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## THE EXCHANGE OF IONS BETWEEN THE ROOTS OF LUPINUS ALBUS AND CULTURE SOLUTIONS CONTAINING TWO NUTRIENT SALTS<sup>1</sup>

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It has been shown by the authors in a former paper<sup>2</sup> that in un-mixed dilute solutions of the common nutrient salts seedlings of *Lupinus albus* respond differently to different salts with respect to absorption. Calcium salts are absorbed from solutions of all dilutions tested, as indicated by the clearly marked decrease in the electrical conductivity of these solutions during the life of the seedlings grown in them. Magnesium salts are absorbed in a slight degree and only from solutions of a markedly limited range of concentration. Potassium salts either behave like distilled water and cause a loss of electrolytes at all dilutions, as in the cases of  $\text{KH}_2\text{PO}_4$  and  $\text{KCl}$ , or permit only a minimal absorption phase to come to expression in the more favorable concentrations, as in solutions of  $\text{K}_2\text{SO}_4$  and  $\text{KNO}_3$ . It seems that a predominating influence is exerted by the kations; calcium, magnesium or potassium action being clearly marked whatever the accompanying anion may be. The anions, however, are not without significance in relation to absorption.

In this investigation the same test plant, *Lupinus albus* L., was exposed to solutions containing mixtures of the nitrates of Ca, Mg and K in pairs in different proportions and in different total concentrations. The more concentrated members of the series approached in total salt content the soil solution as it is likely to be found in the vicinity of

<sup>1</sup> Published by permission of the Secretary of Agriculture.

<sup>2</sup> True, R. H., and Bartlett, H. H. The exchange of ions between the roots of *Lupinus albus* and culture solutions containing one nutrient salt. Amer. Journ. Bot. 2: 255-278. 1915.



Washington, D. C. This paper therefore deals primarily with the physiological interactions sometimes called antagonisms,<sup>3</sup> as these come to expression in modifying root absorption. It was intended by the use of mixtures of the same salt of several bases to get a comparative expression of the effect of the different combinations of kations concerned.

### METHODS

The methods used have been described elsewhere,<sup>2, 4</sup> and the reader is referred to the details there given. The sole change involved in the investigation reported in the present paper lies in the fact that the solutions contained mixtures of salts in pairs.

### EXPERIMENTAL RESULTS

#### *Calcium Nitrate and Potassium Nitrate. Experiment 1*

It was proposed in this experiment to ascertain the effect of calcium and potassium ions in the presence of the common anion,  $\text{NO}_3^-$ , on the absorption or excretion of electrolytes.

Four groups of solutions were prepared, each of which consisted of five chemically equivalent solutions, grading by fourths from pure  $\text{Ca}(\text{NO}_3)_2$  to pure  $\text{KNO}_3$ , as follows:

1.  $\frac{4}{4} \text{Ca}(\text{NO}_3)_2$ . Ratio of kations to anions,  $4 \text{Ca}^{++} : 8 \text{NO}_3^-$ .
2.  $\frac{3}{4} \text{Ca}(\text{NO}_3)_2 + \frac{1}{4} \text{KNO}_3$ . Ratio of kations to anions,  $3 \text{Ca}^{++} + 2\text{K}^+ : 8 \text{NO}_3^-$ .
3.  $\frac{2}{4} \text{Ca}(\text{NO}_3)_2 + \frac{2}{4} \text{KNO}_3$ . Ratio of kations to anions,  $2 \text{Ca}^{++} + 4 \text{K}^+ : 8 \text{NO}_3^-$ .
4.  $\frac{1}{4} \text{Ca}(\text{NO}_3)_2 + \frac{3}{4} \text{KNO}_3$ . Ratio of kations to anions,  $1 \text{Ca}^{++} + 6 \text{K}^+ : 8 \text{NO}_3^-$ .
5.  $\frac{4}{4} \text{KNO}_3$ . Ratio of kations to anions,  $8 \text{K}^+ : 8 \text{NO}_3^-$ .

Thus, each member of a group had the same  $\text{NO}_3^-$  concentration and approximately the same electrical conductivity. Disregarding valence, the ratios of kations to anions in the five solutions of each group formed the series 4 : 8, 5 : 8, 6 : 8, 7 : 8, and 8 : 8. The four

<sup>3</sup> True, R. H. Antagonism and Balanced Solutions. *Science*, n. s. 41: 653-656. 1915.

<sup>4</sup> True, R. H., and Bartlett, H. H. Absorption and Excretion of Salts by Roots, as Influenced by Concentration and Composition of Culture Solutions. I. Concentration Relations of Dilute Solutions of Calcium and Magnesium Nitrates to Pea Roots. U. S. Department of Agriculture, Bureau of Plant Industry, Bull. 231, 1912.



groups themselves formed a series ranging by intervals of  $120 \text{ N} \times 10^{-6}$  from 120 to  $480 \text{ N} \times 10^{-6}$ . In addition to the twenty salt solutions, there was a check culture in distilled water.

