment contained a small amount of potassium. This, however, should have shown itself in the figures for exchangeable potassium; Tables 1, 2, 3 and 4, however, do not bear this out.

The variation in the effect with crop and soil is also hard to explain. Redtop shows a small increase and lespedeza a large increase on both soils. The bluegrass and sweet clover show a large increase on the Putnam soil but a very small one on the Lindley.

(*c*) *Direct effect of potassium additions.* The well established increase in potassium content of the plant with increasing amounts added to the soil is shown by the present series of experiments. Luxury levels of potassium uptake are suggested in some cases where the percentages rise to 4-5% K. The case of Korean lespedeza stands quite apart from the rest as may be seen from Tables 24 and 26. The

TABLE 24. EFFECTS OF POTASSIUM AND CALCIUM UPON THE POTASSIUM CONTENT OF THE CROPS

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley	Korean lespedeza Putnam	Korean lespedeza Lindley
1. Basal	1.71	2.45	1.93	2.45	1.40	2.40	1.45	1.67
4. Basal 1/4K	3.11	3.99	4.14	4.46	3.39	4.07	2.15	1.93
5. Basal 1/2K	3.27	4.15	4.67	5.08	4.16	4.12	3.01	2.23
2. Basal 1/2Ca	1.68	2.52	1.89	2.46	1.13	2.31	1.22	1.64
10. Basal 1/2Ca 1/4K	3.10	3.91	4.03	4.17	2.90	4.43	2.22	1.98
11. Basal 1/2Ca 1/2K	3.50	3.95	4.48	4.33	3.45	4.25	1.96	2.07
3. Basal 1Ca	1.68	2.31	1.81	2.51	1.28	2.31	1.25	1.61
12. Basal 1Ca 1/4K	3.07	3.97	4.43	4.28	2.97	4.05	---	1.97

TABLE 25. POTASSIUM PERCENTAGES FOR EARLY AND LATE CROPS

Treatment	Bluegrass Early	Bluegrass Late	Redtop Early	Redtop Late	Korean lespedeza Early	Korean lespedeza Late
1. Basal	2.27	1.15	2.63	1.15	2.06	1.52
4. Basal 1/4K	3.57	2.64	5.61	3.62	2.04	1.89
6. Basal 1/4Mg	1.96	1.20	2.38	1.26	1.87	1.54
8. Basal 1/4Na	2.86	1.24	3.15	1.19	2.07	1.74
2. Basal 1/2Ca	2.04	1.32	2.71	1.22	1.95	1.52
5. Basal 1/2K	3.69	2.85	5.86	3.85	2.16	2.25
7. Basal 1/2Mg	2.03	1.24	2.85	1.20	1.92	1.51
9. Basal 1/2Na	2.47	1.55	4.34	1.49	1.96	1.69
10. Basal 1/2Ca 1/4K	3.42	2.78	4.47	3.81	2.32	1.87
13. Basal 1/2Ca 1/4Mg	1.90	1.48	2.95	1.12	1.75	1.41
16. Basal 1/2Ca 1/4Na	2.70	1.24	2.34	1.07	1.95	1.75
3. Basal 1Ca	2.08	1.28	2.53	1.19	1.95	1.51
11. Basal 1/2Ca 1/2K	3.83	3.16	5.26	4.04	2.22	2.01
14. Basal 1/2Ca 1/2Mg	1.88	1.40	2.11	1.26	2.02	1.32
17. Basal 1/2Ca 1/2Na	2.47	1.50	2.13	1.23	2.00	2.56
19. Basal 1/2Ca 1/4K 1/4Mg	3.43	2.78	4.98	3.95	2.33	2.73
12. Basal 1Ca 1/4K	3.37	2.76	5.31	3.90	2.14	1.91
15. Basal 1Ca 1/4Mg	2.06	1.19	2.11	1.13	2.00	1.35
18. Basal 1Ca 1/4Na	2.58	1.53	2.17	1.14	2.38	2.33
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	3.32	2.79	4.67	3.81	2.30	2.59

variation in potassium content is much smaller than that of the other crops.

In the absence of potassium treatments the Lindley soil gives up more potassium to the crops than the Putnam; yet its exchangeable potassium is somewhat lower. It is clear that the plants obtain potassium which is not brought into solution by ammonium acetate, a conclusion which already seemed probable from the soil and crop data presented earlier in Table 5.

(*d*) *Comparison of early and late crops* (Table 25). Bluegrass and redtop consistently give lower potassium figures for the late cuttings than for the early cuttings. Lespedeza changes much less in composition and in a few cases apparently gave higher potassium figures for the late cuttings.

Sodium. As was pointed out earlier the sodium determinations were made spectrographically using the ultraviolet line as the measure of quantity. The presence of sodium as an adventitious impurity

TABLE 26. (a) POTASSIUM PERCENTAGES IN TOTAL CROPS

Treatment	Bluegrass		Redtop		Sweet clover		Korean lespedeza	
	Putnam	Lindley	Putnam	Lindley	Putnam	Lindley	Putnam	Lindley
21. No treatment	---	2.80	---	3.14	---	---	---	2.09
1. Basal	1.71	2.45	1.93	2.45	1.40	2.40	1.45	1.67
4. Basal 1/4K	3.11	3.99	4.14	4.46	3.39	4.07	2.15	1.93
6. Basal 1/4Mg	1.58	2.22	1.83	2.37	1.48	2.33	1.43	1.62
8. Basal 1/4Na	2.05	2.45	2.12	2.55	1.95	2.36	1.73	1.82
2. Basal 1/2Ca	1.68	2.52	1.89	2.46	1.13	2.31	1.22	1.64
5. Basal 1/2K	3.27	4.15	4.67	5.08	4.16	4.12	3.01	2.23
7. Basal 1/2Mg	1.64	2.19	1.95	2.52	1.31	2.23	1.53	1.61
9. Basal 1/2Na	2.01	2.43	2.74	2.46	2.06	2.21	1.75	1.75
10. Basal 1/2Ca 1/4K	3.10	3.91	4.03	4.17	2.90	4.43	2.22	1.98
13. Basal 1/2Ca 1/4Mg	1.69	2.25	1.92	2.36	1.01	2.29	1.16	1.49
16. Basal 1/2Ca 1/4Na	1.97	2.37	1.54	2.33	1.21	2.25	1.47	1.79
3. Basal 1Ca	1.68	2.31	1.81	2.51	1.28	2.31	1.25	1.61
11. Basal 1/2Ca 1/2K	3.50	3.95	4.48	4.33	3.45	4.25	1.96	2.07
14. Basal 1/2Ca 1/2Mg	1.64	2.28	1.64	2.18	0.92	2.15	1.12	1.50
17. Basal 1/2Ca 1/2Na	1.99	2.45	1.54	2.35	1.19	2.15	1.43	2.67
19. Basal 1/2Ca 1/4K 1/4Mg	3.11	3.49	4.35	4.14	3.09	3.54	2.18	2.64
12. Basal 1Ca 1/4K	3.07	3.97	4.43	4.28	2.97	4.05	---	1.97
15. Basal 1Ca 1/4Mg	1.63	2.41	1.53	2.37	0.89	1.98	1.16	1.52
18. Basal 1Ca 1/4Na	2.06	2.27	1.51	2.33	1.26	2.05	1.41	2.35
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	3.01	3.50	4.14	3.62	3.46	3.98	2.17	2.53

