Some Solution Cultures of Wheat without Potassium.¹

By

Koichi Morita and Burton E. Livingstone.²

(With one Text-figure)

Abstract.

This paper reports a preliminary series of cultures of young wheat plants in ninety different solutions without potassium but with all the other essential chemical elements. The plants were grown from the seed in a complete nutrient solution, until they were about 3 cm. high, after which they were placed in the incomplete solutions and

1) Botanical contribution from the Johns Hopkins University, No. 63.
2) Mr. MORITA died suddenly, of influenza, in the Johns Hopkins Hospital, Baltimore, Maryland, on February 8, 1920. He had already accomplished practically all the work required for the degree of Doctor of Philosophy, with the exception of the dissertation, upon which he was well started when the end came. He had completed the detailed plans for the experimentation upon which the dissertation was to be based, and the first series of experimental cultures was actually in progress at the time of his death. The required stock solutions for this series were in readiness for the completion of the series. Mr. H. C. Diehl, of this Laboratory, continued the series until the physiological results seemed to be clear. Mr. J. E. Metzger, of this Laboratory and of the Maryland Experiment Station, took part in the final observations. Mr. Diehl has worked over Mr. Morita's note-books, together with the experimental data, and it has been with his help that I have been able to prepare the present publication. We have thought it desirable and fitting that we should thus place on record in the literature certain somewhat novel points of view embraced by Mr. Morita's well-laid plans, and certain experimental indications brought out by the cultures that he himself began. We shall be glad if this little paper may be received by physiologists and botanists as a report of part of Mr. Morita's work itself, and also as a slight and inadequate memorial of the exceptional research ability and personal devotion of which botanical science has been deprived through Mr. Morita's death. The future seemed to hold forth very great promise for him. Science has lost much by KOICHI MORITA'S death, those who enjoyed personal acquaintance with him have lost more. He was a thorough gentleman, an ever alert scholar, and an indefatigable worker in the cause of scientific advancement. —B. E. L.
grown for three weeks, in an ordinary greenhouse in Baltimore, in the month of February. There were five plants in a culture, each culture jar held about 440 c.c., and the solutions were renewed after 3½ days and at the end of the first and second weeks. At the end of this period they were compared (by five different growth criteria) with the plants of control cultures, which had been grown simultaneously from the 3-cm. stage, in an excellent complete solution (SHIVE's R5C2—1.75 atmospheres, osmotic value). Six different sets of three main salts were employed for the incomplete solutions and 15 different sets of proportions were tested for each of these sets of salts. Every incomplete solution contained Ca, Mg, (H₂PO₄)₂, (NO₃)₂ and SO₄, together with a very small amount of FePO₄. A triangular diagram was used as a guide in selecting the sets of salt proportions to be tested. The FePO₄ was always added to the 3-salt solutions in the same amount. The total concentrations of all incomplete solutions were the same, being 0.015 gram-molecule per liter (of all three main salts taken together) and corresponding to about 1.00 atmosphere of osmotic pressure.—By the criterion of total height the best cultures of the incomplete-solution series were 98 hundredths as good as the average of the controls. By other growth criteria these best incomplete solutions (there were three of them, practically alike as to the growth they produced) were generally somewhat poorer than the average of the controls. Averaging the five growth values obtained for each culture and considering the generalized result as a measure of the physiological worth of the solution used, the three best incomplete solutions were five-sevenths as good as the average of the controls. The plants of these best solutions without potassium appeared perfectly healthy at the end of the 3-week period; their growth might have been continued longer. The poorer solutions gave small plants, with some or nearly all of the leaves yellow or dead, but none of the solutions produced any specifically characteristic symptoms of poisoning or malnutrition.—The good solutions were already among those with the lowest partial volume-molecular concentrations of the dihydrogen-phosphate salt [either Ca (H₂PO₄)₂ or Mg (H₂PO₄)₂]; one-seventh of the total volume-molecular concentration was due to this salt in these best solutions. The worst solutions were among those having higher partial concentrations of the dihydrogen-phosphate salt; the highest partial concentration of this salt was five-sevenths of the total concentration. The value of the ratio of calcium to magnesium was not a controlling condition in determining the physiological worth of any solution, or did any other ratio value exert a noticeable
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influence. The actual partial concentration of $H_2PO_4$ seems to have determined what cultures should give good growth. The suggestion is advanced that this conclusion may not be related to the partial concentration of $PO_4$, but that the controlling feature here encountered may have been the hydrogen-ion concentration ($Pf$). It is especially important to note that very good solutions for these plants, and for the general conditions of these tests, may be obtained without the use of any potassium at all, if the proper salt proportions are employed.—The three best solutions without potassium had the following volume-molecular partial concentrations of their respective salts:

(1) $Ca(NO_3)_2$, 0.00428; $Ca(H_2PO_4)_2$, 0.00214; $MgSO_4$, 0.00856.
(2) $Ca(NO_3)_2$, 0.00642; $Mg(H_2PO_4)_2$, 0.00214; $MgSO_4$, 0.00642.
(3) $Ca(NO_3)_2$, 0.00856; $Mg(H_2PO_4)_2$, 0.00214; $MgSO_4$, 0.00428.

The value given in each case of course represents the fraction of a gram-molecule of the salt contained in a liter of solution.

Introduction.

The six essential chemical elements taken up from the soil by ordinary plants (K, Ca, Mg, N, P and S) may be supplied to the roots in the form of aqueous solutions of inorganic salts. Such salt solutions, or "nutrient solutions," offer the very simplest means for supplying those needed elements to growing plants and they are therefore much better suited to the study of the elementary principles of plant physiology than are other nutrient media, as sand, soil, etc. The presence of solid particles in the medium complicates the problem enormously and the aqueous solution alone avoids many difficulties of interpretation. For these reasons, many workers have turned to solution cultures as a means for studying the fundamental relations that hold between the plant and its root environment. The preliminary study here reported deals with solution cultures of young wheat plants.

It is often stated, and it is of course obvious to every one, that plants grown with their roots in liquid media alone do not usually develop in exactly the same manner as do plants with their roots surrounded by the two- or three-phase system (solid, liquid, gas) presented by a soil. The ordinary soil solution is of course an aqueous solution of mineral salts and other substances, and if a finely divided and insoluble solid such as quartz is used for experimental cultures, any solution may be added to the dry solid phase, thus avoiding many dissolved compounds that generally exist in soil solutions. But the
chemical and physical properties of the given solution are subject to profound alteration in the presence of the insoluble particles, so that a nutrient solution of known make-up cannot be expected to remain unchanged when suspended in the interstices of a finely divided solid, even though the solid is really insoluble in the solution. In such an artificial soil the solid phase is not without influence upon the liquid phase, even though the kinds of solutes may not be altered. The partial concentration of every solute in the original solution is generally greatly changed when the solid phase (particles of quartz, etc.) is brought into contact with it. Furthermore, the packing of the solid phase greatly influences the rate at which water, oxygen and carbon dioxide,—as well as the dissolved salts, ions, etc., of the original liquid,—may come to the root surfaces of the plant. Since no means have been devised by which the extremely complicated 3 phase system of even such a simple soil as moist quartz sand may be analyzed and understood, and since it is often possible to obtain well-grown plants in the single-phase media offered by aqueous solutions alone, it is highly desirable that the physiological relations between such liquid media and plants rooted therein should be well worked out. Only in this manner can the first steps be made toward an understanding of the simpler principles of the salt nutrition of plants.

Nutrient solutions for physiological experiments with plants have generally been prepared with four or five salts besides the iron salt, but Shive's studies made it clear that satisfactory growth may be obtained, with wheat and buckwheat at least, when the six main mineral elements are supplied as the nitrate, phosphate and sulphate, of potassium, calcium and magnesium—that is, with only three salts besides the very small amount of the one containing iron.

Plants growing in aqueous solution are influenced by several features or properties of the solution, as far as its salt content is concerned. The first of these features, which all work together to produce what may be called the solution-complex, is the total concentration. This may be measured in terms of the lowering of the freezing point, the osmotic value, the vapor tension, the ratio of salt molecules to water molecules used, the number of gram-molecules of salts contained in unit volume, etc. Each dissolved salt, of course, has its own partial concentration, and the total concentration of the medium is simply the sum of all the partial concentrations (however these may be measured)

of the various component salts. It is clear that the total concentration may have any one of a very large number of magnitudes.

A 3-salt solution may be said to have another important characteristic besides its total concentration; namely its particular set of salt proportions. The total amount of salts in unit volume may be the same for two different solutions, but nevertheless the proportions of the three salts may not be at all alike in the two cases. The salt proportions represent what has been called the physiological balance of such solutions, although this term should include all other solutes besides the salts—such as oxygen, carbon dioxide, etc.