In figure 1 the daily concentration of each member of the four groups of solutions is shown for a total experimental period of 16 days. On the horizontal axis the unit is one day. The original total salt concentration of any solution in terms of gram equivalents per million liters is given at the left on the perpendicular axis. An increase in concentration of a solution during the experiment is therefore indicated by an upward trend of the curves; a decrease by the converse. The changes in concentration of the five solutions belonging to each group are of course indicated by a family of curves departing from the same point on the axis of ordinates. The course of the concentration changes taking place in the distilled water check is indicated by a curve starting at 0 on the axis of ordinates and covering about 12 days prior to the onset of changes attributed to exhaustion of the plants.

In the  $120 \text{ N} \times 10^{-6}$  group of solutions all members seemed to gain ions during the first two days. This apparent loss of electrolytes

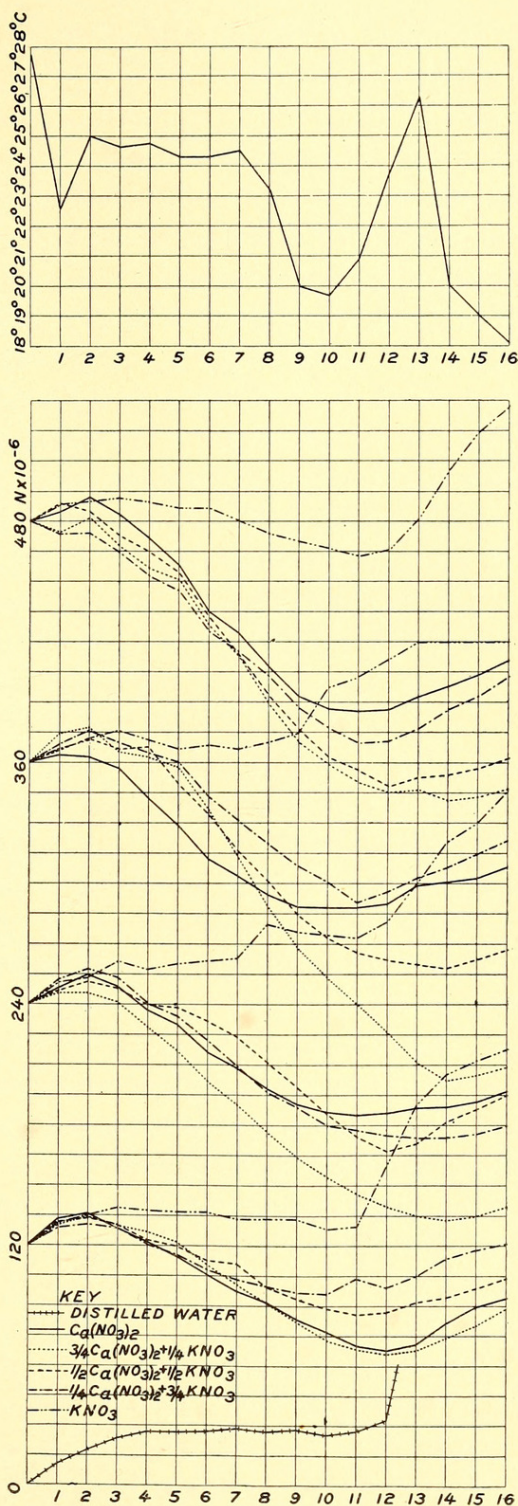


FIG. 1. Curves showing the change in concentration of the  $\text{Ca}(\text{NO}_3)_2$  and  $\text{KNO}_3$  solutions used in experiment I.



