GROWTH RESPONSES OF BARLEY SEEDLINGS IN RELATION TO POTASSIUM AND SODIUM NUTRITION

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(WITH THREE FIGURES)

Introduction

In a previous paper (**15**) the effects on young barley plants of variations of the anions and cations in a three-salt nutrient solution were described. The present work was designed to study the effect brought about by various interrelations of the anions of a three-salt nutrient solution in the absence of potassium, using the same general method, and to do further work on the calcium-magnesium relationship which has been reported for other plants (**4**). As will be noted, these original plans were later changed owing to the pronounced growth response of the plants to the substitution of sodium for potassium in the nutrient solution. Work was then done to study the relationship of potassium and sodium in the nutrition of barley plants.

PART I

This phase of the work originally had three separate objectives: A, to determine the optimum amount of potassium in the nutrient solution for barley seedlings; B, to determine the effect of the nitrate, sulphate, and phosphate ions of the nutrient solution upon plant growth in the absence of potassium; and C, to investigate the calcium-magnesium relationship in barley seedlings.

Materials and general methods

Barley seeds selected for uniformity were planted in white, pure quartz sand in glazed self-draining crocks four inches in diameter by eight inches in depth. The seeds were watered with distilled water until they germinated, after which they were at once placed upon the experimental treatments and were given nutrient solution every other day. After germination the seedlings were thinned out to eight plants per pot. A total of about 2000 plants was used in the first runs for these investigations. Several duplicate runs for A and C, which were made in addition, gave similar results. Seedlings were grown under ordinary greenhouse conditions of light and humidity and were harvested when 20 days old. The average height of plants given each treatment was recorded. They were then divided at the sand level into tops and roots, and were dried at 80° C. for 12 hours. Fresh and dry weights of each fraction were determined.

The three objectives mentioned were studied in the following manner:

A.—Eight groups each containing 50 plants were placed in a series.

Each was fed with a nutrient solution containing a different amount of potassium. The amounts used were 0, 5, 10, 20, 30, 40, 50, and 60 p.p.m. The solutions were made by substituting in a modified SHIVE's three-salt solution various amounts of NaH_2PO_4 for KH_2PO_4 to give the concentrations of potassium mentioned above. This was done in accordance with the procedure which workers often use when studying potassium deficiency in artificial culture media (**7, 17, 19**).

B.—Three stock solutions, N, S, and P respectively, were used for this triangle in which the anions (nitrates, sulphates, and phosphates) were varied but in which the cations (calcium, sodium, and magnesium) were kept constant. Since it was planned to vary the anions in the absence of potassium, sodium was substituted for that cation throughout. The concentrations of the salts used with the exception of the calcium salts were 4.5 millimolar; the calcium salts were 6.0 millimolar. Solution N was made up of the nitrate salts of sodium, magnesium, and calcium. Solution S consisted of the sulphate salts of sodium, magnesium, and calcium. Solution P contained sodium dihydrogen phosphate, monobasic magnesium phosphate, and monobasic calcium phosphate. Finely powdered calcium sulphate dissolved readily when slowly sifted into solution S. This was easier than the method previously reported (**15**).

Plants at one corner of the triangle were given only the nitrate salts; at a second corner only the sulphate salts; at the third corner only the phosphate salts. All intermediate points were fed with solutions made by mixing together various amounts of N, S, and P so that each point in the triangle varied by $\frac{1}{6}$ from all adjacent points. Fifty plants were set aside for each nutrient treatment in the triangle.

C.—A series of plants was given nutrient solutions which completely lacked potassium and in which all of the anions were kept relatively constant. The calcium and magnesium content was varied by steps of $\frac{1}{6}$ in each solution from the one extreme of all calcium to the other extreme of all magnesium. This was done by mixing together various amounts of solutions M and C. M contained the following magnesium salts, all 4.5 millimolar: nitrate, sulphate, and monobasic phosphate. C contained the nitrate, sulphate, and monobasic phosphate salts of calcium, all 6.0 millimolar.