TABLE 26. (b) POTASSIUM CONTENT IN GRAMS OF TOTAL CROPS

Treatment	Bluegrass		Redtop		Sweet clover		Korean lespedeza	
	Putnam	Lindley	Putnam	Lindley	Putnam	Lindley	Putnam	Lindley
21. No treatment	---	0.38	---	0.99	---	---	---	0.64
1. Basal	1.83	1.68	2.08	2.06	0.50	0.85	0.84	0.77
4. Basal 1/4K	3.12	3.04	4.49	4.05	2.23	1.86	1.34	1.18
6. Basal 1/4Mg	1.53	1.75	1.83	2.00	0.81	0.97	0.95	1.00
8. Basal 1/4Na	1.71	1.85	1.96	2.28	1.34	0.85	1.08	0.96
2. Basal 1/2Ca	1.35	1.72	1.78	2.10	0.77	0.92	0.80	1.00
5. Basal 1/2K	2.69	3.28	5.04	4.72	3.77	2.05	1.38	1.56
7. Basal 1/2Mg	1.44	1.81	1.86	2.18	0.92	0.87	1.10	1.15
9. Basal 1/2Na	1.40	1.70	2.57	2.18	1.49	0.94	0.80	1.04
10. Basal 1/2Ca 1/4K	2.68	3.14	4.42	4.09	2.80	2.25	1.66	1.40
13. Basal 1/2Ca 1/4Mg	1.60	1.64	1.80	2.09	0.76	0.98	0.86	0.99
16. Basal 1/2Ca 1/4Na	1.39	1.88	1.39	2.14	1.17	1.08	0.96	1.21
3. Basal 1Ca	1.38	1.83	1.89	2.13	1.06	1.04	0.81	1.14
11. Basal 1/2Ca 1/2K	3.20	3.40	4.77	4.06	3.66	2.27	1.31	1.58
14. Basal 1/2Ca 1/2Mg	1.62	1.70	1.58	1.93	0.80	0.95	0.80	1.02
17. Basal 1/2Ca 1/2Na	1.24	1.70	1.33	2.17	1.50	0.92	0.84	1.65
19. Basal 1/2Ca 1/4K 1/4Mg	2.49	2.85	5.46	3.86	3.33	2.08	1.31	1.76
12. Basal 1Ca 1/4K	3.04	3.30	5.25	4.04	3.64	2.16	---	1.44
15. Basal 1Ca 1/4Mg	1.55	1.69	1.45	2.11	0.86	1.04	0.84	0.94
18. Basal 1Ca 1/4Na	1.43	1.69	1.51	2.09	1.56	1.01	0.86	1.61
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	2.83	2.70	4.71	3.43	5.05	2.21	0.65	1.77

from glassware and reagents made it unprofitable to attempt to determine very small quantities using the sensitive yellow D line. The operation of the microphotometer set a threshold at about 0.04-06%, but values slightly above these could be determined with some accuracy once the maximum was distinguished from the background on the plate.

(*a*) *Effects of calcium and magnesium.* Table 27 gives the percentages for all the crops except Korean lespedeza, whose sodium content remained entirely below the threshold value.

TABLE 27. SODIUM PERCENTAGES IN THREE CROPS IN RELATION TO CALCIUM AND MAGNESIUM ADDITIONS TO TWO SOILS.

Treatment	Putnam 1939-40 Bluegrass	Putnam 1939-40 Redtop	Putnam 1939-40 Sweet clover	Lindley 1940-41 Bluegrass	Lindley 1940-41 Redtop	Lindley 1940-41 Sweet clover
1. Basal	.04	.10	.04	.06	.07	.07
4. Basal 1/4Mg	.03	.10	.07	.06	.07	.08
2. Basal 1/2Ca	.04	.10	.05	.06	.08	.07
7. Basal 1/2Mg	.04	.07	.07	.06	.06	.08
13. Basal 1/2Ca 1/4Mg	.03	.09	---	.06	.06	.06
14. Basal 1/2Ca 1/2Mg	.04	.07	---	.06	.06	.10
3. Basal 1Ca	.04	.14	.05	.06	.06	.06
15. Basal 1Ca 1/4Mg	.04	.09	---	.06	.04	.09

It is seen that magnesium and calcium have little effect upon the sodium figures, although, of course, the relative accuracy is not sufficient to preclude small variations.

(*b*) *Effect of potassium.* The accuracy of the sodium figures is not adequate for a tabulation of percentage increase or decrease in sodium due to potassium treatment as compared with magnesium treatment. An examination of the results shows that the the ½ K level a consistent fall in sodium percentage occurs, whereas at the ¼ K level the result is uncertain. In general we are probably justified in concluding that potassium depresses the sodium content of the plants slightly under the conditions of these experiments for bluegrass, redtop and sweet clover.

(*c*) *Direct effect of sodium additions.* The addition of sodium to the soil caused well marked increases in the sodium content of all the crops except Korean lespedeza, which, even with the highest applications, remained below the threshold value. This species must therefore be regarded as belonging to the class of "low sodium" plants, several of which have been recorded in the literature. The results for the other crops are to be found in Table 28.

Of the four crops redtop contains the most sodium and it shows the greatest variability in sodium content. On the Lindley soil the differences due to sodium treatment are considerably less than on

TABLE 28. (a) SODIUM PERCENTAGES ON TOTAL CROPS

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley
21. No treatment	---	.06	---	.06	---	---
1. Basal	.04	.06	.09	.07	.04	.07
4. Basal 1/4K	.03	.06	.05	.04	.08	.10
6. Basal 1/4Mg	.03	.06	.10	.07	.07	.08
8. Basal 1/4Na	.18	.11	.53	.30	.36	.17
2. Basal 1/2Ca	.04	.06	.10	.08	.05	.07
5. Basal 1/2K	.03	.06	.07	.06	.06	.05
7. Basal 1/2Mg	.04	.06	.07	.06	.07	.08
9. Basal 1/2Na	.54	.15	.73	.38	.57	.25
10. Basal 1/2Ca 1/4K	.03	.06	.11	.06	<.04	.07
13. Basal 1/2Ca 1/4Mg	.03	.06	.09	.06	<.04	.06
16. Basal 1/2Ca 1/4Na	.23	.09	.56	.16	.25	.11
3. Basal 1Ca	.04	.06	.14	.06	.06	.06
11. Basal 1/2Ca 1/2K	.02	.06	.05	.06	<.04	.06
14. Basal 1/2Ca 1/2Mg	.04	.06	.07	.06	<.04	.10
17. Basal 1/2Ca 1/2Na	.62	.13	1.06	.37	.38	.21
19. Basal 1/2Ca 1/4K 1/4Mg	.02	.06	.05	.05	<.04	.04
12. Basal 1Ca 1/4K	.02	.06	.04	.04	<.04	.05
15. Basal 1Ca 1/4Mg	.04	.06	.09	.04	<.04	.09
18. Basal 1Ca 1/4Na	.32	.06	.61	.15	.21	.10
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.21	.06	.13	.07	<.04	.07

TABLE 28. (b) SODIUM CONTENT IN GRAMS OF TOTAL CROPS

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley
21. No treatment	---	---	---	.02	---	---
1. Basal	.04	---	.10	.06	.01	.03
4. Basal 1/4K	.03	---	.05	.04	.05	.05
6. Basal 1/4Mg	.03	---	.10	.06	.04	.03
8. Basal 1/4Na	.17	.08	.49	.27	.25	.06
2. Basal 1/2Ca	.03	---	.10	.06	.03	.03
5. Basal 1/2K	.02	---	.07	.06	.05	.02
7. Basal 1/2Mg	.03	---	.07	.05	.05	.03
9. Basal 1/2Na	.41	.11	.69	.33	.41	.09
10. Basal 1/2Ca 1/4K	.02	---	.12	.06	---	.04
13. Basal 1/2Ca 1/4Mg	.02	---	.08	.06	---	.03
16. Basal 1/2Ca 1/4Na	.20	.07	.50	.15	.24	.05
3. Basal 1Ca	.03	---	.15	.05	.05	.03
11. Basal 1/2Ca 1/2K	.02	---	.05	.06	---	.03
14. Basal 1/2Ca 1/2Mg	.03	---	.07	.05	---	.04
17. Basal 1/2Ca 1/2Na	.43	.09	.92	.35	.48	.09
19. Basal 1/2Ca 1/4K 1/4Mg	.01	---	.06	.05	---	.02
12. Basal 1Ca 1/4K	.02	---	.04	.04	---	.03
15. Basal 1Ca 1/4Mg	.04	---	.08	.04	---	.05
18. Basal 1Ca 1/4Na	.25	---	.62	.13	.25	.05
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.20	---	.15	.07	---	.04

the Putnam; it must be remembered, however, that the actual additions were also much less.