on the part of the plants was probably due in a large measure to the gradual saturation of the solution with  $\text{CO}_2$  from the living roots rather than to the loss of salts.<sup>5</sup> The plants in the  $\text{KNO}_3$  solution lost electrolytes at a rather regular rate until the 11th day when probably through exhaustion or injury the roots began to give up ions rapidly, a course continued during the five remaining days of the experimental period. This course was closely paralleled by the plants grown in the control culture in distilled water. The plants in the  $\text{Ca}(\text{NO}_3)_2$  solution began to absorb fairly rapidly on the third day and continued to do so at a relatively uniform rate for the next ten days. At that turning point, the plants began to give up ions more rapidly than they absorbed them and continued to do so at a relative uniform rate until the close of the experiment. All mixtures in this group were more favorable for absorption than  $\text{KNO}_3$  alone. When the solution contained  $\frac{3}{4} \text{Ca}(\text{NO}_3)_2 + \frac{1}{4} \text{KNO}_3$  the result differed but little from that seen in the pure  $\text{Ca}(\text{NO}_3)_2$  solution. In the solution containing  $\frac{2}{4} \text{Ca}(\text{NO}_3)_2 + \frac{2}{4} \text{KNO}_3$  a clear decrease in absorption took place. When  $\frac{1}{4} \text{Ca}(\text{NO}_3)_2 + \frac{3}{4} \text{KNO}_3$  was offered the favorable action of the small quantity of Ca salt so greatly outweighed in its influence the larger quantity of  $\text{KNO}_3$  present that a marked net absorption was seen although it was less than in all other mixtures of this total concentration. The most favorable mixture was that containing  $\frac{3}{4} \text{Ca}(\text{NO}_3)_2 + \frac{1}{4} \text{KNO}_3$ .

In the group having a total concentration of  $240 \text{ N} \times 10^{-6}$  a very similar situation was found in the solutions of the pure salts. In  $\text{KNO}_3$  the plants lost electrolytes at all stages of the experiment, rather slowly and regularly for the first week, more rapidly in the immediately succeeding days and very rapidly after the 11th day. In respect to absorption the  $\text{KNO}_3$  solution was obviously again in the same class as distilled water. In the  $\text{Ca}(\text{NO}_3)_2$  solution, after the usual preliminary period of stand-still, absorption set in and continued to the end of the experiment, a somewhat greater total absorption being seen than in the weaker solution of the same salt in the  $120 \text{ N} \times 10^{-6}$  group. In the mixed solutions the favorable influence of combining calcium with potassium was strikingly seen. In all proportions of these kations the excess of absorption over loss was greater after the 9th day than in the pure calcium nitrate solution, although potassium nitrate in a pure condition was itself detrimental to the absorption

<sup>5</sup> For a full discussion of this point see Amer. Jour. Bot. 2: 259. 1915.



process. The greatest net absorption was seen after the 13th day in the mixture containing  $3/4 \text{ Ca(NO}_3)_2 + 1/4 \text{ KNO}_3$ , from which the total amount of ions absorbed was approximately double that taken out of  $4/4 \text{ Ca(NO}_3)_2$  solution. Absorption from the solution containing equal proportions of the two salts lagged slightly behind that from the full calcium solution during the first ten days but during the succeeding six days exceeded it. A somewhat similar record was made in the solution containing  $1/4 \text{ Ca(NO}_3)_2 + 3/4 \text{ KNO}_3$ . The plants in this mixture absorbed for the first ten days practically as they did in the full  $\text{Ca(NO}_3)_2$  solution but showed a marked gain in the latter part of the period. Although the roots could not maintain a balance in favor of absorption when grown in a solution of pure  $\text{KNO}_3$ , nevertheless this salt greatly facilitated absorption when it was mixed with  $\text{Ca(NO}_3)_2$ . It also appears clear that a small proportion of  $\text{Ca(NO}_3)_2$  is able to give to a mixture containing a large proportion of  $\text{KNO}_3$  such properties as enable the roots to maintain active absorption. In the  $240 \text{ N} \times 10^{-6}$  group of solutions the mutually helpful influence of Ca and K ions in respect to absorption comes sharply to the front.

In the third group of solutions each member had a total salt concentration of  $360 \text{ N} \times 10^{-6}$ . The effects on root absorption were in general like those seen in the last group. The increase of total salt content, however, seemed to cause an increased absorption of ions from all solutions. Although in the  $\text{KNO}_3$  solution a net gain in ions by the plant was not indicated at any time, there was an absorption phase between the third and eighth days, succeeded by the usual period of loss during the remainder of the experiment. In the  $4/4 \text{ Ca(NO}_3)_2$  solution root absorption was greater than in the less concentrated solutions of this salt. The maximum reduction in the concentration of the solution, attained during the period from the ninth to the twelfth day, was over  $72 \text{ N} \times 10^{-6}$ . The greatly increased absorption in the mixture containing  $3/4 \text{ Ca(NO}_3)_2$  to  $1/4 \text{ KNO}_3$  was very striking, the maximum quantity of electrolytes gained by the plants prior to the fourteenth day being indicated by a change of about  $158 \text{ N} \times 10^{-6}$  in the concentration of the culture solution, *i. e.*, over double that gained from the pure solution of  $\text{Ca(NO}_3)_2$ . In the solution containing  $2/4 \text{ Ca(NO}_3)_2 + 2/4 \text{ KNO}_3$  the maximum absorption was reached about the fourteenth day and caused a reduction of about  $102 \text{ N} \times 10^{-6}$  in the concentration of the culture solution, a markedly greater absorption than that from the  $4/4 \text{ Ca(NO}_3)_2$  solution.