Control plants were given the modified SHIVE's three-salt nutrient solution composed of the following: 6 millimoles of calcium nitrate; 4.5 millimoles of magnesium sulphate; and 4.5 millimoles of potassium dihydrogen phosphate.

Results

A.—Differences began to appear in 12 to 14 days. At the time of harvest nearly all of the plants grown at the different levels of potassium were in a good vegetative state. Plants grown in the total absence of potassium but receiving sodium were stunted, and the leaves were yellowed or brown at the tips, while the general color of the plants was a yellowish green. Plants given 5 p.p.m. of potassium were light in color and had a few yellowed leaf tips. Those given 10 p.p.m. were not quite as vigorous as those grown at higher levels but the differences in their weights were not marked. The data are given in table I.

TABLE I

DRY WEIGHTS (IN GRAMS) OF GROUPS OF 50 PLANTS GROWN AT DIFFERENT LEVELS OF K. VARIOUS AMOUNTS OF NaH_2PO_4 SUBSTITUTED FOR KH_2PO_4 IN A COMPLETE SOLUTION TO GIVE THE REQUIRED P.P.M. OF K

	P.P.M. OF K								
	0	5	10	20	30	40	50	60	180 (CONTROL)
Tops	1.22	1.44	1.53	1.57	1.58	1.62	1.84	1.39	1.75
Roots	1.29	1.17	1.33	1.50	1.59	1.59	1.61	1.50	1.53
Total	2.51	2.61	2.86	3.07	3.17	3.21	3.45	2.89	3.28

B.—Here the effects brought about by the variation of the anions in the nutrient solutions where potassium was replaced by sodium were not very different from those effects, already reported (**15**), brought about in the presence of potassium. Nevertheless, at the time of harvest the plants were a lighter green than normal, this undoubtedly being the first sign of potassium deficiency. Among those plants on a low nitrogen level this yellow color was more pronounced owing to nitrogen starvation as well as to lack of potassium. These latter plants were stunted as well as yellowed. Data showing the dry weights and heights are given in figure 1. Data for the control of B are given in the legend of figure 1.

C.—Deficiency symptoms appeared here astonishingly quickly. Within three or four days after the first application of the deficient solutions the older leaves became yellowed at the tips and thereafter died back rapidly (**3**). At the time of harvest these symptoms were severe and if the plants had been left longer before harvesting they would undoubtedly have died completely. It apparently did not matter whether calcium was high and magnesium low or vice versa; in either case the plants died back with equal rapidity presumably owing to the lack of potassium. Data concerning the dry weights are given in table II. Control plants were vigorous and showed no deficiency symptoms.

When the results of A, B, and C are compared, several points are seen to be salient. First, the potassium-deficient plants in C were affected a week to ten days before the plants in A and B, and the deficiency symptoms were much more pronounced and severe. Secondly, in B no new effects were

