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THE EXCHANGE OF IONS BETWEEN THE ROOTS OF *LUPINUS ALBUS* AND CULTURE SOLUTIONS CONTAINING THREE NUTRIENT SALTS[1]

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Elsewhere in this Journal the authors have given data on root absorption from solutions containing a single nutrient salt,[2] and also from mixed solutions of two salts.[3] It may be recalled that the roots of young seedlings of *Lupinus albus* actively absorb calcium salts. Magnesium salts are absorbed to a less extent and only from solutions which are so weak that toxic action does not occur. Potassium and sodium stand in marked contrast to calcium and magnesium. Their solutions greatly resemble distilled water in that the roots placed in them either excrete electrolytes regardless of the concentration or else effect a minimal absorption. The somewhat different effect of different salts of the same base indicates that absorption is influenced not only by the cation but also by the anion.

The addition of even a very small amount of a calcium salt to a solution of a magnesium salt increases absorption to a remarkable degree. The same effect is also observed when calcium is added to a potassium salt. In mixtures of two nutrient nitrates there usually seems to be a ratio which is more favorable to absorption than any other. In certain cases where the total salt concentration was $240 \text{ N} \times 10^{-6}$ the absorption from mixtures was found to be greater than from either constituent salt alone. In weaker solutions

[1] Published by permission of the Secretary of Agriculture.

[2] 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.

[3] True, R. H., and Bartlett, H. H., The Exchange of Ions between the Roots of *Lupinus albus* and Culture Solutions Containing Two Nutrient Salts. Amer. Journ. Bot. 2: 311–31. 1915.

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the absorption was more likely to be a mean between that of the unmixed constituent salts at the same total concentration.

The present paper deals primarily with absorption from mixtures of three salts. Two experiments are reported, one of which was carried out with the nitrates of potassium, calcium and magnesium, the other with monopotassium phosphate, calcium nitrate and magnesium sulphate. In each experiment 36 culture solutions were used, the uniform concentration of which was 140 N $\times$ 10^{-6}. Mono-

Table I.

Composition			Daily Concentration				
KNO_3	$Ca(NO_3)_2$	$Mg(NO_3)_2$		1	2	3	4
140 N $\times 10^{-6}$	0 N $\times 10^{-6}$	0 N $\times 10^{-6}$	1.000	1.033	1.043	1.077	1.086
120 "	20 "	0 "	1.000	1.027	1.036	1.037	1.036
120 "	0 "	20 "	1.000	1.027	1.043	1.048	1.040
100 "	40 "	0 "	1.000	1.032	1.045	1.018	1.021
100 "	20 "	20 "	1.000	1.063	1.011	0.934	0.894
100 "	0 "	40 "	1.000	1.048	1.054	1.039	1.022
80 "	60 "	0 "	1.000	1.061	1.087	1.059	1.038
80 "	40 "	20 "	1.000	1.065	1.073	1.039	1.019
80 "	20 "	40 "	1.000	1.041	1.052	1.042	1.036
80 "	0 "	60 "	1.000	1.041	1.057	1.046	1.030
60 "	80 "	0 "	1.000	1.038	1.053	1.034	1.029
60 "	60 "	20 "	1.000	1.065	1.035	0.943	0.878
60 "	40 "	40 "	1.000	1.061	1.001	0.901	......
60 "	20 "	60 "	1.000	1.061	1.073	1.023	1.003
60 "	0 "	80 "	1.000	1.045	1.058	1.015	0.995
40 "	100 "	0 "	1.000	1.059	1.124	1.112	1.141
40 "	80 "	20 "	1.000	1.029	1.058	......	1.046
40 "	60 "	40 "	1.000	1.033	1.027	0.948	0.915
40 "	40 "	60 "	1.000	1.055	1.083	1.058	1.052
40 "	20 "	80 "	1.000	1.048	1.043	0.988	0.964
40 "	0 "	100 "	1.000	1.042	1.058	1.036	1.015
20 "	120 "	0 "	1.000	1.062	1.098	1.084	1.093
20 "	100 "	20 "	1.000	1.054	1.058	1.003	0.983
20 "	80 "	40 "	1.000	1.069	1.088	1.043	1.037
20 "	60 "	60 "	1.000	1.083	1.141	1.147	1.169
20 "	40 "	80 "	1.000	1.014	1.003	0.921	0.889
20 "	20 "	100 "	1.000	1.022	1.030	0.963	0.939
20 "	0 "	120 "	1.000	1.018	1.018	0.982	0.969
0 "	140 "	0 "	1.000	1.027	0.980	0.919	0.875
0 "	120 "	20 "	1.000	1.019	1.007	0.949	0.916
0 "	100 "	40 "	1.000	1.007	0.996	0.930	0.890
0 "	80 "	60 "	1.000	1.040	0.996	0.920	0.880
0 "	60 "	80 "	1.000	1.031	1.001	0.948	0.910
0 "	40 "	100 "	1.000	1.054	1.039	0.982	0.954
0 "	20 "	120 "	1.000	1.030	1.039	1.000	0.986
0 "	0 "	140 "	1.000	1.017	1.036	1.025	0.998