From the solution containing  $1/4 \text{ Ca(NO}_3)_2 + 3/4 \text{ KNO}_3$  there was somewhat less absorption than from the  $4/4 \text{ Ca(NO}_3)_2$  solution.

In the group of strongest solutions, with a total salt concentration of  $480 \text{ N} \times 10^{-6}$ , a further general increase in the rate of absorption was seen. Absorption in the mixtures increased as the calcium content increased, all being more favorable for absorption than the check in  $4/4 \text{ Ca(NO}_3)_2$  solution. A clearly marked absorption phase was seen for the first time in the solution of  $\text{KNO}_3$ . This was probably due to the concentration factor, as has been indicated in a former study<sup>6</sup> of absorption in  $\text{KNO}_3$  solutions.

The most striking results of this experiment may be summarized briefly as follows:

1. Root absorption from dilute solutions of  $\text{Ca(NO}_3)_2$ , of  $\text{KNO}_3$ , and of mixtures of these in a graded series increased in general with the increase of concentration from 120 to  $480 \text{ N} \times 10^{-6}$ . Except in the highest concentration tested the plants lost more electrolytes in  $\text{KNO}_3$  solutions than they absorbed and in the highest concentration the net gain of ions was small. Calcium nitrate in all concentrations supported an active absorption. It seems clear that in the series of concentrations here studied the ratio of Ca ions to K ions most favorable to the process of absorption is  $3 \text{ Ca}^{++}$  to  $2 \text{ K}^+$  ( $3/4 \text{ Ca(NO}_3)_2 + 1/4 \text{ KNO}_3$ ). In every group except that having the lowest total concentration there was greater absorption from mixtures in all proportions than from solutions of either of the component salts in a pure state.

In the solutions having the lowest concentration, it is likely that the small quantity of salts present was the limiting factor, it being perhaps insufficient to satisfy the necessary demands of the plant.

#### *Calcium Nitrate and Magnesium Nitrate. Experiment 2*

It was next desired to test the activity of root absorption in solutions of calcium and magnesium nitrates. Accordingly four groups of solutions were prepared having a total salt content of 120, 240, 360, and  $480 \text{ N} \times 10^{-6}$ , respectively, each group consisting of the following numbers:  $4/4 \text{ Ca(NO}_3)_2$ ,  $2/4 \text{ Ca(NO}_3)_2 + 2/4 \text{ Mg(NO}_3)_2$ ,  $1/4 \text{ Ca(NO}_3)_2 + 3/4 \text{ Mg(NO}_3)_2$ ,  $1/10 \text{ Ca(NO}_3)_2 + 9/10 \text{ Mg(NO}_3)_2$ , and  $4/4 \text{ Mg(NO}_3)_2$ . As before, each solution received four seedlings and concentration changes were followed by means of a daily reading of

<sup>6</sup> Amer. Journ. Bot. 2: 1915.



the electrical conductivity. The daily concentration of each solution during the experimental period of 19 days is shown in figure 2.