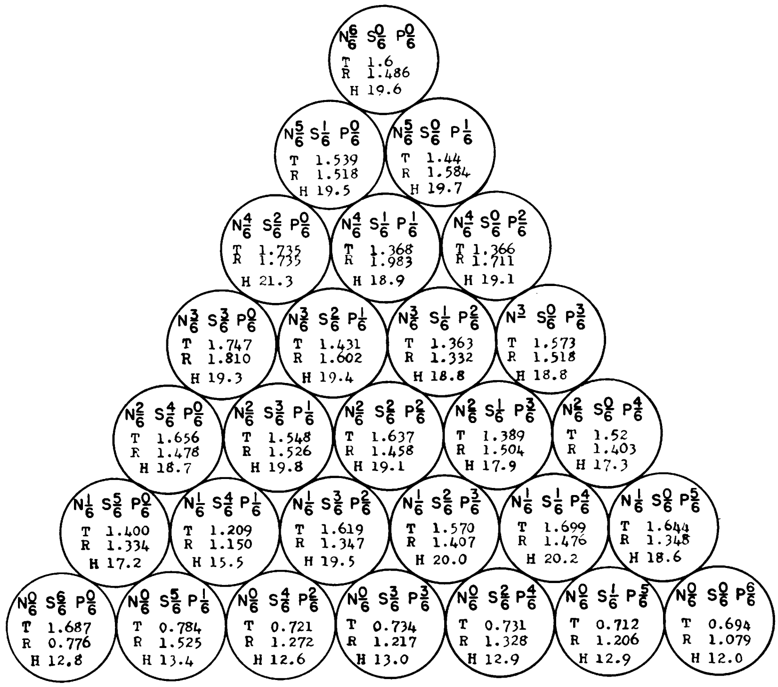

FIG. 1. Results of part I, B. Each point of triangle, representing data of 50 plants, was watered with the fractions of solutions N, S, and P indicated in each circle. Solution N contained various nitrates; S, sulphates; and P, phosphates. Numbers refer to dry weights in grams of tops and roots, and average heights in cm. Data for control: tops, 2.535 gm.; roots, 1.919 gm.; height, 20.5 cm.

TABLE II

DRY WEIGHTS (IN GRAMS) AND AVERAGE HEIGHTS (IN CM.) OF GROUPS OF 25 PLANTS GIVEN SOLUTIONS CONTAINING VARIOUS AMOUNTS OF Mg AND Ca BUT NO K OR Na

	FRACTIONS OF STOCKS "M" AND "C" MAKING UP EACH SOLUTION							
	M1, CO	M5/6. C1/6	M2/3, C1/3	M1/2, C1/2	M1/3, C2/3	M1/6, C5/6	MO, C1	COMPLETE SOLUTION
Top weight	0.31	0.57	0.49	0.46	0.42	0.28	0.21	1.02
Root weight	0.63	0.67	0.76	0.63	1.07	0.86	0.86	1.58
Total weight	0.94	1.24	1.25	1.09	1.49	1.14	1.07	2.59
Average height	9.4	15.4	19.0	15.7	13.6	10.0	9.4	18.6

brought about by varying the relative amounts of the anions in the absence of potassium other than those found in its presence. Note that here sodium salts had been substituted for potassium salts in the nutrient solution. Third, there was general agreement as to the time of occurrence and the severity of the potassium deficiency symptoms in A and B at the zero level of potassium, but results of C were not at all comparable in this respect with results of A and B.

With this in mind, later experiments were devised to determine answers to these questions: 1. Were the swift and severe symptoms in C brought about by the toxicity of the phosphate ions? If they were due to some toxicity this might be likely because the results in C as well as in a previous preliminary investigation show that there is no toxicity of magnesium when calcium is at a low level or absent at the magnesium concentration used here. Other investigations have indicated that phosphates may be toxic and that sulphates and nitrates are not, unless in unusually high concentrations (**5**, **14**, **15**), which was not the present case.

2. Were these symptoms brought about through lack of potassium in itself?

3. Can sodium actually substitute partially for potassium during early growth of barley seedlings as is apparently indicated by results of A and B as compared with C?

PART II

A.—The solutions used in "C" of part I had contained twice the amount of phosphate which was present in the controls. To determine whether phosphate toxicity was causing the severe die-back, and if pH might be linked with it, as well as to determine whether Na had been substituting for K, each of the following solutions was fed to a different group of young seedlings, each group containing 50 plants. The experiment was later repeated.

1. Control solution, a modified SHIVE's three-salt solution.
2. Solution 1 acidified to pH 3.8 through the addition of H_2SO_4. In all cases where low pH was involved the nutrient solution was adjusted to the desired pH and plants were watered with it. The pots were not flushed with acidified water in between.
3. Solution 1 acidified to pH 2.2 through the addition of H_2SO_4.
4. $-$K and $-$Na; otherwise same ions present as in 1.
5. $-$K and $-$Na; twice as much phosphate present as in 1.
6. $-$K and $-$Na; phosphate concentration half that of 1.
7. $-$K and $-$Na; corresponds to solution made by mixing $\frac{1}{2}M + \frac{1}{2}C$ used in "C" of part I, but modified so that the NO_3 concentration was increased by half, and the PO_4 concentration decreased by half.
8. Control solution, but with NaH_2PO_4 substituted for KH_2PO_4.
9. $-$K, $+$Na; twice as much PO_4 and Na as 8.