potassium phosphate was treated as though it were a salt of a univalent acid, on account of the fact that it dissociates for the most part in K^+ and $H_2PO_4^-$ ions. The 36 solutions provided all the possible combinations of one, two, or three salts which could be obtained in which each constituent salt had a partial concentration of $20 \text{ N} \times 10^{-6}$ or some multiple of that concentration. If the composition of the 36 solutions were represented by a triangular diagram, in the manner which has become familiar to plant physiologists through the work of Schreiner and Skinner[4] the apices of the triangle would indicate the three unmixed constituent salts, the remaining peripheral positions would indicate the various mixtures of the three different pairs of

TABLE I.

Daily Concentration											
5	6	7	8	9	10	11	12	13	14	15	16
1.108	1.073	1.066	1.031	1.035	1.026	0.984	0.982	0.963	0.966	0.981	1.027
1.004	0.989	0.974	0.945	0.914	0.889	0.864	0.869	0.859	0.879	0.931	1.015
1.022	1.001	0.998	0.968	0.960	0.966	0.958	0.968	0.978	......	1.053	1.164
0.994	0.971	0.947	0.893	0.824	0.768	0.732	0.714	0.694	0.683	0.701	0.735
0.861	0.833	0.791	0.753	0.706	0.681	0.658	0.662	0.665	0.678	0.716	0.767
1.000	0.984	0.968	0.936	0.924	0.908	0.893	0.915	0.931	0.960	1.026	1.126
1.022	1.005	0.950	0.896	0.815	0.744	0.703	0.681	0.672	0.672	0.710	0.767
0.995	0.972	0.916	0.866	0.797	0.748	0.730	0.747	0.755	0.788	0.840	0.907
1.028	1.013	0.979	0.937	0.890	0.835	0.796	0.791	0.792	0.826	0.896	1.007
1.008	0.985	0.959	0.922	0.897	0.891	0.875	0.876	0.893	0.914	0.965	1.041
1,028	1.032	1.009	0.975	0.890	0.818	0.757	0.715	0.680	0.668	0.703	0.780
0.815	0.796	0.744	0.707	0.638	0.567	0.511	0.478	0.450	0.436	0.458	0.521
0.798	0.767	0.708	0.661	0.593	0.542	0.506	0.492	0.490	0.511	0.567	0.641
0.990	0.969	0.928	0.885	0.817	0.763	0.714	0.672	0.654	0.649	0.679	0.735
0.971	0.953	0.915	0.871	0.832	0.798	0.771	0.769	0.778	0.803	0.863	0.952
1.158	1.139	1.112	1.047	0.937	0.836	0.774	0.712	0.661	0.629	0.631	0.663
1.056	1.044	0.970	0.905	0.796	0.705	0.653	0.614	0.591	0.569	0.598	0.661
0.873	0.859	0.787	0.739	0.656	0.589	0.542	0.506	0.467	0.448	0.438	0.472
1.050	1.041	1.007	0.954	0.853	0.755	0.691	0.657	0.636	0.635	0.672	0.739
0.921	0.901	......	0.804	0.745	0.705	0.669	0.666	0.675	0.680	0.714	0.754
1.001	0.994	0.946	0.904	0.846	0.811	0.796	0.805	0.823	0.851	0.905	0.973
1.080	1.056	1.010	0.960	0.905	0.830	0.779	0.711	0.657	0.608	0.612	0.649
0.949	0.914	0.841	......	0.815	0.761	0.575	0.529	0.494	0.481	0.503	0.559
1.003	0.977	0.928	0.857	0.760	0.683	0.658	0.670	0.686	0.726	0.785	0.864
1.193	1.195	1.148	1.115	1.046	0.962	0.905	0.818	0.749	0.694	0.710	0.765
0.844	0.816	0.755	0.716	0.659	0.590	0.546	0.514	0.480	0.458	0.465	0.508
0.923	0.907	0.872	0.835	0.771	0.770	0.672	0.639	0.625	0.629	0.662	0.725
0.945	0.935	0.919	0.892	0.853	0.820	0.795	0.776	0.763	0.760	0.784	0.824
0.849	0.812	0.786	0.749	0.707	0.639	0.596	0.571	0.543	0.546	0.573	0.617
0.924	0.921	0.921	0.981	0.860	0.812	0.788	0.739	0.684	0.633	0.622	0.640
0.871	0.854	0.818	0.771	0.729	0.685	0.654	0.635	0.617	0.591	0.607	0.660
0.840	0.810	0.787	0.749	0.713	0.667	0.636	0.612	0.585	0.584	0.625	0.676
0.889	0.870	0.845	0.810	0.756	0.702	0.657	0.621	0.592	0.575	0.600	0.651
0.913	0.877	0.823	0.770	0.717	0.665	0.624	0.615	0.631	0.652	0.698	0.767
0.988	0.974	0.956	0.912	0.864	0.799	0.752	0.726	0.732	0.741	0.790	0.850
0.966	0.941	0.917	0.878	0.872	0.863	0.872	0.907	0.942	0.988	1.078	1.185