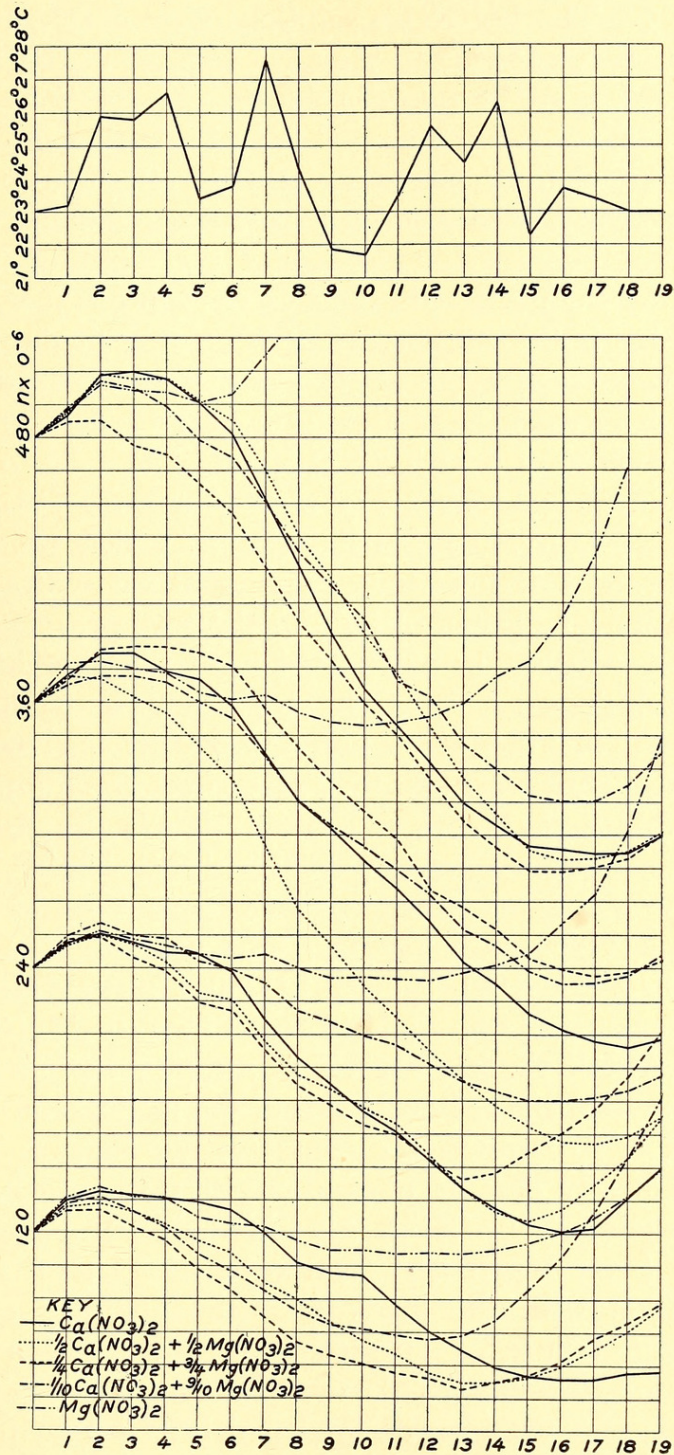


FIG. 2. Curves showing the change in concentration of the  $\text{Ca}(\text{NO}_3)_2$  and  $\text{Mg}(\text{NO}_3)_2$  solutions used in experiment 2.



In this series of cultures it was again noted that in general absorption increased with the increasing total salt concentration, although not proportionately. The  $\text{Mg}(\text{NO}_3)_2$  solutions were an exception to this otherwise general rule, owing to the great toxicity of this salt.

In the  $120 \text{ N} \times 10^{-6}$  group of solutions the solutions gained ions for a period of two or three days. It is probable that in both the Mg and the Ca solutions there was some excretion of salts from the plants, since nearly a week passed before this loss was made up, whereas the smaller apparent loss seen in the case of the mixtures might all be accounted for by the increase in the  $\text{CO}_2$  content of the solutions. It will be noted that in the solution of  $\text{Ca}(\text{NO}_3)_2$  after the initial period of about two days marked by an active loss of ions, absorption began to take place with increasing rapidity until near the end of the experiment a net decrease of nearly  $90 \text{ N} \times 10^{-6}$  had taken place in the concentration of the solution. The record for  $\text{Mg}(\text{NO}_3)_2$  was similar to that for  $\text{Ca}(\text{NO}_3)_2$  for seven days after, which time absorption slackened and the solution stood at equilibrium with a small net absorption until near the end of the experimental period, when loss of salts from the roots set in and lasted until the experiment closed. In all mixed solutions a more active absorption was made during the first 12 days than in either of the unmixed solutions. It will be noted that the greatest net absorption took place from the solution containing  $1/4 \text{ Ca}(\text{NO}_3)_2 + 3/4 \text{ Mg}(\text{NO}_3)_2$  although late in the experiment the plants in that containing  $2/4 \text{ Ca}(\text{NO}_3)_2 + 2/4 \text{ Mg}(\text{NO}_3)_2$  reached practically the same maximum, exceeding that made in the  $4/4 \text{ Ca}(\text{NO}_3)_2$  by a very small margin. The solution containing  $1/10 \text{ Ca}(\text{NO}_3)_2 + 9/10 \text{ Mg}(\text{NO}_3)_2$  showed a loss in concentration of over  $60 \text{ N} \times 10^{-6}$  against about  $12 \text{ N} \times 10^{-6}$  for  $10/10 \text{ Mg}(\text{NO}_3)_2$ . The net absorption from the  $4/4 \text{ Mg}(\text{NO}_3)_2$  solution was multiplied five times by the replacement of one-tenth of the magnesium by calcium. In the  $240 \text{ N} \times 10^{-6}$  group the characteristic features are: (1) the increased and nearly parallel absorption for thirteen days from the solutions containing  $4/4 \text{ Ca}(\text{NO}_3)_2$ ,  $2/4 \text{ Ca}(\text{NO}_3)_2 + 2/4 \text{ Mg}(\text{NO}_3)_2$ , and  $1/4 \text{ Ca}(\text{NO}_3)_2 + 3/4 \text{ Mg}(\text{NO}_3)_2$ ; (2) the lengthening of the period of active absorption with the increase of the quantity of  $\text{Ca}(\text{NO}_3)_2$  present; (3) the failure of absorption in the solution containing  $1/10 \text{ Ca}(\text{NO}_3)_2 + 9/10 \text{ Mg}(\text{NO}_3)_2$  to keep its place relative to the other mixtures; and the long delayed and brief period of slight net absorption from the solution containing  $4/4 \text{ Mg}(\text{NO}_3)_2$ .