10. $-K$ and $-Na$; corresponds to solution made by mixing $\frac{5}{6}M + \frac{1}{6}C$ used in "C" of part I.

11. Same as 10 except that proportion is $\frac{1}{6}M$ to $\frac{5}{6}C$.

12. $-K$, $+Na$; same as $\frac{1}{2}M + \frac{1}{2}C$ but with 4.5 millimoles of Na_2SO_4 added.

The pH and compositions of these solutions are given in table III.

TABLE III

pH AND MILLIMOLE COMPOSITIONS OF THE 12 CULTURE SOLUTIONS

	1, 2, 3*	4	5	6	7	8	9	10	11	12
$Ca(NO_3)_2$	6.0	6.0	6.0	6.0	4.5	6.0	6.0	1.0	5.0	3.0
$MgSO_4$	4.5	2.2		3.4	2.3	4.5	4.5	3.7	0.75	2.3
KH_2PO_4	4.5									
H_2SO_4		2.2	4.5	1.1						
$Mg(H_2PO_4)_2$		2.2	4.5	1.1	1.1			3.7	0.75	2.3
$Mg(NO_3)_2$					3.4			3.7	0.75	2.3
$CaSO_4$					3.0			1.0	5.0	3.0
$Ca(H_2PO_4)_2$					1.5			1.0	5.0	3.0
NaH_2PO_4						4.5	9.0			
Na_2SO_4										4.5
pH	1 – 4.8 2 – 3.8 3 – 2.2	2.6	2.2	3.0	2.8	4.8	4.2	4.6	3.8	4.0

* pH varied by addition of H_2SO_4.

Results of applying these various solutions to the sand cultures are shown in table IV, which gives data for the dry weights and heights of the plants.

TABLE IV

DRY WEIGHTS (IN GRAMS) OF GROUPS OF 50 PLANTS

	Solution number											
	1	2	3	4	5	6	7	8	9	10	11	12
Tops	2.36	2.35	1.10	1.15	0.66	0.80	1.00	1.65	1.53	1.13	0.77	1.53
Roots	1.05	1.10	0.91	0.78	0.68	0.90	0.87	0.99	1.01	0.76	1.02	0.88
Total	3.41	3.45	2.01	1.93	1.34	1.70	1.87	2.64	2.54	1.89	1.79	2.41

In omitting the Na and K ions from certain of the solutions, all or part of the SO_4 was added as H_2SO_4; by this means no additional new ion would have to be introduced and the concentration of all the ions could be kept approximately the same as in the control solution 1, so that accurate comparisons could be made. This was true of solutions 4, 5, and 6. In each case this brought the pH down to between 2.2 and 3.0. Solution 3, which was solution 1 acidified to pH 2.2, was used as a check, and it can be seen that the low pH did have a detrimental effect upon the dry weight as compared with plants given solution 1. Nevertheless, when noting results of solution 4 as compared with solutions 5, 6, and 7, all lacking both Na and K, and all of very low pH, it can be seen that varying the concentration of PO_4 as was done here makes no significant difference in the final dry weights at that low pH, although there may be some PO_4 toxicity indicated in 5. Since there are only the slightest indications of PO_4 toxicity under such unfavorable conditions as these pH values it would seem that under more favorable conditions for growth the PO_4 would not prove to be toxic at all. That this was so at the concentrations used in part I, C, can be seen by comparing results of 8 and 9; these solutions are essentially similar except for the PO_4 concentration. Since the solutions used in part I, C, were all above pH 4.0, it is therefore clear that the severe dieback could not have been caused by the concentration of the PO_4 or by the pH, but must have been caused by the fact that there was no Na present to substitute for the lack of K.