[4] Schreiner, O., and Skinner, J. J., Ratio of Phosphate, Nitrate and Potassium on Absorption and Growth. Bot. Gaz. **50**: 1–30. 1910; Some Effects of a Harmful Soil Constituent. Bot. Gaz. **50**: 161–181. 1910.

salts, and the interior positions the mixtures of all three salts. The method used in carrying out the present work was exactly that detailed in previous papers. The electrical conductivity of each solution was read before the lupine seedlings were placed in it. During the progress of the experiments the conductivity and temperature of the solutions were read daily. Unfortunately temperature regulation was impossible, but the conductivities were of course reduced to a uniform temperature. The effect of temperature on absorption is still to be determined. From some of the experiments reported in our former papers it appears that the temperature effect within a limited range is not great. Since further work must be done in order to determine the precise effect of temperature on absorption, we have not included the daily temperature readings in this paper.

Experiment I. $KNO_3 + Ca(NO_3)_2 + Mg(NO_3)_2$

This experiment was carried out with the nitrates of potassium, calcium and magnesium, and lasted 16 days. The composition and daily concentration of each solution is expressed in Table I.[5] To facilitate interpretation the original concentration of each solution is taken as unity. In this way the magnitude of absorption or excretion as compared with the total original concentration is most readily made apparent. It was impossible, on account of the large number of culture solutions, to state the results intelligibly by means of curves. A concentration greater than unity indicates that excretion of electrolytes from the roots has taken place; absorption, on the contrary, is indicated if the concentration is less than unity.

In figure 1 we have stated on a triangular diagram the residual concentrations of the 36 culture solutions at the time of maximum absorption. The residual concentration is stated, as in the table, as a fraction of the original concentration. The greatest absorption was of course attained in different solutions on different days. Each point in the figure represents a solution, the original composition of which is indicated on the three intersecting axes reading upwardly from the intersection. The sum of the numerals on the three axes

[5] *Table I.*—Concentration changes in culture solutions containing KNO_3, $Ca(NO_3)_2$ and $Mg(NO_3)_2$, due to absorption and excretion of electrolytes by roots of *Lupinus albus*. The initial concentration ($140\ N \times 10^{-6}$) of each solution is represented by 1.000. The daily concentration is therefore stated as a ratio of residual concentration to initial concentration. To obtain the absolute concentration, in terms of $N \times 10^{-6}$, multiply by 140.

at any point is 140, indicating a total concentration of 140 N $\times$ 10^{-6}. For instance, the point marked 80 KNO_3, 20 $Ca(NO_3)_2$, 40 $Mg(NO_3)_2$