In the group having a total salt concentration of  $360 \text{ N} \times 10^{-6}$  the introductory period during which the solutions gained ions was strongly marked in all solutions except that containing  $2/4 \text{ Ca(NO}_3)_2 + 2/4 \text{ Mg(NO}_3)_2$ . In that solution net absorption became evident more quickly than in the other members of the group and the lead was held throughout the experiment. The net change in concentration of the solution containing  $4/4 \text{ Ca(NO}_3)_2$  amounted to over  $150 \text{ N} \times 10^{-6}$  a change exceeded only in the most favorable mixture, that containing  $2/4 \text{ Ca(NO}_3)_2 + 2/4 \text{ Mg(NO}_3)_2$ . In this mixture the absorption corresponded to a change in concentration of about  $200 \text{ N} \times 10^{-6}$  by the 17th day. The absorption from mixtures containing smaller proportions of  $\text{Ca(NO}_3)_2$  was less than that from  $4/4 \text{ Ca(NO}_3)_2$  solution. The  $\text{Mg(NO}_3)_2$  solution showed the same features as heretofore.

In the group having a total salt concentration of  $480 \text{ N} \times 10^{-6}$  it will be noted that in general the courses of all curves representing calcium-containing solutions agreed more closely than in the more dilute solutions, even that containing but  $1/10 \text{ Ca(NO}_3)_2$  to  $9/10 \text{ Mg(NO}_3)_2$  acting relatively more favorably than in the less concentrated solutions. Apparently the mixtures were approaching a situation in which the Ca demand was satisfied even in those containing the smaller proportions of this ion. In the  $4/4 \text{ Ca(NO}_3)_2$  solution the maximum net absorption was attained as heretofore near the end of the experimental period. By the 18th day the concentration of the solution had diminished about  $185 \text{ N} \times 10^{-6}$ . The most favorable mixture was that containing  $1/4 \text{ Ca(NO}_3)_2 + 3/4 \text{ Mg(NO}_3)_2$  from which the net absorption on the 15th day corresponded to a drop in concentration of about  $200 \text{ N} \times 10^{-6}$ . It is clear that a toxic concentration of  $4/4 \text{ Mg(NO}_3)_2$  had been reached since at the end of six days very marked leaching began, and at no time was there a net absorption.

Looking at this experiment as a whole a number of features attract attention. The contrast between  $\text{Ca(NO}_3)_2$  and  $\text{Mg(NO}_3)_2$  in regard to their influence on root absorption is very marked. The calcium salt favored this process in all concentrations here tested. Magnesium nitrate in no case supports more than a slight net absorption in the most favorable concentrations, and the poisonous action of the Mg ion promptly appeared at a concentration between  $360$  and  $480 \text{ N} \times 10^{-6}$ . All mixtures with  $\text{Ca(NO}_3)_2$  in all proportions were more freely absorbed than  $\text{Mg(NO}_3)_2$  alone. The solutions most



favorable for absorption contained  $2/4$  or  $1/4$   $\text{Ca}(\text{NO}_3)_2$ . Although much less favorable for absorption than the solutions containing higher proportions of calcium nitrate, the solution containing but  $1/10$   $\text{Ca}(\text{NO}_3)_2$  to  $9/10$   $\text{Mg}(\text{NO}_3)_2$  was incomparably better than that containing  $10/10$   $\text{Mg}(\text{NO}_3)_2$ . In its effect upon absorption, as upon root growth, a small amount of calcium has an effect all out of proportion to the quantity actually present.

*Magnesium Nitrate and Potassium Nitrate. Experiment 3*

In this experiment, as before, four groups of solutions were made up having a total salt content of 120, 240, 360, and  $480 \text{ N} \times 10^{-6}$ , respectively, each group containing solutions of the salts in the following proportions:  $4/4$   $\text{Mg}(\text{NO}_3)_2$ ,  $3/4$   $\text{Mg}(\text{NO}_3)_2 + 1/4$   $\text{KNO}_3$ ,  $2/4$   $\text{Mg}(\text{NO}_3)_2 + 2/4$   $\text{KNO}_3$ ,  $1/4$   $\text{Mg}(\text{NO}_3)_2 + 3/4$   $\text{KNO}_3$  and  $4/4$   $\text{KNO}_3$ . As in experiment 1 the anion concentration was the same for the five solutions of each group. Since in the mixtures an ion with a valence of two had to be replaced by two ions with a valence of 1, the ratios of kations to anions formed the series 4 : 8, 5 : 8, 6 : 8, 7 : 8, and 8 : 8. The electrolytic conductivity of each solution was observed daily during an experimental period of 14 days.