Since it is not possible to make a solution with the same ionic concentrations, as 1 and 8, and which will lack both Na and K without lowering the pH considerably, the solutions used instead were 10, and 11, which thus served as an additional check on the earlier work. Although the former is high in Mg and the latter high in Ca, the dry weights produced by each when applied to the sand cultures were almost the same, and were less than the dry weights produced by 8, which has Na added, and much less than 1, which has K instead of Na. A further comparison of results of 10 and 11 with those of 12 show that when Na_2SO_4 is added to a solution like that used in C, the results are brought into conformity with results of A and B. This is further brought out by comparing results of 12 with 10, 8, and 1. Therefore in A, and B, sodium must have substituted at least partially for potassium since the symptoms there were so much less severe.

B.—The object of this experiment was to study the interrelations of Na and K and to determine approximately to what extent the two are interchangeable. For each run about 1500 barley seeds were planted in two-gallon, self-draining glazed crocks in pure quartz sand and were watered from the time of germination with various nutrient solutions. Each crock was thinned to contain 25 plants. They were divided into two groups. Crocks of one group were given solutions containing the following p.p.m. of K, respectively: 0, 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 100, 140, and 180. The other group in addition had enough sodium added to the solution given each crock so that the total concentration of sodium plus potassium ions given to any one was 180 p.p.m. which is approximately the amount of K in the control nutrient solution used here. Thus half the plants were receiving only varying amounts of K while the other half were receiving varying amounts of K + Na. In addition to the amounts of K and K + Na just noted, one group of plants was given 180 p.p.m. of K + 90 p.p.m. of Na; another was given 180 p.p.m. of K + 180 p.p.m. of Na. Groups of fifty plants were given each type of nutrient solution. The basic – K solution consisted of 6.0 millimoles of calcium nitrate, 2.3 millimoles of magnesium sulphate, and 2.3 millimoles of magnesium phosphate, and had a pH of 5.1. K was added as KCl and Na was added as NaCl.

To act as a check upon the chloride ion, two groups of plants were set aside. One group was given sodium chloride, and the other group was given sodium sulphate. Results showed that the chloride ion had no detectable effect upon the dry weight or heights of plants grown under these conditions.

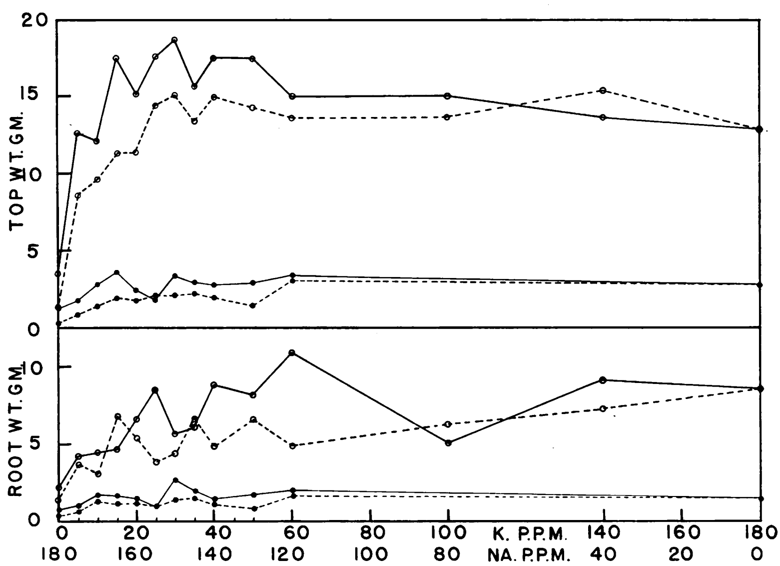

FIG. 2. Results of part II, B. Dry weights in grams of tops and roots, each point representing data for 50 plants. Dotted lines: plants given K but no Na. Solid lines: plants given total of 180 p.p.m. K + Na; *e.g.*, the fifth circle of upper solid line represents plants having been fed 20 p.p.m. of K + 160 p.p.m. of Na; corresponding point on dotted line shows plants that had 20 p.p.m. of K and no Na. Upper graph in each case is of tops and of roots 70 days old; lower graphs of plants 40 days old.