Whether a plant grows well or poorly in a given nutrient solution depends as far as the salts are concerned, upon: (1) the total concentrations, (2) the salt proportions, and (3) the kinds of salts employed. If we supply the six main essential mineral elements in the form of just three salts, and if we consider these salts as composed of the potential ions, K, Ca, Mg, NO₃, H₂PO₄, and SO₄, we have to deal with six different types of 3-salt solution, as has been pointed out by LIVINGSTON and TOTTINGHAM,¹ for the potassium may be placed in the solution as either the nitrate, the di-hydrogen-phosphate, or the sulphate, and similarly for the other two cations. The solutions employed in the experiment dealt with in this paper were 3-salt solutions in this general sense.

The brief summary just given shows how very complex a nutrient solution is, even when it is limited to three salts besides the trace of iron salt, and how extremely difficult it is to determine experimentally what may be the best set of salt-solution conditions for the growth of any given plant in any stated phase of its development and under any given complex of climatic conditions. In order to determine what sort of solution complex may represent the best physiological balance for any given set of non-solution conditions, it is necessary to test experimentally a large number of different solutions. But if the solutions to be tested are to be well chosen, so as to represent the range of physical, chemical, and physiological possibilities, choice must be guided by some mathematical system. The most satisfactory system for this sort of work is the one introduced into culture experiments by SCHREINER and SKINNER.² This is based on a triangular diagram, representing a 3-dimensional

system of coördinates on a plane surface. By this means, equally-spaced points in the diagram represent various different solutions of a single type. All contain the same salts and have the same total concentration, but each one differs from all the others in its salt proportions.\(^1\)

Little serious attention has thus far been given to the partial concentration of the very important solutes, oxygen and carbon-dioxide, in such nutrient solutions as are here considered. Experimental solutions are generally prepared very carefully with regard to their salt contents, but their oxygen and carbon-dioxide contents are mainly left to chance. In the experiment here reported no attention was given to the partial concentrations of these two non-salt solutes, excepting to plan the cultures so that all jars were of the same size, shape, etc., all solutions were employed in the same volume and with the same extent of aerial surface, and all were renewed at the same time intervals.

Similarly, the temperature of the nutrient medium (and of the roots surrounded by it) is of great importance in determining the manner and rate of growth of the culture plants. In experiments of the kind with which we have to deal, the temperature of the nutrient solution follows rather closely the air temperature of the place where the cultures stand, especially when the direct heating effect of sunshine upon the culture jars is largely prevented by the use of an opaque jacket around each jar. It must be remembered, however, that the growth of the culture plants is externally influenced not by the root environment alone but also by the surroundings of the leaves, etc., which are not in the solution but are bathed by the air. Consequently, the kind of growth that will be obtained by the use of any given plant with any given solution is not to be predicted from a knowledge of the chemical make-up and temperature of the solution; to these solution conditions must be added all the influential conditions that are active in the aerial surroundings of the plant. Among these aerial conditions may be mentioned, especially: air temperature, air humidity, air movement, the carbon-dioxide content of the air, and the group of conditions generally treated as those of light (radiation

\(^1\) The whole subject here reviewed is clearly presented in a "Plan for co-operative research on the salt requirements of representative agricultural plants," published by the Special Committee on Salt Requirements of Representative Agricultural Plants, of the Division of Biology and Agriculture of the U. S. National Research Council (Baltimore, 1919), copies of which may be obtained from the Committee.
conditions. No attempt was made in our experiment to control either the solution temperature or any of the aerial conditions; these were furnished by the greenhouse room in which the cultures stood and they were approximately like those of any rather dry, artificially heated greenhouse in which plants are being grown, in a climate like that of the month of February in Baltimore. Some of the aerial conditions of our culture plants are roughly described by the thermometric and atmometric data that will be mentioned below.—The present preliminary study is thus seen to deal with the relations holding between (a) the growth of young wheat plants in solution culture, and (b) the non-temperature conditions of the solution, when the frequency of change of the solution and the solution temperature, as well as all the influential aerial conditions, had the intensities and fluctuations that characterized our greenhouse during the experiment period. It is unfortunate that plant physiology has not yet advanced far enough to make it possible to control a larger number of the influential conditions, or at least to record their values in quantitative terms. It is safe to say that the results obtained by us would have been very markedly different, if the climatic conditions and the oxygen and carbon-dioxide conditions of our cultures had been sufficiently different. Also, the results would surely have been different if we had employed some other kind of plant.