(*d*) *Comparison of early and late crops* (Table 29). The data for bluegrass are consistent in showing that in absence of sodium addi-

TABLE 29. SODIUM PERCENTAGES FOR EARLY AND LATE CROPS

	Putnam Soil 1939-40			
	Bluegrass		Redtop	
Treatment	Early	Late	Early	Late
1. Basal	.06	.02	.11	.08
4. Basal 1/4K	.05	.01	.06	.04
6. Basal 1/4Mg	.06	.01	.12	.09
8. Basal 1/4Na	.15	.21	.44	.62
2. Basal 1/2Ca	.06	.01	.11	.10
5. Basal 1/2K	.06	.01	.06	.08
7. Basal 1/2Mg	.07	.01	.08	.07
9. Basal 1/2Na	.52	.57	.43	.97
10. Basal 1/2 1/4K	.06	.01	.21	.06
13. Basal 1/2Ca 1/4Mg	.04	.01	.07	.10
16. Basal 1/2Ca 1/4Na	.16	.31	.30	.71
3. Basal 1Ca	.06	.02	.16	.13
11. Basal 1/2Ca 1/2K	.04	.01	.04	.06
14. Basal 1/2Ca 1/2Mg	.05	.02	.06	.08
17. Basal 1/2Ca 1/2Na	.46	.78	.72	1.25
19. Basal 1/2Ca 1/4K 1/4Mg	.04	---	.04	.05
12. Basal 1Ca 1/4K	.03	.01	.04	.03
15. Basal 1Ca 1/4Mg	.07	.02	.07	.10
18. Basal 1Ca 1/4Na	.31	.34	.35	.76
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.21	.21	.03	.19

tions to the soil the late crop contains less sodium than the early cuttings. With sodium additions the converse is true. Redtop shows in absence of sodium additions cases in which the late crop contains less sodium than the early, and conversely. With sodium additions the late crop is higher in sodium than the early crop.

Discussion of potassium and sodium.—A comparison of the effects of sodium and potassium upon the crops reveals some similarities and some marked differences. The sodium and potassium contents of the crops are greatly different, yet on adding calcium and magnesium to the soil the percentages of both elements are only slightly depressed. There seems to be no strong specific action of calcium or magnesium upon either. The four crops studied displayed considerable quantitative differences in the ease of uptake of the monovalent ions. Even with the maximum sodium additions no crop took up as much sodium as it did potassium. Redtop took up sodium most readily, then bluegrass and sweet clover gave somewhat lower percentages and Korean lespedeza behaves entirely as a low sodium plant and never took up as much as 0.1%. With respect to potassium content we again find this same order Redtop > sweet clover > bluegrass > Korean lespedeza. Lespedeza, the low sodium plant, does not enter into "luxury" consumption of potassium like the other three crops and the variation in potassium content is over a smaller range than the others display. It will be recalled that lespedeza gave increases rather than decreases in Sr, Ca, and Mg as a result of potassium and sodium additions to the soil. In the other crops sodium gave smaller depressions than potassium. These facts strongly suggest that the proportion of ions entering the plant is a function of those already present. From the complementary ion principle alone we should have expected sodium to be more effective in depressing the divalent ions than potassium. The fact that it is less effective may be connected with the low sodium content of the plants. The results with lespedeza, whose sodium content is very small and whose potassium content is more nearly constant than that of the other crops, are in agreement with this standpoint.

The very striking difference between sodium and potassium in the experiments is that whereas potassium additions slightly depressed the sodium, sodium additions distinctly raised the potassium. This last effect seems surprising since several authors have stated that sodium can replace potassium to a limited extent. However, if we look upon it as a mechanism operating inside the plant it seems equally plausible to assume that the uptake of an increased amount of sodium increases the permeability towards potassium. The most extensive early investigations on the potassium-sodium relationships were those of Hellriegel (11) who found in sand cultures that several crops showed the same behavior as was found here, namely that addition of sodium raised the potassium content. Later workers (10, 16, 22) have found the opposite behavior but it is extremely difficult to compare the different results obtained since the conditions of the experiments and the ionic activities of the nutrient solutions used vary so widely.

Total cations.—Van Itallie (17) found that when the cationic constituents are calculated in milliequivalents per 100 gm. dry matter and then added together, the totals show only slight variation with treatment. In order to examine this point Table 30 has been compiled. The variations are seen to be similar to those reported by Van Itallie for his first cutting of Italian rye grass (which fell in the range 182-215 milliequivalents per 100 gm. dry matter) although in several cases the present series give distinctly greater variations. No clear cut relationship between this total and the treatments applied has been found. However, where high percentages of potassium or magnesium occur in the crops the total cationic content rises also. Thus Van Itallie's statement that the cations replace one another in equivalent amounts is only a very crude approximation. A very slight increase in the total as the base level rises shows itself in several instances. On comparing the four crops the sweet clover is found to give appreciably higher totals than the others.

TABLE 30. SUM OF CALCIUM, MAGNESIUM, POTASSIUM, AND SODIUM IN MILLIEQUIVALENTS PER 100 GM. DRY MATTER

Treatment	Bluegrass		Redtop		Sweet clover		Korean lespedeza	
	Putnam	Lindley	Putnam	Lindley	Putnam	Lindley	Putnam	Lindley
21. No treatment	-----	112.9	-----	141.7	-------	-----	-----	162.4
1. Basal	138.6	131.6	154.9	149.4	177.3	219.7	132.9	124.5
4. Basal 1/4K	132.2	147.3	162.1	173.2	192.3	221.6	133.2	124.7
6. Basal 1/4Mg	128.9	124.7	162.5	157.9	262.8	219.4	136.2	128.4
8. Basal 1/4Na	120.0	130.7	151.7	159.9	197.6	214.3	135.6	129.7
2. Basal 1/2Ca	124.4	131.3	168.8	155.2	225.5	220.9	139.9	126.9
5. Basal 1/2K	129.7	151.7	169.8	196.7	199.3	228.0	136.0	129.4
7. Basal 1/2Mg	134.3	136.0	169.4	173.8	304.1	230.4	139.1	125.9
9. Basal 1/2Na	133.7	126.9	165.9	139.5	194.7	208.6	131.4	127.4
10. Basal 1/2Ca 1/4K	139.2	148.8	167.9	171.6	188.8	146.8	139.0	134.4
13. Basal 1/2Ca 1/4Mg	147.2	146.3	160.4	160.3	200.9	226.5	126.8	124.0
16. Ba sal 1/2Ca 1/4Na	136.9	136.2	138.0	152.6	176.1	203.7	131.9	140.9
3. Basal 1Ca	136.4	129.5	169.9	152.1	242.3	222.8	148.6	126.9
11. Basal 1/2Ca 1/2K	142.5	146.1	189.2	164.3	192.6	234.9	135.4	130.7
14. Basal 1/2Ca 1/2Mg	147.3	150.6	156.2	157.2	199.8	232.5	140.5	134.3
17. Basal 1/2Ca 1/2Na	137.4	132.9	163.2	149.4	195.3	209.4	143.8	186.9
19. Basal 1/2Ca 1/4K 1/4Mg	133.7	143.6	188.9	181.5	243.2	204.4	140.0	189.9
12. Basal 1Ca 1/4K	152.0	145.8	193.4	178.9	189.1	228.1	-----	136.7
15. Basal 1Ca 1/4Mg	139.0	151.7	159.1	153.0	203.5	225.3	132.3	140.3
18. Basal 1Ca 1/4Na	143.6	120.8	164.3	144.4	196.2	199.0	138.6	191.4
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	142.7	134.4	184.2	149.8	185.2	219.0	143.1	177.9

TABLE 31. SUM OF CALCIUM, MAGNESIUM, POTASSIUM, AND SODIUM IN MILLIEQUIVALENTS PER 100 GM. DRY MATTER FOR EARLY AND LATE CUTTINGS.