During the course of the work all the crocks were shifted about so as to minimize local differences of environmental factors in the greenhouse. The experiment was repeated twice, the last time with older plants. The first set was harvested when 40 days old; the second run gave confirmatory results which are therefore not given here. The third set were allowed to grow on until 70 days old in order to determine whether the same results would be obtainable beyond the seedling stage. Data are given for an older and a younger set in figure 2. This figure, however, does not include results obtained when plants were given 180 p.p.m. of K + 90 and 180 p.p.m. of Na, respectively. In certain cases the additional Na brought about a decided increase in the dry weight even when 180 p.p.m. of K was already present. One such case in shown in figure 3, D.

The plants given no Na showed a gradual increase in height, color, and vigor from 0 up to 30 to 40 p.p.m. of K, which was apparently the optimum

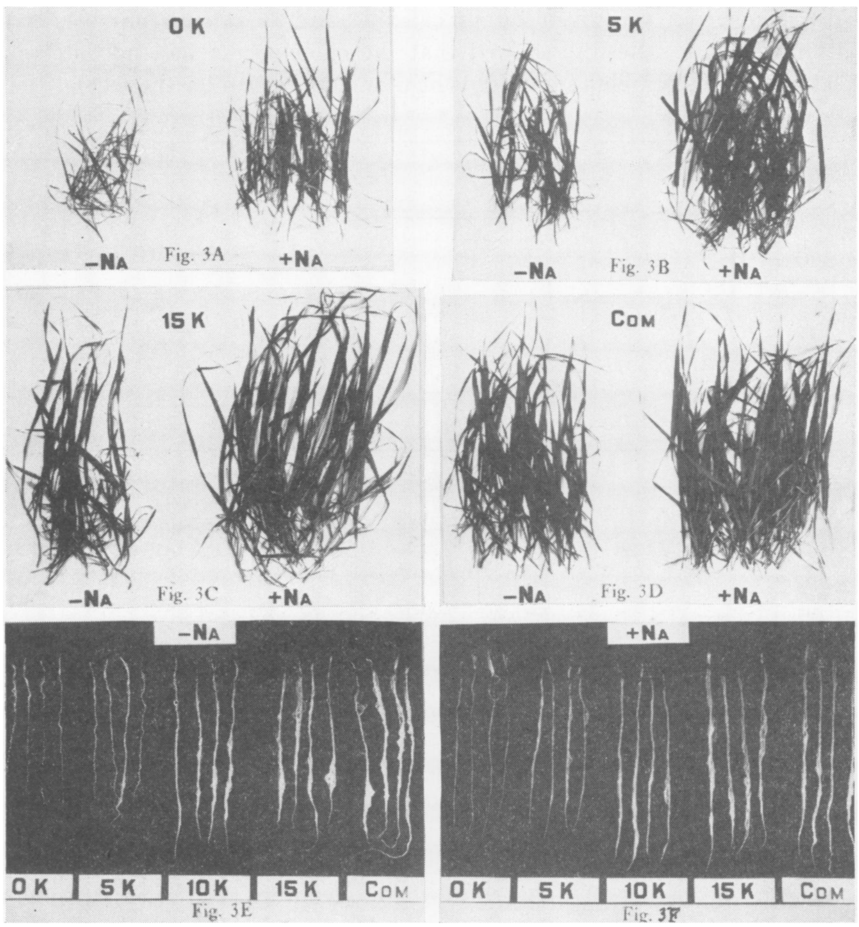

FIG. 3. Photographs of tops and roots of seedlings given varying p.p.m. of K with and without Na in an otherwise complete nutrient solution. The complete solution contained 180 p.p.m. of K and no Na. The + Na plants of fig. 3D had Na added to the complete solution.