In the series of curves shown in figure 3 a number of novel features appear. The very general tendency of the root absorption to increase with the increase of the total salt concentration, so clearly seen in the foregoing experiments, is here absent. The best absorption in  $4/4$   $\text{Mg}(\text{NO}_3)_2$  took place in the weak  $120 \text{ N} \times 10^{-6}$  solution, although the  $240 \text{ N} \times 10^{-6}$  solution was nearly as good. In the higher concentrations injury appeared only a few days after the experiment was begun as was indicated by a rapid loss of ions by the plants.

The best absorption in  $4/4$   $\text{KNO}_3$  was seen in the strongest solution where a distinct though brief net absorption phase lasted from the 6th to 8th days. A minimal net absorption was seen in the  $320 \text{ N} \times 10^{-6}$  solution on the 7th day. In the weaker solutions there was no net absorption. The greatest loss of salts by the plants occurred in the weakest solution.

The roots made a net absorption in every mixture of whatever proportion or concentration. Among the mixtures with a total salt concentration of  $120 \text{ N} \times 10^{-6}$  none showed as great absorption as the  $4/4$   $\text{Mg}(\text{NO}_3)_2$  solution. The roots showed a decreased absorption as the proportion of  $\text{Mg}(\text{NO}_3)_2$  was reduced. In the mixtures having



a total concentration of  $240 \text{ N} \times 10^{-6}$  the best absorption took place in that containing  $3/4 \text{ Mg}(\text{NO}_3)_2 + \text{KNO}_3$ . Nearly as favorable was  $1/4 \text{ Mg}(\text{NO}_3)_2 + 3/4 \text{ KNO}_3$ . These were both decidedly better than the pure  $\text{Mg}(\text{NO}_3)_2$  solution. The greater loss of ions by roots in the mixture containing equal parts of the two salts is believed to be an aberrant result due perhaps to the use of less vigorous roots than those usually employed. Roots growing in mixtures having a total concentration of  $360 \text{ N} \times 10^{-6}$  in every case absorbed more freely than from either of the unmixed solutions of the components. The  $4/4 \text{ Mg}(\text{NO}_3)_2$  solution was clearly toxic while in  $4/4 \text{ KNO}_3$  the plants even at the height of the absorption phase were hardly able to recover a quantity of electrolytes equal to that previously lost. In all the mixtures a marked net absorption took place although it was somewhat less than in the case of the  $240 \text{ N} \times 10^{-6}$  mixtures. The advantage seemed to lie with the solutions containing the lesser proportions of  $\text{Mg}(\text{NO}_3)_2$ .

In the group of solutions having a total salt content of  $480 \text{ N} \times 10^{-6}$  the harmful action of  $4/4 \text{ Mg}(\text{NO}_3)_2$  and of the mixture containing  $3/4 \text{ Mg}(\text{NO}_3)_2$  was clearly marked on the 7th day. The higher concentration of the  $4/4 \text{ KNO}_3$  solution seemed nevertheless to be more favorable to absorption than any of the lower concentrations, for a slight but undoubted net absorption of ions took place during the first