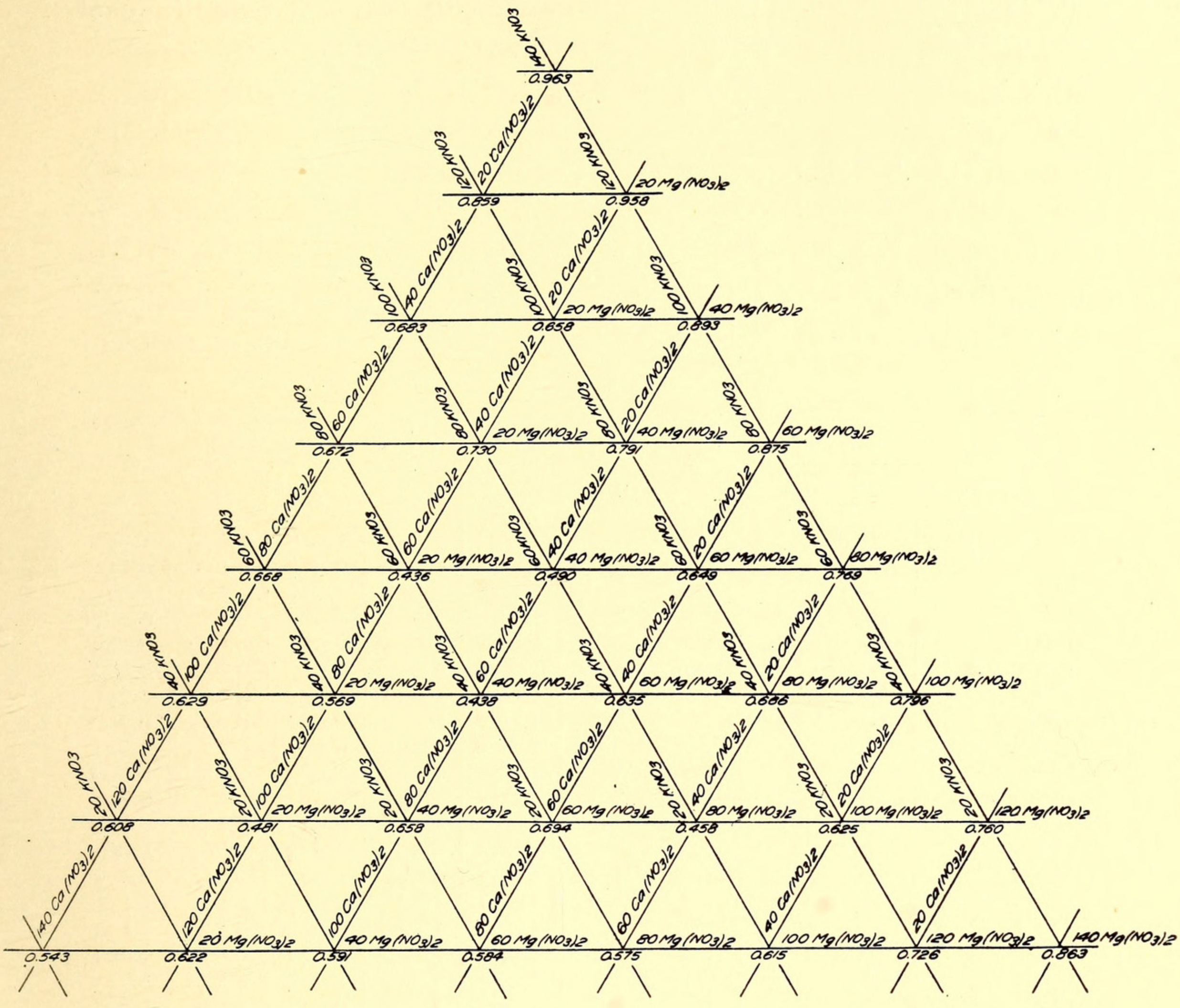

FIG. 1. Residual concentration of solutions containing KNO_3, $CA(NO_3)_2$ and $Mg(NO_3)_2$, at the time of maximum absorption.

represents a solution with a total concentration of 140 N $\times$ 10^{-6}, in which 80/140 of the NO_3^- ions were derived from KNO_3, 20/140 from $Ca(NO_3)_2$ and 40/140 from $Mg(NO_3)_2$.

Inspection of the results shows in nearly all cases a preliminary rise in the conductance of the solutions, probably due, as we have suggested elsewhere, to carbon dioxide given off by the roots. After this preliminary rise the conductance in most cases rapidly diminishes until the twelfth to fifteenth day, due to the absorption of salts by the roots. In the cases of five out of fifteen of the solutions which contained all three salts, the absorption exceeded that in the solution of $Ca(NO_3)_2$ alone. These five solutions in order of magnitude of absorption, beginning with the greatest, were as follows:

$60 N \times 10^{-6}$	KNO_3 :	$40 N \times 10^{-6}$	$Ca(NO_3)_2$:	$40 N \times 10^{-6}$	$Mg(NO_3)_2$,
20 "	KNO_3 :	100 "	$Ca(NO_3)_2$:	20 "	$Mg(NO_3)_2$,
20 "	KNO_3 :	40 "	$Ca(NO_3)_2$:	80 "	$Mg(NO_3)_2$,
40 "	KNO_3 :	60 "	$Ca(NO_3)_2$:	40 "	$Mg(NO_3)_2$,
60 "	KNO_3 :	60 "	$Ca(NO_3)_2$:	20 "	$Mg(NO_3)_2$.

From the remaining solutions absorption was less than from the simple $Ca(NO_3)_2$ solution. It is likely that a repetition of this experiment

TABLE II.