amount. Plants given more than that were about the same in appearance and dry weight. Plants given Na in addition to the K did not show the pronounced gradation over as long a range as did those given only K. The former were superior in every respect, though the most pronounced improvements were found only up to about 60 p.p.m. and were most marked at the lower K levels. The differences between the plants given no Na and no K and those given 180 p.p.m. of Na and no K were especially marked. The former made little growth even in early stages, then began to die back rapidly; at the time of harvest, in one run, only 16 of the original 50 plants were alive; of the plants given the Na, 39 were alive and although they were not vigorous yet several of them had begun to stool. It was found that in several cases even the plants given 180 p.p.m. of K were definitely stimulated by the addition of Na.

Discussion

The idea that sodium can be partially substituted for potassium is not a new one. Some early work on this problem was done as far back as 1860. Probably the best-known early work was that of HELLRIEGEL in 1898 as mentioned in RUSSELL's text (**18**). Some of the earliest work in this country was done at the Rhode Island Agricultural Experiment Station (**8, 9**). Then for a long time not much attention was paid to this problem. Within the last few years, however, experiments have again been carried on with certain field crops, with results indicating that sodium is quite important under certain conditions of plant nutrition. This is particularly true of sugar beets and cotton (**12, 13**). LEHR (**10, 11**) even states that for beets sodium may almost be deemed an indispensable nutrient element, approaching potassium in importance. Very favorable increases in yield have been obtained with other crops as well (**2, 6**). A rather comprehensive review of European literature in this field is given by LEHR (**10**).

Certain workers have found that sodium will produce increased yields when the potassium supply is low. BUTKEVICH and MARUASHVILI (**1**) have stated that sodium can be substituted for as much as 25 per cent. to 75 per cent. of the potassium without detrimental results in yield. In fact, they state that at periods of stalk formation and heading in wheat the complete elimination of K and its replacement with Na in the culture solution results in a marked increase in yield. Still others have found that sodium salts give increases in crop yield in the field even when potassium salts are present (**2, 18**). Of course, different plants vary in their responses to this element. For example, HARTT (**7**) concluded from her experimental work that sodium could not be substituted for potassium in sugar cane.

But even though this is no new idea it has been almost neglected in work which has been done by the plant physiologist using artificial culture media. Most workers have assumed that sodium cannot replace potassium at all. The fact that plants could grow perfectly well in a culture medium entirely lacking in sodium doubtless caused the assumption that the plants would not utilize it. Work carried on simultaneously with the present work, however, and published elsewhere (**16**) indicates that sodium can be substituted to some extent for potassium in young tomato plants grown under controlled nutrient conditions, and the present work indicates the same for both barley seedlings and plants grown through a period of 70 days. To what extent this affects the chemical composition of the plants in question is not known but the presence of sodium certainly affects the speed as well as their severity, with which the potassium deficiency symptoms appear. It also affects the amount of dry matter synthesized by the plant. It has been shown here that potassium deficiency is one of the first and severest of any of the mineral deficiencies to manifest itself, killing the plants to the ground rapidly in the young stage. But barley plants given sodium in place of potassium are even enabled to make a small amount of growth before showing potassium deficiency symptoms. These plants remain alive for a long period of time and are larger and synthesize more dry matter than those lacking both potassium and sodium; the latter die quickly. It is therefore probable that the sodium itself is utilized in place of the potassium when the latter is present in insufficient amounts. Therefore, to get an accurate picture of the effect of potassium on plants, sodium as well should be excluded from the nutrient solution.

Conclusion and summary

1. The effects brought about by the variation of the anions in a nutrient solution where potassium was replaced by sodium were not very different from those effects, already reported, brought about in the presence of potassium.

2. The severe dieback reported here of plants grown without either Na or K was found to be due to a deficiency of K rather than to interrelations of PO_4 and NO_3, or Ca and Mg, or a toxicity of one of these.