Treatment	Putnam Soil 1939-40				Lindley Soil 1940-41	
	Bluegrass		Redtop		Korean lespedeza	
	Early	Late	Early	Late	Early	Late
1. Basal	164.7	111.5	171.7	135.6	150.3	113.8
4. Basal 1/4K	150.3	113.0	205.7	142.9	146.6	116.9
6. Basal 1/4Mg	142.8	113.4	175.2	151.0	147.5	121.3
8. Basal 1/4Na	139.6	100.6	173.1	133.4	156.4	120.5
2. Basal 1/2Ca	132.9	114.8	183.9	155.8	153.1	116.6
5. Basal 1/2K	142.6	116.0	205.5	145.8	148.5	123.0
7. Basal 1/2Mg	146.4	120.0	189.1	152.8	164.9	122.3
9. Basal 1/2Na	141.3	125.4	198.3	141.7	148.7	121.0
10. Basal 1/2Ca 1/4K	144.8	133.3	188.3	157.8	160.6	125.6
13. Basal 1/2Ca 1/4Mg	147.8	144.7	184.4	141.4	147.0	117.8
16. Basal 1/2Ca 1/4Na	151.3	121.7	141.2	135.1	185.7	129.1
3. Basal 1Ca	140.6	132.1	185.9	157.9	157.7	118.1
11. Basal 1/2Ca 1/2K	151.0	132.3	200.0	182.3	148.9	124.2
14. Basal 1/2Ca 1/2Mg	146.1	148.1	156.5	154.9	161.5	124.5
17. Basal 1/2Ca 1/2Na	135.2	139.4	141.6	175.2	183.9	181.5
19. Basal 1/2Ca 1/4K 1/4Mg	146.2	120.2	209.3	176.4	189.2	190.4
12. Basal 1Ca 1/4K	173.5	128.8	208.5	184.6	155.3	130.6
15. Basal 1Ca 1/4Mg	151.9	124.4	171.2	150.2	198.7	120.6
18. Basal 1Ca 1/4Na	145.0	141.2	145.5	173.7	210.0	182.8
20. Basal 1/2Ca 1/4K	150.3	134.6	191.5	180.2	186.6	175.2
1/4Mg 1/4Na	150.3	134.6	191.5	180.2	186.6	175.2

In comparing the early and late crops (Table 31) we find that in most cases the totals are lower for the late cuttings, although some

TABLE 32. NITROGEN PERCENTAGES OF EARLY AND LATE CROPS.

	Putnam Bluegrass		Putnam Redtop		Lindley Korean lespedeza	
Treatment	Early	Late	Early	Late	Early	Late
21. No treatment	-----	-----	-----	-----	4.00	2.87
1. Basal	4.46	3.55	4.68	4.01	3.93	2.03
4. Basal 1/4K	4.14	3.51	4.67	4.01	3.23	2.53
6. Basal 1/4Mg	4.07	3.61	4.44	4.23	3.59	2.59
8. Basal 1/4Na	4.36	3.79	5.01	4.53	3.82	2.53
2. Basal 1/2Ca	4.23	3.74	4.91	4.32	3.32	2.47
5. Basal 1/2K	4.19	3.40	4.79	3.99	3.41	2.70
7. Basal 1/2Mg	4.18	3.70	4.87	4.32	3.33	2.47
9. Basal 1/2Na	4.35	3.60	5.06	4.72	3.45	2.57
10. Basal 1/2Ca 1/4K	4.17	3.33	5.12	4.27	3.50	2.70
13. Basal 1/2Ca 1/4Mg	4.23	3.74	5.16	4.43	3.31	2.53
16. Basal 1/2Ca 1/4Na	4.41	3.66	5.29	4.69	3.66	2.75
3. Basal 1Ca	4.32	3.77	5.00	4.51	3.60	2.54
11. Basal 1/2Ca 1/2K	4.33	3.48	5.08	4.17	3.32	2.87
14. Basal 1/2Ca 1/2Mg	4.39	3.71	5.09	4.50	3.46	2.65
17. Basal 1/2Ca 1/2Na	4.37	3.71	5.52	4.55	3.80	2.63
19. Basal 1/2Ca 1/4K 1/4Mg	4.33	3.32	5.04	4.19	3.46	2.70
12. Basal 1Ca 1/4K	4.34	3.45	5.01	4.29	3.39	2.87
15. Basal 1Ca 1/4Mg	4.41	3.61	5.21	4.61	3.52	2.80
18. Basal 1Ca 1/4Na	4.32	3.62	5.42	4.68	3.78	2.70
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	4.40	3.55	5.25	4.45	3.65	2.63

exceptions are found. These occur chiefly at the higher base levels where sodium and calcium were added.

In general it would seem that the total cations vary in the same way as the total nitrogen, although when the figures are examined in detail it is seen that this generalization is subject to a number of exceptions. Nevertheless, there may be here a reflection of a similar generalization favored by Steward and Hoagland and their co-workers, namely that cationic uptake follows the general level of metabolic activity.

VII. THE CATIONS AS THEY AFFECT OTHER CONSTITUENTS IN THE PLANT

Nitrogen

As was pointed out earlier, the basal dressing used supplied phosphorus and nitrogen in the case of the grasses, but only phosphorus in that of the inoculated legumes. Nitrogen in solution was given to the grasses during the growing season. It is not surprising therefore that their nitrogen content should show little variation with treatment. The variations in the case of the two legumes are a little greater but there is still no apparent relation to the treatment. Some consistent differences in the behavior towards the two soils are seen in Table 33. The bluegrass grown on the Lindley soil in 1940-41 is richer in nitrogen than that grown on the Putnam in 1939-40, but the converse is true of the redtop, sweet clover and Korean lespedeza.

TABLE 33. (a) NITROGEN PERCENTAGES IN TOTAL CROPS.

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley	Korean lespedeza Putnam	Korean lespedeza Lindley
21. No treatment	---	3.90	---	3.89	---	---	---	3.18
1. Basal	4.01	4.53	4.36	4.05	4.62	4.54	3.05	2.56
4. Basal 1/4K	3.83	4.42	4.37	4.00	4.88	4.56	3.32	2.73
6. Basal 1/4Mg	3.84	4.42	4.35	4.11	4.23	4.66	3.42	2.85
8. Basal 1/4Na	4.08	4.49	4.76	4.26	5.09	4.86	3.51	2.86
2. Basal 1/2Ca	3.99	4.52	4.59	4.07	4.80	4.47	3.34	2.72
5. Basal 1/2K	3.80	4.39	4.36	4.03	4.66	4.54	3.99	2.87
7. Basal 1/2Mg	3.94	4.38	4.57	4.15	4,93	4.70	3.57	2.68
9. Basal 1/2Na	3.98	4.58	4.88	4.44	5.00	4.70	3.99	2.76
10. Basal 1/2Ca 1/4K	3.75	4.26	4.55	3.88	5.06	4.58	3.58	2.89
13. Basal 1/2Ca 1/4Mg	3.99	4.40	4.75	4.16	5.03	4.63	3.81	2.72
16. Basal 1/2Ca 1/4Na	4.04	4.51	4.91	4.26	4.98	4.80	4.17	2.94
3. Basal 1Ca	4.05	4.44	4.74	4.16	4.89	4.67	3.60	2.77
11. Basal 1/2Ca 1/2K	3.91	4.27	4.51	3.97	4.54	4.40	3.75	2.99
14. Basal 1/2Ca 1/2Mg	4.05	4.46	4.77	4.26	5.15	4.56	3.88	2.86
17. Basal 1/2Ca 1/2Na	4.04	4.58	4.90	4.32	4.90	4.69	4.09	2.82
19. Basal 1/2Ca 1/4K 1/4Mg	3.83	4.38	4.51	4.11	4.71	4.51	4.13	2.84
12. Basal 1Ca 1/4K	3.90	4.31	4.56	3.91	5.01	4.60	---	3.00
15. Basal 1Ca 1/4Mg	4.01	4.44	4.86	4.27	5.13	4.52	3.92	2.99
18. Basal 1Ca 1/4Na	3.97	4.59	4.95	4.43	4.86	4.58	4.11	2.94
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	3.98	4.42	4.75	4.30	4.64	4.27	3.91	2.84

TABLE 33. (b) NITROGEN CONTENT IN GRAMS OF TOTAL CROPS.