Composition			Daily Concentration Relations				
KH_2PO_4	$Ca(NO_3)_2$	$MgSO_4$		1	2	3	4
$140 N\times10^{-6}$	$0 N\times10^{-6}$	$0 N\times10^{-6}$	1.000	1.037	1.078	1.079	1.052
120 "	20 "	0 "	1.000	0.967	0.917	0.820	0.758
120 "	0 "	20 "	1.000	1.018	1.036	....	0.973
100 "	40 "	0 "	1.000	1.003	0.969	0.879	0.812
100 "	20 "	20 "	1.000	1.005	0.952	0.849	0.783
100 "	0 "	40 "	1.000	1.012	1.005	0.958	0.902
80 "	60 "	0 "	1.000	0.994	0.942	0.864	0.797
80 "	40 "	20 "	1.000	0.976	0.942	0.835	0.760
80 "	20 "	40 "	1.000	0.974	0.903	0.779	0.691
80 "	0 "	60 "	1.000	1.005	0.983	0.910	0.890
60 "	80 "	0 "	1.000	0.997	0.959	0.873	0.821
60 "	60 "	20 "	1.000	0.985	0.931	0.825	0.761
60 "	40 "	40 "	1.000	0.977	0.899	0.764	0.683
60 "	20 "	60 "	1.000	0.972	0.887	0.755	0.674
60 "	0 "	80 "	1.000	1.021	0.997	0.923	0.876
40 "	100 "	0 "	1.000	1.022	0.965	0.903	0.834
40 "	80 "	20 "	1.000	1.022	0.947	0.830	0.761
40 "	60 "	40 "	1.000	1.008	0.945	0.826	0.747
40 "	40 "	60 "	1.000	0.993	0.933	0.810	0.727
40 "	20 "	80 "	1.000	0.997	0.932	0.798	0.706
40 "	0 "	100 "	1.000	1.037	1.034	0.986	0.957
20 "	120 "	0 "	1.000	1.034	1.009	0.946	0.908
20 "	100 "	20 "	1.000	1.005	0.930	0.808	0.752
20 "	80 "	40 "	1.000	1.016	0.934	0.806	0.734
20 "	60 "	60 "	1.000	0.997	0.920	0.775	0.705
20 "	40 "	80 "	1.000	0.999	0.901	0.749	0.652
20 "	20 "	100 "	1.000	0.997	0.913	0.730	0.624
20 "	0 "	120 "	1.000	1.023	1.007	0.951	0.929
0 "	140 "	0 "	1.000	1.075	1.083	1.051	1.040
0 "	120 "	20 "	1.000	1.061	1.050	0.999	0.970
0 "	100 "	40 "	1.000	1.053	1.011	0.929	0.868
0 "	80 "	60 "	1.000	1.035	0.996	0.886	0.827
0 "	60 "	80 "	1.000	1.039	0.988	0.871	0.807
0 "	40 "	100 "	1.000	1.014	0.971	0.885	0.831
0 "	20 "	120 "	1.000	1.012	0.959	0.865	0.816
0 "	0 "	140 "	1.000	1.029	1.019	0.950	0.927

would show somewhat different results, because the individual variation in seedlings introduces an error which is surely of considerable magnitude. The general fact is nevertheless clear that mixtures of three nitrates are more favorable to absorption than solutions of single nitrates or mixtures of two. Our former work (l. c.) on mixtures of two salts indicates that if the total concentration of the solutions had been greater, there would have been a much greater difference between the absorption from single salts and that from the less favorable mixtures. However that may be, the contrast between this experiment and the next is very great. The fact to be kept in mind is that in even the most favorable mixtures of the three nitrates

TABLE II.