3. About 30 to 40 p.p.m. of K is optimum for growth of young barley seedlings under the conditions of these experiments.

4. In the absence of both Na and K, K deficiency symptoms appear much earlier and are much more severe than when Na is present. In fact, this is one of the earliest of any of the deficiencies to appear in barley.

5. In young stages of growth Na can and does replace K to some extent even though it cannot replace it entirely. This is especially marked when K is low in amount.

6. When studying the effect of K at various nutritional levels sodium must be excluded from the nutrient solution in order to obtain an accurate picture of the rôle of K in plant metabolism.

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LITERATURE CITED

1. BUTKEVICH, W. S., and MARUASHVILI, L. V. Plant's uptake of potassium and yield as induced by sodium chloride. Compt. Rend. Acad. Sci. U.R.S.S. **22**: 127–130. 1939.
2. COOPER, H. P., and WALLACE, R. W. Effect of additions of sodium in the fertilizer on the yields of cotton. South Carolina Agr. Exp. Sta. Ann. Report **49**: 109–115. 1936.
3. ECKSTEIN, O., BRUNO, ALBERT, and TURRENTINE, J. W. Potash deficiency symptoms. 1937.
4. GAUCH, H. Responses of the bean plant to calcium deficiency. Plant Physiol. **15**: 1–21. 1940.
5. HAMNER, C. L. Growth responses of Biloxi soybeans to variation in relative concentrations of phosphate and nitrate in the nutrient solution. Bot. Gaz. **101**: 637–649. 1940.
6. HARMER, P. M., and BENNE, E. J. Effects of applying common salt to a muck soil on the yield, composition, and quality of certain vegetable crops and on the composition of the soil producing them. Jour. Amer. Soc. Agron. **33**: 952–979. 1941.
7. HARTT, C. E. Some effects of potassium upon the growth of sugar cane and upon the absorption and migration of ash constituents. Plant Physiol. **9**: 399–452. 1934.
8. HARTWELL, B. L., and WESSELS, P. H. The effect of sodium manuring on the composition of plants. Rhode Island Agr. Exp. Sta. Bull. 153. 89–118. 1913.
9. ———, and PEMBER, F. R. Sodium as a partial substitute for potassium. Rhode Island Agr. Exp. Sta. Rep. 1908, pp. 243–285.
10. LEHR, J. J. The importance of sodium for plant nutrition: I. Soil Sci. **52**: 237–244. 1941.
11. ———. The importance of sodium for plant nutrition: II. Effect on beets of the secondary ions in nitrate fertilizers. Soil Sci. **52**: 373–379. 1941.
12. LILL, J. G., BYALL, S., and HURST, L. A. The effect of applications of common salt upon the yield and quality of sugar beets and upon the composition of the ash. Jour. Amer. Soc. Agron. **30**: 97–106. 1938.
13. MATTHEWS, E. D. Evidence of the value of the sodium ion in cotton fertilizers. Georgia Agr. Exp. Sta. Circular 127. 1941.
14. MOORE, R. H. Nutritional levels in the peanut. Bot. Gaz. **98**: 464–489. 1937.
15. MULLISON, W. R. The effect on barley seedlings of some interrelations of cations and anions in a three-salt nutrient solution. Plant Physiol. **16**: 813–820. 1941.

16. ————. Certain aspects of the nutrition of tomato seedlings in sand culture. Proc. Indiana Acad. Sci. **51**: 94–99. 1942.
17. NIGHTINGALE, G. T., SCHERMERHORN, L. G., and ROBBINS, W. R. Some effects of potassium deficiency on the histological structure and nitrogenous and carbohydrate constituents of plants. New Jersey Agr. Exp. Sta. Bull. 499. 1930.
18. RUSSELL, E. J. Soil conditions and plant growth. 1937.
19. WALL, M. E. The rôle of potassium in plants: III. Nitrogen and carbohydrate metabolism in potassium-deficient plants supplied with either nitrate or ammonium nitrogen. Soil Sci. **49**: 393–409. 1940.