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley	Korean lespedeza Putnam	Korean lespedeza Lindley
21. No treatment	---	0.53	---	1.23	---	---	---	0.97
1. Basal	4.39	3.10	4.69	3.41	1.65	1.60	1.76	1.19
4. Basal 1/4K	3.91	3.37	4.74	3.63	3.21	2.08	2.07	1.66
6. Basal 1/4Mg	3.80	3.51	4.34	3.47	2.33	1.94	2.26	1.75
8. Basal 1/4Na	3.75	3.38	4.41	3.81	3.50	1.75	2.19	1.50
2. Basal 1/2Ca	3.30	3.09	4.32	3.48	3.27	1.78	2.18	1.66
5. Basal 1/2K	3.13	3.47	4.70	3.74	4.22	2.26	1.83	2.00
7. Basal 1/2Mg	3.56	3.62	4.35	3.59	3.44	1.84	2.57	1.92
9. Basal 1/2Na	2.87	3.21	4.57	3.93	3.64	1.74	1.82	1.63
10. Basal 1/2Ca 1/4K	3.24	3.42	4.99	3.81	4.88	2.30	2.68	2.05
13. Basal 1/2Ca 1/4Mg	3.83	3.22	4.45	3.69	3.81	1.98	2.82	1.80
16. Basal 1/2Ca 1/4Na	3.11	3.57	4.42	3.92	4.81	2.30	2.72	1.99
3. Basal 1Ca	3.47	3.51	4.95	3.54	4.06	2.11	2.33	1.97
11. Basal 1/2Ca 1/2K	3.55	3.68	4.80	3.72	4.82	2.35	2.51	2.29
14. Basal 1/2Ca 1/2Mg	4.07	3.22	4.59	3.77	4.48	2.02	2.78	1.95
17. Basal 1/2Ca 1/2Na	2.60	3.18	4.22	3.99	6.16	2.00	2.39	1.74
19. Basal 1/2Ca 1/4K 1/4Mg	3.05	3.58	5.67	4.11	5.08	2.65	2.47	1.89
12. Basal 1Ca 1/4K	3.84	3.58	5.40	3.69	6.14	2.46	---	2.20
15. Basal 1Ca 1/4Mg	4.04	3.12	4.61	3.79	4.97	2.37	2.83	1.85
18. Basal 1Ca 1/4Na	2.92	3.42	4.96	3.98	6.03	2.25	2.52	2.01
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	3.73	3.41	5.41	4.07	6.77	2.37	1.16	1.99

In comparing the early and late crops of bluegrass (1939-40), redtop (1939-40), and Korean lespedeza (1940-41), the early cuttings give consistently higher nitrogen contents than the late (Table 32). The

TABLE 34. PHOSPHORUS PERCENTAGES OF EARLY AND LATE CROPS.

Treatment	Bluegrass Early	Bluegrass Late	Redtop Early	Redtop Late	Korean lespedeza Early	Korean lespedeza Late
21. No treatment	---	---	---	---	.19	.21
1. Basal	.33	.19	---	.34	.28	.30
4. Basal 1/4K	.31	.19	---	.33	.27	.29
6. Basal 1/4Mg	.29	.24	---	.34	.28	.29
8. Basal 1/4Na	.32	.25	---	.35	.28	.28
2. Basal 1/2Ca	.30	.22	---	.31	.29	.29
5. Basal 1/2K	.32	.19	---	.33	.28	.28
7. Basal 1/2Mg	.29	.23	---	.33	.28	.28
9. Basal 1/2Na	.33	.28	---	.31	.27	.28
10. Basal 1/2Ca 1/4K	.30	.21	---	.32	.28	.28
13. Basal 1/2Ca 1/4Mg	.28	.23	---	.32	.26	.28
16. Basal 1/2Ca 1/4Na	.30	.24	---	.33	.26	.28
3. Basal 1Ca	.31	.24	---	.34	.29	.28
11. Basal 1/2Ca 1/2K	.30	.22	---	.29	.28	.29
14. Basal 1/2Ca 1/2Mg	.31	.25	---	.32	.27	.29
17. Basal 1/2Ca 1/2Na	.32	.32	---	.37	.26	.37
19. Basal 1/2Ca 1/4K 1/4Mg	.30	.24	---	.31	.25	.39
12. Basal 1Ca 1/4K	.28	.23	---	.30	.27	.29
15. Basal 1Ca 1/4Mg	.33	.25	---	.36	.27	.30
18. Basal 1Ca 1/4Na	.30	.24	---	.34	.26	.39
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.32	.25	---	.34	.27	.38

proportionate difference is most marked in the case of the lespedeza. This is not unexpected since as the season advanced the lespedeza was able to proceed, at least partially, to the flowering stage in spite of regular cutting. To a lesser extent, this was true of the grasses. The late cuttings, and in particular the last cutting of all, thus included some material which had reached a greater maturity than that typical of the early cuttings.

Phosphorus

What was said of nitrogen is true in very large measure of phosphorus. Apart from the controls (No. 21) with no additions whatsoever, the various treatments show little influence upon the phosphorus content. As regards the two soils the Lindley gives lower phosphorus figures than the Putnam. The difference is well marked in the case of the sweet clover, but it is much smaller and some exceptions are found with the bluegrass and lespedeza.

On comparing the early and late crops we find that the early bluegrass was considerably higher in phosphorus content than the late. A smaller difference in the opposite sense was shown by the lespedeza. Thus in the case of the early and late lespedeza the behavior of phosphorus is opposite from that of nitrogen.

TABLE 35. (a) PHOSPHORUS PERCENTAGES ON TOTAL CROPS,

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley	Korean lespedeza Putnam	Korean lespedeza Lindley
21. No treatment	---	.18	---	.43	---	---	---	.20
1. Basal	.26	.29	---	.38	.33	.29	.33	.30
4. Basal 1/4K	.25	.29	---	.36	.35	.29	.32	.28
6. Basal 1/4Mg	.27	.28	---	.38	.31	.28	.35	.28
8. Basal 1/4Na	.29	.30	---	.39	.35	.30	.38	.28
2. Basal 1/2Ca	.26	.29	---	.38	.33	.28	.34	.29
5. Basal 1/2K	.26	.28	---	.38	.31	.30	.39	.28
7. Basal 1/2Mg	.26	.28	---	.37	.34	.28	.35	.28
9. Basal 1/2Na	.31	.31	---	.39	.35	.29	.38	.27
10. Basal 1/2Ca 1/4K	.26	.31	---	.34	.30	.28	.35	.28
13. Basal 1/2Ca 1/4Mg	.26	.31	---	.35	.33	.27	.36	.28
16. Basal 1/2Ca 1/4Na	.27	.29	---	.36	.35	.25	---	.27
3. Basal 1Ca	.28	.28	---	.41	.35	.28	.35	.28
11. Basal 1/2Ca 1/2K	.26	.30	---	.32	.34	.28	.36	.29
14. Basal 1/2Ca 1/2Mg	.28	.27	---	.35	.36	.28	.36	.29
17. Basal 1/2Ca 1/2Na	.32	.28	---	.36	.37	.29	.35	.35
19. Basal 1/2Ca 1/4Mg 1/4Mg	.27	.27	---	.23	.32	.26	.32	.36
12. Basal 1Ca 1/4K	.26	.30	---	.32	.33	.29	---	.29
15. Basal 1Ca 1/4Mg	.29	.29	---	.38	.35	.29	.35	.30
18. Basal 1Ca 1/4Na	.27	.27	---	.37	.36	.27	.31	.36
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	.29	.28	---	.30	.35	.28	.31	.36

TABLE 35 (b) PHOSPHORUS CONTENT IN GRAMS OF TOTAL CROPS.