Daily Concentration Relations									
5	6	7	8	9	10	11	12	13	14
1.037	0.998	0.918	0.831	0.757	0.735	0.723	0.770	0.900	......
0.659	0.576	0.533	0.499	0.466	0.464	0.511	0.607	0.857	......
0.937	0.897	0.880	0.848	0.797	0.801	0.837	0.913	1.020	......
0.712	0.619	0.531	0.444	0.370	0.360	0.401	0.510	0.761	......
0.653	0.528	0.432	0.358	0.306	0.296	0.322	0.361	0.492	......
0.824	0.723	0.665	0.629	0.591	0.614	0.708	0.869	1.186	......
0.688	0.571	0.487	0.393	0.300	0.231	0.208	0.249	0.387	......
0.578	0.517	0.432	0.345	0.263	0.198	0.176	0.198	0.301	......
0.563	0.441	0.349	0.296	0.254	0.256	0.303	0.380	0.551	......
0.805	0.728	0.672	0.640	0.607	0.595	0.618	0.661	0.753	......
0.738	0.642	0.576	0.476	0.406	0.342	0.295	0.262	0.285	......
0.660	0.551	0.464	0.400	0.349	0.310	0.290	0.298	0.363	......
0.548	0.430	0.352	0.261	0.186	0.144	0.127	0.187	0.216	......
0.549	0.441	0.356	0.298	0.243	0.211	0.195	0.198	0.267	......
0.806	0.732	0.683	0.649	0.612	0.610	0.632	0.663	0.736	......
0.748	0.675	0.640	0.576	0.502	0.445	0.402	0.379	0.403	......
0.671	0.593	0.517	0.443	0.375	0.328	0.288	0.271	0.312	......
0.589	0.441	0.344	0.276	0.206	0.160	0.143	0.137	0.190	......
0.533	0.368	0.278	0.216	0.162	0.132	0.121	0.133	0.228	0.451
0.550	0.415	0.341	0.292	0.243	0.208	0.199	0.221	0.335	0.571
0.910	0.846	0.828	0.812	0.774	0.759	0.763	0.784	0.832	0.917
0.851	0.793	0.733	0.667	0.600	0.546	0.500	0.471	0.449	0.491
0.691	0.620	0.585	0.544	0.499	0.453	0.399	0.354	0.387	0.514
0.624	0.550	0.491	0.440	0.388	0.346	0.320	0.289	0.294	0.367
0.578	0.476	0.395	0.322	0.255	0.211	0.189	0.196	0.247	0.354
0.518	0.427	0.339	0.287	0.218	0.174	0.151	0.132	0.140	0.227
0.494	0.410	0.359	0.312	0.263	0.224	0.205	0.193	0.227	0.337
0.895	0.851	0.829	0.805	0.765	0.749	0.741	0.740	0.762	0.839
1.003	0.969	0.916	0.868	0.803	0.735	0.705	0.682	0.733	0.852
0.885	0.807	0.738	0.670	0.586	0.514	0.476	0.448	0.453	0.549
0.750	0.653	0.560	0.484	0.401	0.343	0.323	0.331	0.400	0.553
....	0.653	0.599	0.528	0.452	0.406	0.379	0.361	0.400	0.534
0.699	0.614	0.534	0.464	0.395	0.332	0.305	0.291	0.339	0.456
0.734	0.650	0.590	0.541	0.489	0.468	0.472	0.489	0.547	0.657
0.733	0.665	0.616	0.576	0.525	0.493	0.474	0.464	0.513	0.660
0.920	0.831	0.822	0.807	0.781	0.794	0.805	0.835	0.888	0.978

little more than half of the salt content of the solutions had been absorbed by the roots at the time of maximum absorption. In the most favorable mixtures the concentration of Ca^{++} was electrolytically more than equivalent to the sum of $Mg^{++} + K^{+}$ and the two latter ions were either about equivalent, electrolytically, to one another, or else the K^{+} concentrations were somewhat more than equivalent electrolytically to the Mg^{++} concentration. In other words the numerical ratio of ions in the best mixtures was about 2 Ca^{++} : 1 Mg^{++} : 2K^{+}. Further experiments, however, must be carried out before any great stress is laid on this ratio as the most favorable for absorption.

Experiment 2. $KH_2PO_4 + Ca(NO_3)_2 + MgSO_4$

This experiment was carried out in order to determine the extent to which the anions influence absorption. Accordingly, cultures were grown in solutions of potassium dihydrogen phosphate (which dissociates for the most part into the univalent ions K^{+} and $H_2PO_4^{-}$), calcium nitrate and magnesium sulphate. The composition and daily concentration of each solution is stated in Table II,[6] which is in every respect comparable with Table I.

In figure 2 we have indicated the residual concentration of the 36 culture solutions at the time of maximum absorption. Inspection of the table and the figure shows important differences between the cultures containing three anions and those containing only the NO_3^{-} anion. In but three out of 15 mixtures containing all three salts did the plants fail to show absorption during the first day. This result is in marked contrast to that of experiment 1, and seems to indicate that root absorption was so active from the very start as to overbalance the effect of CO_2 excretion. Rapid absorption was maintained in most of the mixtures throughout the experiment.

The maximum absorption, attained after ten or eleven days, was in every case greater than in the corresponding nitrate solution, and was attained one or two days sooner. Whereas in the nitrate solutions only a third of the mixtures showed a total absorption

[6] *Table II.*—Concentration changes in culture solutions containing KH_2PO_4, $Ca(NO_3)_2$ and $MgSO_4$, due to absorption and excretion of salts by roots of *Lupinus albus*. The initial concentration (140 N $\times$ 10^{-6}) of each solution is represented by 1.000. The daily concentration is therefore stated as a ratio of residual concentration to initial concentration. To obtain the absolute concentration, in terms of N $\times$ 10^{-6}, multiply by 140.

greater than that from calcium nitrate alone, in the solutions with three anions all of the mixtures were superior to calcium nitrate alone. In the nitrate mixtures the most favorable solution was reduced to little below half its original concentration, but in the mixtures containing different anions the best solutions were reduced to about one