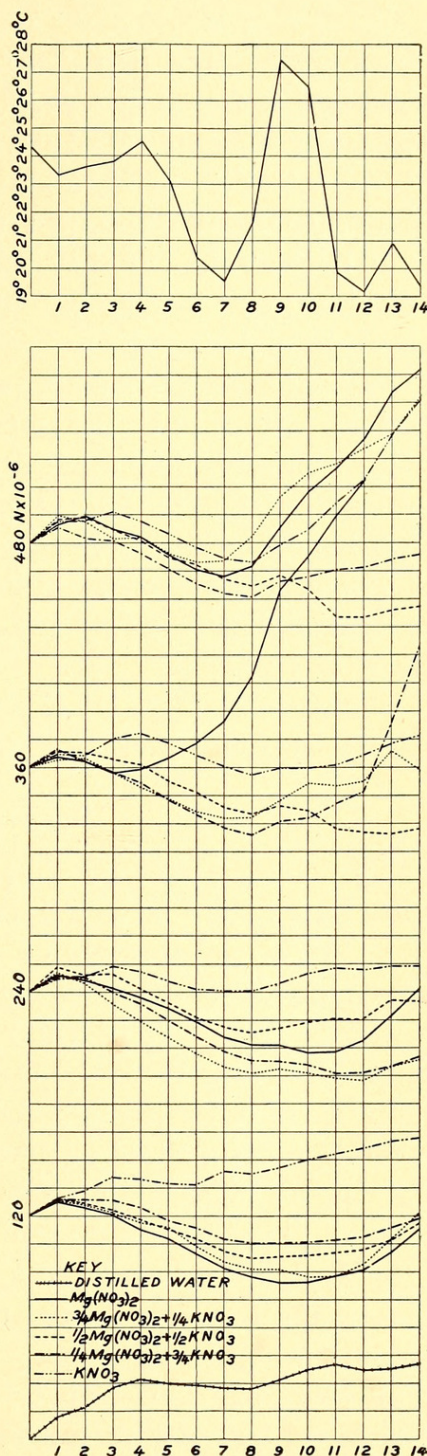


FIG. 3. Curves showing the change in concentration of the  $\text{Mg}(\text{NO}_3)_2$  and  $\text{KNO}_3$  solutions used in experiment 3.



week. After this period a rapid loss of ions by the plant set in. A marked and well sustained net absorption was seen in the mixtures containing  $2/4$  and  $1/4$   $\text{Mg}(\text{NO}_3)_2$ , respectively, the maximum change in concentration being about  $40 \text{ N} \times 10^{-6}$  on the 11th day in the solution containing equal parts of the two salts.

It is clear that of this pair of kations  $\text{Mg}^{++}$  is more favorable to root absorption in the concentrations here used than  $\text{K}^+$ . But for its relatively high degree of toxicity, which restricts life to a narrow range of concentrations, magnesium would bear a certain resemblance to calcium. Here as before potassium brings about a loss of ions by the plant. Nevertheless mixtures of the two nitrates are able to support a very considerable absorption, though it is little when compared with mixtures containing Ca ions.

The greatest absorption in the Mg-K series was made in the solution containing  $3/4$   $\text{Mg}(\text{NO}_3)_2 + 1/4$   $\text{KNO}_3$  in a total concentration of  $240 \text{ N} \times 10^{-6}$ .

Mixtures of Mg and K ions showed in this experiment a marked superiority over either ion alone, as judged by the process of absorption.

#### SUMMARY OF RESULTS

The chief results obtained in this series of experiments with the white lupine may be summarized as follows:

1. When the nitrates of calcium, magnesium and potassium are offered in pairs in solutions varying in concentration from  $120 \text{ N} \times 10^{-6}$  to  $480 \text{ N} \times 10^{-6}$  it is usually the case that the roots absorb more electrolytes than from the pure solutions. It seems also true that for the range of concentration here concerned absorption tends to increase in mixtures as well as in pure solutions as the salt content increases. The case of magnesium salts offers an exception owing to the narrow range of physiologically useful concentrations of the Mg ion.

2. In mixtures of  $\text{Ca}(\text{NO}_3)_2$  and  $\text{KNO}_3$  the inimical effect of K ions on root absorption is seen in the high ratio of Ca to K required to give maximum absorption, viz.,  $3 \text{ Ca}^{++} : 2 \text{ K}^+$  ( $3 \text{ Ca}(\text{NO}_3)_2 + 1/4 \text{ KNO}_3$ ) in all concentrations tested. The value of a small amount of K ions is however proved by the excess of absorption in the mixture over that in  $\text{Ca}(\text{NO}_3)_2$  alone. The absolute amount of Ca present in mixtures seems to be of great influence since as the proportion of Ca increases in the greater dilutions, absorption is increased. The favorable influence of Ca ions is therefore striking in the mixtures as well as in the pure solutions.



3. In mixtures of  $\text{Ca}(\text{NO}_3)_2$  and  $\text{Mg}(\text{NO}_3)_2$  the greater absorption of the Mg ion in comparison with the K ion appears in the greater proportion of Mg to Ca seen in the most favorable ratio. The greatest absorption is found in the ratios  $2 \text{Ca}^{++} : 2 \text{Mg}^{++}$  or  $1 \text{Ca}^{++} : 3 \text{Mg}^{++}$  in the concentrations here tested. The great significance of even a small proportion of Ca is seen in the relatively high absorption made in a mixture containing 1 Ca to 9 Mg at the highest concentrations here tested.

4. In pure solutions the Mg ion is much more favorable to absorption than the K ion in the weaker concentrations while the K ion is more favorable in the highest concentration. They are absorbed to about the same extent at a concentration of  $360 \text{ N} \times 10^{-6}$ . Absorption from mixtures exceeds that from either pure solution except in the weakest concentrations. Although a most favorable ratio can hardly be designated, the general tendency of the results seems to indicate that a high proportion of Mg is more favorable in weaker concentrations.

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