Treatment	Bluegrass Putnam	Bluegrass Lindley	Redtop Putnam	Redtop Lindley	Sweet clover Putnam	Sweet clover Lindley	Korean lespedeza Putnam	Korean lespedeza Lindley
21. No treatment	---	.025	---	.14	---	---	---	.06
1. Basal	.28	.20	---	.32	.12	.10	.19	.14
4. Basal 1/4K	.25	.22	---	.33	.23	.13	.20	.17
6. Basal 1/4Mg	.26	.22	---	.32	.17	.12	.23	.18
8. Basal 1/4Na	.26	.23	---	.35	.24	.11	.24	.15
2. Basal 1/2Ca	.21	.20	---	.33	.23	.11	.22	.18
5. Basal 1/2K	.20	.22	---	.36	.28	.15	.18	.20
7. Basal 1/2Mg	.23	.23	---	.32	.24	.11	.25	.20
9. Basal 1/2Na	.22	.22	---	.34	.25	.11	.17	.16
10. Basal 1/2Ca 1/4K	.22	.25	---	.33	.29	.14	.16	.20
13. Basal 1/2Ca 1/4Mg	.24	.23	---	.31	.25	.12	.27	.18
16. Basal 1/2Ca 1/4Na	.21	.23	---	.34	.34	.12	---	.19
3. Basal 1Ca	.23	.22	---	.34	.29	.13	.23	.20
11. Basal 1/2Ca 1/2K	.23	.26	---	.30	.36	.15	.24	.22
14. Basal 1/2Ca 1/2Mg	.28	.20	---	.31	.31	.13	.26	.20
17. Basal 1/2Ca 1/2Na	.21	.19	---	.33	.46	.12	.20	.22
19. Basal 1/2Ca 1/4K 1/4Mg	.22	.22	---	.21	.34	.15	.19	.24
12. Basal 1Ca 1/4K	.25	.24	---	.30	.40	.15	---	.21
15. Basal 1Ca 1/4Mg	.29	.20	---	.34	.34	.15	.25	.18
18. Basal 1Ca 1/4Na	.20	.20	---	.34	.45	.13	.19	.25
20. Basal 1/2Ca 1/4K 1/2Mg 1/4Na	.27	.21	---	.29	.51	.16	.09	.25

Silica

The analytical results for silica are incomplete but certain general conclusions can be drawn from the results presented in Table 36. It is clear that the two grasses can take up much larger amounts of silica than the legumes. The sweet clover shows very small silica percentages.

TABLE 36. SILICA PERCENTAGES ON TOTAL CROPS.

Treatment	Bluegrass Lindley	Redtop Putnam*	Redtop Lindley	Sweet clover Putnam	Korean lespedeza Putnam	Korean lespedeza Lindley*
21. No treatment	4.20	----	7.53	----	----	.85
1. Basal	2.05	1.70	3.49	.21	.44	.24
4. Basal 1/4K	2.38	1.76	3.18	.10	.22	.53
6. Basal 1/4Mg	1.72	.96	3.31	.19	.38	.68
8. Basal 1/4Na	2.14	.78	2.80	.12	.24	.68
2. Basal 1/2Ca	2.02	1.26	3.05	.15	.16	.16
5. Basal 1/2K	1.51	.97	2.84	.07	.14	.56
7. Basal 1/2Mg	1.16	.81	2.92	.14	.16	.53
9. Basal 1/2Na	1.73	.79	2.68	.13	.13	1.20
10. Basal 1/2Ca 1/4K	1.87	1.05	3.14	.09	.06	1.29
13. Basal 1/2Ca 1/4Mg	1.35	.74	2.84	.13	.16	.50
16. Basal 1/2Ca 1/4Na	1.97	.78	2.59	.07	.16	.31
3. Basal 1Ca	1.83	1.26	2.47	.08	.09	.86
11. Basal 1/2Ca 1/2K	1.50	1.03	2.46	.16	.16	.96
14. Basal 1/2Ca 1/2Mg	1.50	.85	2.40	.13	.14	.42
17. Basal 1/2Ca 1/2Na	1.66	.60	2.41	.08	.27	.42
19. Basal 1/2Ca 1/4K 1/4Mg	2.19	1.02	2.29	.03	.13	.63
12. Basal 1Ca 1/4K	1.35	1.09	2.37	.14	----	1.03
15. Basal 1Ca 1/4M g	1.50	.79	2.34	.11	.17	.46
18. Basal 1/2Ca 1/4Na	1.30	.75	2.28	.07	.23	.47
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Mg 1/4Na	1.32	.84	2.16	.04	.13	.39

*Late only.

As regards treatments, there is considerable irregularity in the results and because of difficulties in securing uniform conditions in the separation of plant silica from sand it is not certain where true significance lies. On the Lindley soil it is clear that the plants grown with no treatment whatsoever (No. 21) were very considerably higher in silica than those which had the basal dressing. Treatments with the various bases seem to cause on the average a lowering of silica content as the total base content rises.

The Lindley soil gives higher silica figures than the Putnam. This may be due in part to the greater acidity, since the bases added were underestimated as compared with the case of the Putnam soil.

VIII. THE CATIONS AS THEY AFFECT TOTAL YIELDS OF DRY MATTER

In tabulating the results for the two years and the four crops concerned (Tables 37 and 38) the treatments have been rearranged so as to show more readily the influence of calcium in presence and in absence of potassium, magnesium, and sodium. For each set of five pots comprising a given treatment with a single crop, the standard deviation has been calculated by the formula S. D. $= \sqrt{\frac{\Sigma d^2}{n-1}}$ and these values are tabulated alongside the yields per pot. These standard deviations show great variation, as would be expected and in order to determine whether a given difference in yield between two treatments is significant or not all the treatments for a given crop have been taken into consideration as follows: Five replications give four degrees of freedom within each set. If m is the number of sets (20 in 1939-40 and 21 in 1940-41), the total variance is given by $\sigma^2 = \frac{\Sigma d^2}{(n-1)\,m}$

The fiducial limits for 99% and for 95% probability have then been calculated using the respective formulae.

$$\text{(For 99\% probability) fiducial limit} = 3.355 \sqrt{\frac{2\sigma^2}{10}}$$

$$\text{(For 95\% probability) fiducial limit} = 2.306 \sqrt{\frac{2\sigma^2}{10}}$$

the constants 3.355 and 2.306 having been taken from R. A. Fisher's tables (8). This means for example, that if two treatments differ by more than the fiducial limit for 95% probability the chances are 19 to 1 that this difference is significant. Unfortunately the detailed greenhouse records for the 1939-40 bluegrass and redtop have been lost so that it is not possible to calculate the standard deviations or the fiducial limits. The results are discussed separately for each crop below.

Bluegrass

The 1939-40 series on the Putnam soil is notable for the fact that the basal treatment gave the highest yield by a significant margin. Calcium, potassium, magnesium, and sodium treatments all produced a depression, which for potassium, magnesium and sodium became greater as larger amounts were given. Sodium produces a very striking depression. Calcium sometimes slightly accentuates but more generally reduces these depressions of yield. Potassium and magnesium both reduce the depression caused by calcium alone but sodium further accentuates the calcium depression.

In the 1940-41 series using the Lindley soil the calcium, potassium, magnesium, and sodium treatments all gave significant increases

TABLE 37. AVERAGE YIELDS OF TOPS IN GRAMS PER POT AND STANDARD DEVIATIONS FOR CROPS GROWN ON PUTNAM SOIL (1939-40). TREATMENTS IN QUINTUPLICATE.

Treatment	Bluegrass Yield	Bluegrass S. D.	Redtop Yield	Redtop S. D.	Sweet clover Yield	Sweet clover S. D.	Korean lespedeza Yield	Korean lespedeza S. D.
1. Basal	22.28		21.50		7.13	.281	11.54	.395
2. Basal 1/2Ca	16.76		18.84		13.64	.558	13.05	.684
3. Basal 1Ca	17.42		20.90		16.59	1.780	12.94	1.123
4. Basal 1/4K	20.76		21.74		13.03	1.396	12.49	.873
5. Basal 1/2K	16.74		21.58		18.12	1.712	9.15	1.067
10. Basal 1/2Ca 1/4K	17.88		21.92		19.28	1.752	14.99	.431
11. Basal 1/2Ca 1/2K	18.84		21.32		21.36	1.555	13.39	.348
12. Basal 1Ca 1/4K	20.24		23.70		24.50	1.212	-----	------
6. Basal 1/4Mg	19.90		19.96		10.79	1.118	13.24	1.374
7. Basal 1/2Mg	18.20		19.04		13.92	.867	14.36	.811
13. Basal 1/2Ca 1/4Mg	19.48		18.74		15.15	.809	14.84	.312
14. Basal 1/2Ca 1/2Mg	20.48		19.28		17.40	1.039	14.33	.663
15. Basal 1Ca 1/4Mg	20.74		19.00		19.38	1.015	14.45	.671
8. Basal 1/4Na	18.76		18.52		13.76	.784	13.28	.567
9. Basal 1/2Ma	14.80		18.76		14.55	.658	11.43	.792
16. Basal 1/2Ca 1/4N 1/4Na	15.84		18.02		19.33	.452	13.06	.518
17. Basal 1/2Ca 1/2Na	13.10		17.24		25.15	.649	11.70	.880
18. Basal 1Ca 1/4Na	15.12		20.04		14.82	1.131	12.25	.793
19. Basal 1/2Ca 1/4K 1/4Mg	16.16		25.14		21.57	1.315	11.98	1.025
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	19.32		22.78		29.20	1.109	5.96	.636
Fiducial Limit 99%						1.337		.990
Fiducial Limit 95%						1.111		.767

(except the ½ Ca treatment), those of magnesium being the greatest. Calcium enhances the increases due to potassium, but diminishes those due to magnesium. The effect of calcium upon sodium is scarcely significant. The effect of potassium upon calcium is a further enhancement of yield. On the other hand, magnesium and sodium sometimes increase and sometimes decrease the yields due to calcium alone.