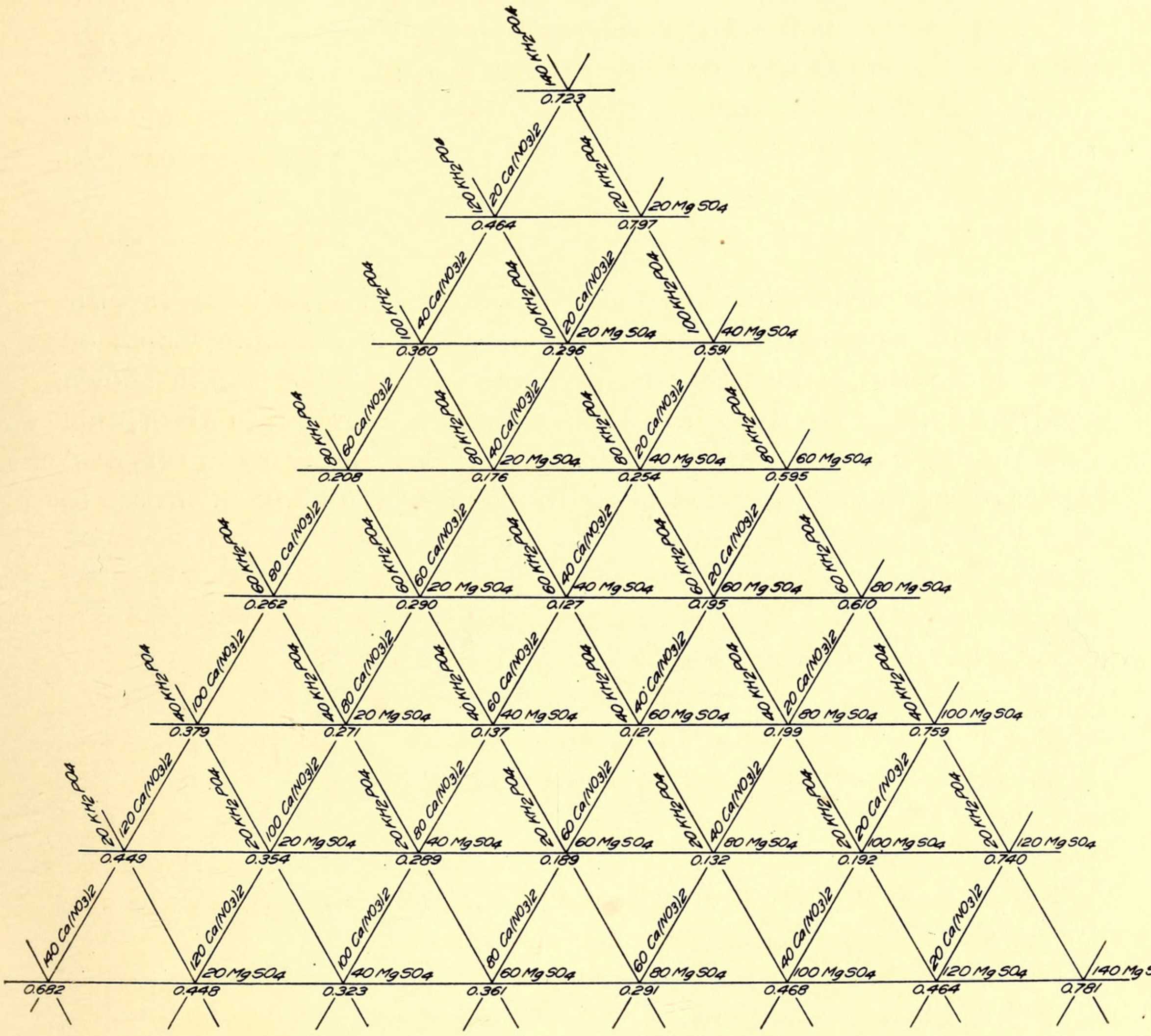

FIG. 2. Residual concentration of solutions containing KH_2PO_4, $Ca(NO_3)_2$ and $MgSO_4$, at the time of maximum absorption.

tenth of their original concentration. In the nitrate series there was a wide range of variation in the absorption from the 15 mixtures of all three salts, but in the mixed anion series there was much greater uniformity in the final result. The least favorable mixtures did not depart widely from the average. Taking a maximum total absorption of 80 percent as the dividing line, the plants in the following mixtures absorbed most efficiently:

40	$N \times 10^{-6}$	KH_2PO_4 :	20	$N \times 10^{-6}$	$Ca(NO_3)_2$:	80	$N \times 10^{-6}$	$MgSO_4$,
20	"	KH_2PO_4 :	20	"	$Ca(NO_3)_2$:	100	"	$MgSO_4$,
60	"	KH_2PO_4 :	20	"	$Ca(NO_3)_2$:	60	"	$MgSO_4$,
20	"	KH_2PO_4 :	60	"	$Ca(NO_3)_2$:	60	"	$MgSO_4$,
80	"	KH_2PO_4 :	40	"	$Ca(NO_3)_2$:	20	"	$MgSO_4$,
40	"	KH_2PO_4 :	60	"	$Ca(NO_3)_2$:	40	"	$MgSO_4$,
20	"	KH_2PO_4 :	40	"	$Ca(NO_3)_2$:	80	"	$MgSO_4$,
60	"	KH_2PO_4 :	40	"	$Ca(NO_3)_2$:	40	"	$MgSO_4$,
40	"	KH_2PO_4 :	40	"	$Ca(NO_3)_2$:	60	"	$MgSO_4$,