In comparing the results for the two soils it must be borne in mind that the bases added to the Lindley soil were much smaller in quantity both relatively and absolutely than in the case of the Putnam.

Redtop

In 1939-40, on the Putnam soil, calcium, magnesium, and sodium each produced a depression of yield whilst with potassium there was no significant change over the basal treatment. The effects of calcium upon potassium, magnesium and sodium were small. Potassium significantly increases the yields given by calcium treatments alone whilst magnesium and sodium have little effect. It is perhaps significant that the B.½Ca½Na treatment gives the lowest yields of any both for bluegrass and redtop.

TABLE 38. AVERAGE YIELDS OF TOPS IN GRAMS PER POT AND STANDARD DEVIATIONS FOR CROPS GROWN ON LINDLEY SOIL (1940-41). ALL TREATMENTS IN QUINTUPLICATE.

Treatment	Bluegrass Yield	Bluegrass S. D.	Redtop Yield	Redtop S. D.	Sweet clover Yield	Sweet clover S. D.	Korean lespedeza Yield	Korean lespedeza S. D.
21. No treatment	2.72	.285	6.11	.241	3.06	.436	6.11	.308
1. Basal	13.69	.578	16.85	.581	7.05	.745	9.28	.371
2. Basal 1/2Ca	13.48	.397	17.09	.410	7.98	.392	12.21	.353
3. Basal 1Ca	15.75	1.021	17.00	.369	9.57	.983	14.18	.281
4. Basal 1/4K	15.23	.783	18.17	.712	8.96	1.087	12.19	.980
5. Basal 1/2K	15.80	.300	18.57	.491	9.95	.824	13.97	.504
10. Basal 1/2Ca 1/4K	16.06	.925	19.62	.696	10.04	.636	14.41	1.389
11. Basal 1/2Ca 1/2K	17.23	.683	18.93	.891	10.69	.343	15.30	.511
12. Basal 1Ca 1/4K	16.60	.633	18.85	.839	10.70	.502	14.63	2.470
6. Basal 1/4Mg	15.86	.618	16.89	1.140	8.34	.186	12.31	.950
4. Basal 1/2Mg	16.53	.644	17.30	.547	7.82	.397	14.36	.795
13. Basal 1/2Ca 1/4Mg	14.62	.814	17.72	.529	8.53	.604	13.21	.506
14. Basal 1/2Ca 1/2Mg	14.92	1.920	17.70	.548	8.86	.591	13.66	.993
15. Basal 1Ca 1/4Mg	14.06	1.250	17.78	.441	10.06	.818	12.38	1.157
8. Basal 1/4Na	14.86	.693	17.50	1.430	7.22	.666	12.09	.985
9. Basal 1/2Na	14.02	1.035	17.72	1.000	7.40	.366	11.99	1.936
16. Basal 1/2Ca 1/4Na	15.84	.532	18.41	.460	9.55	.725	13.13	1.516
17. Basal 1/2Ca 1/2Na	13.82	.702	18.46	.874	7.55	1.395	12.38	1.195
18. Basal 1Ca 1/4Na	14.92	.409	17.95	.986	9.82	.370	12.73	1.307
19. Basal 1/2Ca 1/4K 1/4Mg	16.30	.855	18.65	1.417	11.75	.789	12.73	1.307
20. Basal 1/2Ca 1/4K 1/4Mg 1/4Na	15.44	.849	18.93	.547	11.10	.745	14.05	.521
Fiducial Limit 99%		1.115		1.054		.909		1.449
Fiducial Limit 95%		.863		.815		.704		1.121

In 1940-41 on the Lindley soil calcium, magnesium, and sodium singly caused no significant change in yield whilst potassium gave a small increase. Calcium additions slightly enhanced the increases due to potassium alone but had little effect in presence of magnesium or sodium. Potassium in presence of calcium caused a significant increase in yield, whereas magnesium had no appreciable effect and sodium gave only a small increase. The total range of variation in these comparisons was small; from 16.85 to 19.62.

Sweet clover

In discussing the results for the two legumes it must be remembered that the basal treatment contained no nitrogen. Hence the various treatments affected the yield in two ways; directly and also by increased nitrogen supply due to increased fixation. The gradations in yield are much more marked with sweet clover than with the grasses.

In 1939-40 on the Putnam soil applications of calcium and potassium gave notable increases in yield over the basal treatment, sodium somewhat smaller increases, and magnesium the least. The increases due to potassium, magnesium, and sodium were enhanced by calcium, the combination of sodium with calcium giving unusually high yields.

Potassium and sodium both strongly enhanced the yields obtained by calcium applications whilst the effect of magnesium was much smaller. The results as a whole strongly suggest that sweet clover thrives best on the alkaline side of the neutral point where it can tolerate relatively large proportions of exchangeable sodium in the soil.

In the 1940-41 series on the Lindley soil the neutral point was not reached in any treatment and the differences were less marked than in the Putnam series. Calcium, potassium, and magnesium added singly all produced significant yield increases over the basal treatment. Sodium gave an insignificant increase. The increases due to potassium, magnesium and sodium additions were all enhanced by calcium. The increases due to calcium were significantly enhanced by potassium and to a lesser extent by magnesium. The effect of sodium was variable.

Korean lespedeza

Like the sweet clover, this crop also was forced to rely on its own fixation of atmospheric nitrogen to provide sufficient for the higher yields.

On the Putnam soil in 1939-40 this crop showed itself to be considerably affected by treatments which caused deterioration of the soil structure. Treatment 12, failed entirely for this reason and 20 gave a very poor yield indeed. With respect to the bases taken singly this crop behaved quite differently from the sweet clover. The ½Ca, ¼K, ¼Mg and ¼Na treatments all gave significant increases over the basal treatment, but further additions diminished the yields significantly with potassium and sodium. Calcium increased the yields obtained by potassium additions alone and had no significant effect upon those afforded by the magnesium and sodium treatments. Potassium enhanced slightly the yields given by calcium treatments, magnesium had little effect upon them whilst sodium depressed the calcium yields.

In 1940-41 on the Lindley soil the following results are apparent. Calcium, potassium, magnesium and sodium all gave increased yields when compared with the basal treatment. Calcium enhanced the increases due to potassium and sodium, and had little effect on those due to magnesium. Potassium significantly increased the yields given by calcium alone whilst magnesium and sodium gave variable results.

IX. DISCUSSION

We have seen in examining the effects of the monovalent ions potassium and sodium upon the divalent ions present in the crop that the complementary ion principle does not play the predominant role. This is perhaps best shown in the case of the element magnesium, since here the proportion removed by the crop (around 5-10% where no magnesium was added) is intermediate between the smaller figures for strontium and calcium (1-2%) and the much larger losses of exchangeable potassium 70-90%). It is precisely in the intermediate region in which magnesium lies that a very marked complementary ion effect operates in the release of exchangeable magnesium from the soil, as Tables 3 and 4 very clearly show. From the sodium-treated soils much smaller quantities of magnesium are liberated by a 10% exchange against H than from those potassium-treated. Nevertheless, the magnesium contents of the crops grown are closely alike. We may conclude therefore that even though there is often a reduction in the content of divalent ions due to addition of monovalent, this does not prove that complementary ion effects predominate. The evidence of this present study cannot be said to constitute strict proof, but it is certainly much more in accord with a predominant uptake of nutrients by contact exchange between the soil colloid and the plant root than with a release of nutrients into the free soil solution and a subsequent absorption by the plant.

The case of the element manganese is also illuminating in considering possible mechanisms by which cationic nutrients move from the soil into the plant. We have already seen that the amount of exchangeable manganese liberated from the soil by neutral ammonium acetate varies considerably according to the pH of the soil and that complementary ion effects, in partial exchange against acid, can be detected but are subordinate to the pH factor. It was shown that the Putnam soil contained relatively small amounts of exchangeable manganese but that the acid used in partial exchange experiments brought much larger quantities into solution. On the other hand, the Lindley soil had a much greater content of exchangeable manganese and this showed only slight increase on acid treatment. The manganese content of the crops, however, followed very closely the relative amounts of manganese exchanged by ammonium acetate. This suggests a mechanism of contact exchange rather than a solution of manganese hydroxide by acid secretions from the roots. At any rate it would seem that if both mechanisms operate, then that of contact exchange greatly predominates.

To sum up, we now have clear evidence from the relative effects of potassium and sodium on the divalent ions strontium, calcium, and magnesium that a preponderance of these ions does not pass into the free and separable soil solution and that a direct passage from the ionic atmosphere of the soil colloids to the root best explains the results. This is further substantiated by considerations of the element manganese in its passage from the soil to the plant. There will, of course, always be some uptake of every nutrient from the free and separable soil solution. These conclusions are in no way contradictory to the general experience of plant physiologists who have worked with culture solutions or to the view that cationic uptake is a reflection of the general metabolic activity of the root (12, 13, 25). Indeed the fairly close parallelism in our experiments between the total cations and total nitrogen is entirely consistent with this modern view.

Nutritional characteristics of the four crops studied

We can best form an idea of the relative nutrient contents of the four crops by a qualitative comparison in which they are placed in order. We then arrive at the following series.

For phosphorus: Redtop > Sweet clover = Bluegrass = Korean lespedeza
For total cations: Sweet clover > Redtop > Bluegrass = Korean lespedeza
For strontium: Sweet clover > Korean lespedeza > Redtop > Bluegrass
For calcium: Sweet clover > Korean lespedeza > Redtop > Bluegrass
For magnesium: Sweet clover > Redtop > Bluegrass > Korean lespedeza
For manganese: Redtop > Bluegrass > Korean lespedeza = Sweet clover
For potassium: Redtop > Bluegrass = Sweet clover > Korean lespedeza
For sodium: Redtop > Sweet clover > Bluegrass > Korean lespedeza

As regards nitrogen, it must be remembered that this was applied as fertilizer to the grasses but not to the legumes. The Korean lespedeza was lower in nitrogen content than the sweet clover, the difference being particularly great in 1940-41 on the Lindley soil.

In the case of silicon, the grasses were very much higher than the legumes.

Of the two grasses redtop shows the greater variability in composition. As far as responses to bases go, under the conditions of this experiment the Putnam soil is not deficient. In fact the distinct depressions in yield caused by additions of bases call for some explanation. This does not lie in a decreased availability of phosphorus at the higher pH values, since N. C. Smith in the 1937-38 series (M.A. Thesis entitled "Calcium and Phosphorus as They Influence Growth and Composition of Some Pasture Forages"), showed this effect to be absent on the Putnam soil under similar conditions. The element which is strongly decreased in available quantity by addition of bases is manganese. It seems probable that this element has acted as a limiting factor at the higher pH values. On the Lindley soil this is not the case. Application of bases here increased the yields and there was always an adequate supply of exchangeable manganese. It will be noted that the two grasses need larger quantities of manganese than the legumes. The sweet clover on the Putnam soil does not show any sign of a limitation in yield but there are some indications of a manganese shortage with Korean lespedeza.

The special characteristics of Korean lespedeza have already been mentioned under the individual elements concerned but it is worthwhile to consider them together. This crop is remarkable chemically in several ways—it is a low sodium plant; it maintains a greater constancy of base ratios than the others; it is the lowest in nitrogen content (but not in phosphorus); it is lowest in magnesium but second highest in calcium and strontium; it is lowest in potassium content and does not attain "luxury" levels of consumption.

SUMMARY

1. A base exchange investigation of the two soils used, the Putnam silt loam and the Lindley silt loam, showed (a) that apart from differences in exchangeable Ca, Mg, Sr, K, and Na, the manganese reserves are differently distributed in the two soils. The Lindley has a large amount of exchangeable manganese and acids further liberate only moderate quantities. The Putnam has much less exchangeable manganese but relatively large amounts are liberated by acid treatment; (b) experiments on limited exchange against acid showed that sodium treatments produced a well marked complementary ion effect whereas potassium, magnesium and calcium treatments did not.

2. Analyses of the four crops grown, bluegrass, redtop, sweet clover, and Korean lespedeza gave the following general results.
   (a) The complementary ion principle does not, in general, seem to govern the uptake of the divalent ions strontium, calcium, and magnesium when the crops were grown on soils with potassium or sodium additions.
   (b) Uptake of manganese by the crops depended largely on the pH of the soil, and on the exchangeable manganese present.
   (c) Uptake of sodium and potassium was but little affected by additions of Ca or Mg to the soil, but sodium additions definitely increased the potassium in the crops.
   (d) The total cations per 100 gm. dry matter, calculated in equivalents, were relatively constant under various treatments. Such variations as were found agree qualitatively with similar variations in nitrogen content and somewhat less closely with variations in phosphorus.
   (e) As to the four crops, differences in uptake of the various elements were recorded. The Korean lespedeza was outstanding for its very low sodium content, which could not be increased to .06% even by sodium additions, and also for its relative constancy in regard to the other cations.

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APPENDIX A

Greenhouse Data

1939-40 series Putnam silt loam

Basal dressing added to each pot 3.0 grams of 38% superphosphate, equivalent to 857 pounds per acre of 2,000,000 pounds of soil. This is 0.50 gram P per pot.

Nitrogen was added to grasses in solution in six equal portions during growth. Total given was 4.2 gram of ammonium nitrate per pot (1.47 gram N), equivalent to 250 pounds of sodium nitrate per acre of 2,000,000 pounds of soil.

Tabulation of Greenhouse Procedure

Crop	*Sowing Date*	*Inoculation Date*	*Dates of successive cuttings*				
Bluegrass	Greenhouse data lost. Seven cuttings were made. First three combined as "early" crop, last four as "late".						
Redtop			Ditto				
			1	2	3	4	5
Sweet clover	Nov. 4	Dec. 4	Feb. 17,	Mar. 21,	Apr. 24,	May 31,	June 19
Korean lespedeza	Apr. 6	Apr. 6	June 12,	July 16,	Aug. 15		

In this series the calcium and magnesium carbonates were added in powdered form and the sodium and potassium bicarbonate in solution. The latter caused severe caking of the soil and after the pots had stood for some time it was necessary to remix each one before sowing. The failure of one lespedeza treatment was probably due largely to bad physical condition of the soil.

1940-41 series, Lindley silt loam

Basal dressing added to each pot (except those of No. 21, no treatment) 3.0 grams of 38% superphosphate, equivalent to 857 pounds per acre of 2,000,000 pounds soil. This is 0.50 gram P per pot.

Nitrogen was added to grasses in solution during growth in five equal portions, each of 0.5 gram ammonium nitrate per pot. The total is 2.5 grams ammonium nitrate per pot (0.875 gram N), equivalent to 1520 pounds sodium nitrate per acre of 2,000,000 pounds.

Tabulation of Greenhouse Data

Crop	Sowing Date	Inoculation Date	1	2	3	4	5
			Dates of successive cuttings				
Bluegrass	Oct. 21	......	Jan. 18,	Feb. 27,	Mar. 27,	Apr. 27,	May 17
Redtop	Oct. 22	......	Jan. 17,	Mar. 1,	Mar. 27,	Apr. 25,	May 17
Sweet clover	Oct. 22	Nov. 6	Jan. 14,	Mar. 15,	Apr. 18,	May 28	
Korean lespedeza	Dec. 2	Dec. 2	Jan. 25, (Early)	Mar. 15 (Early)	April 21, (Late)	May 29 (Late)	

The Korean lespedeza was given artificial illumination to supplement daylight, since otherwise the seedlings commence to bloom while still small and vegetative growth is retarded. The equivalent of 15 hours total daylight was thus provided and no difficulty was found with premature blooming.

In this series the carbonates or bicarbonates were mixed with air-dry soil first and then this was thoroughly incorporated with the soil for each pot, using a rotary churn.

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