Absorption increased in the order listed. As in the nitrate series the greatest absorption generally took place from solutions in which no one of the three salts greatly predominated. This fact is shown clearly in figure 2. All of the solutions most favorable to absorption occupy the center of the triangle. Nevertheless the wide range of variation in the composition of solutions almost equally favorable to absorption seemed to indicate that, as far as absorption is concerned,

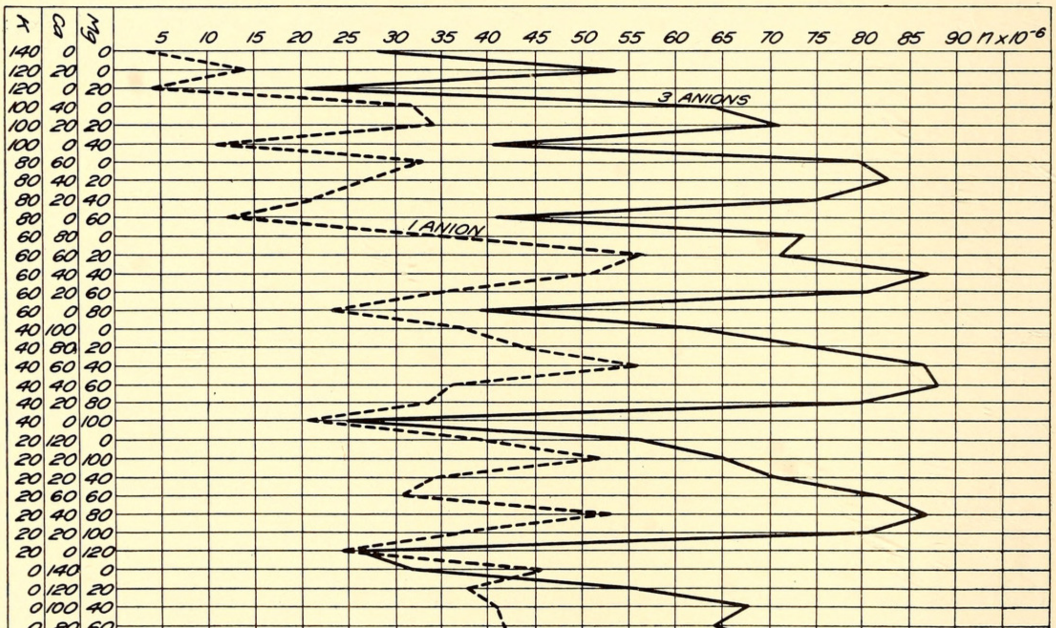

FIG. 3. Graph showing the absorption maxima of the nitrate mixtures (dotted line) and the mixtures with unlike anions (unbroken line).

roots may function efficiently in dilute solutions provided the concentration of no single ion is too greatly reduced. We seem to find here an argument for Liebig's "Law of the Minimum." When a sufficient concentration of an ion is present, the particular ratio of the different ions to one another is, within a rather wide range of variation, relatively immaterial. The significance of a full quota of anions as well as of cations stands out as the most striking feature of the second experiment.

On account of the different and varying temperature conditions under which the two experiments were carried out it would be unsafe to compare them too minutely. There can be no doubt however about the significance of the great difference between the absorption maxima in the two series. They are graphically represented in figure 3, and show the strikingly greater absorption which resulted from the presence of a full quota of anions.

Conclusions

1. In general, seedlings of *Lupinus albus* L. absorb more salts from mixtures of the nitrates of potassium, calcium and magnesium than from equally concentrated solutions containing only one or two of these nitrates.

2. The solutions of the 3 nitrates which were most favorable to absorption were much inferior to corresponding solutions in which three anions, $H_2PO_4^-$, NO_3^- and $SO_4^=$, were present. Under fairly comparable conditions the roots were able to absorb about half of the salts from the best solutions of the 3 nitrates and 85 percent from corresponding solutions with mixed anions.

3. In solutions of KNO_3, $Ca(NO_3)_2$ and $Mg(NO_3)_2$, as well as in solutions of KH_2PO_4, $Ca(NO_3)_2$ and $MgSO_4$ the best absorption occurs when no single ion greatly predominates over the rest. Nevertheless, there is a wide range of variation in the proportion of different ions, within which range the roots absorb with almost equal efficiency.

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