Tottingham,1) Shive,2) and others have noted that when wheat seedlings are grown for several weeks in nutrient solutions having certain characteristics, the plants show recognizable symptoms of what may be called physiological or nutritional diseases. Some 3-salt solutions are well-balanced and support good growth, while others (differing from the well-balanced ones in total concentration, salt proportions, or perhaps only in kinds of salts used) show sickly plants, and in some cases the symptoms of sickness are clear enough to be described morphologically. Among the diseased conditions thus produced in young wheat plants grown in well-controlled aqueous solutions is one called by Tottingham magnesium injury. Shive found that this form of injury occurred after the first two or three weeks of growth in 3-salt solutions made from KI\textsubscript{2}PO\textsubscript{4}, Ca(NO\textsubscript{3})\textsubscript{2} and MgSO\textsubscript{4}, having total concentrations corresponding to either 1.75 or 4.00 atmospheres of osmotic pressure, and having MgSO\textsubscript{4}: Ca(NO\textsubscript{3})\textsubscript{2}-ratio values of 3.00 or

2) Shive, 1916; i.e.
above (especially from 10.0 to 18.0). While the $\text{MgSO}_4: \text{Ca(NO}_3)\text{}_2$-ratio value required to produce noticeable injury was found to be influenced by the total concentration, it did not appear to be affected by the amount of $\text{KH}_2\text{PO}_4$ in the solution; it seemed to be dependent especially on the ratio of Mg to Ca.

Since there has been considerable discussion in the literature,\(^1\) regarding the nutritional relations of magnesium and calcium for plants, and since Japanese writers have taken part in the work hitherto accomplished on this problem, we originally undertook to make a special study of the magnesium injury described for wheat by TOTTINGHAM and SHIVE. Our prospectus included a morphological and histological study\(^2\) of the injured plants, as well as experimentation on the nature of the environmental conditional complexes that bring it about. After some preliminary work we decided to include a thorough experimental study of the growth of wheat seedlings in 3-salt solutions made up from the five potential ions, Ca, Mg, NO\(_3\), $\text{H}_2\text{PO}_4$, thus omitting $K$ altogether. It seemed that such a study might bring forth new information regarding the Mg-Ca relations of these plants, and that the results might also throw light on the K relation. Some of the results of the first complete series of these wheat cultures without any potassium in the medium form the subject of the present paper.

**Methods of Experimentation.**

"Marquis" spring wheat (of the same lot of 1918 seed as has been used by the coöperators with the Special Committee of the U. S. National Research Council; see p. 76, footnote) was employed, and the seedlings were first sprouted on a germination net similar to the one used by SHIVE, and with SHIVE’s solution R5C2 (0.1 atmosphere). When they were about 3 cm. high they were placed in perforated, paraffined corks of the form first used by TOTTINGHAM. Each cork

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2) Mr. MORITA showed very great aptitude for this sort of combination of morphological and physiological study; his mind seemed to turn with equal readiness to the structural-static considerations and to the chemical-physiological ones. Had he lived and continued in scientific work he would have excelled in both these phases of botany. Marked ability in these two lines is rarely encountered in the same person.—B. E. L.
carried five seedlings, and was fitted into the mouth of a "pint Mason" jar of hard glass, which held the nutrient solution (about 440 c.c.). The jars were covered with paper jackets such as were used by Shive, to exclude most of the light, and all stood on a continually rotating table in one of the greenhouse rooms of the Laboratory of Plant Physiology of the Johns Hopkins University, at Baltimore. Temperature, evaporation and sunshine (radio-atmometer) records were obtained for the experimental period, which lasted from January 28 to February 20, 1920. The temperature for the period ranged between a minimum of 11° and a maximum of 30°C. The total corrected loss from a Livingston standard white spherical atmometer (located on the rotating table with the cultures) was 456.1 c.c. for the period. The radio-atmometric difference (corrected loss from black sphere minus corrected loss from white) was 4.4 c.c. for the period. The last two data show that the evaporating power of the air in the culture room was relatively low and that the sunshine intensity was very low indeed.

The solutions were renewed after 3½ days, at the end of the first week and at the end of the second week. A single culture represented each of the 90 different incomplete solutions tested, and six control cultures were provided with a solution that was complete and well-balanced for the early stages of wheat. The control solution used was Shive's R5C2 (1.75 atmospheres), having the following partial volumemolecular concentrations (gram-molecules per liter) of the three main salts: \( \text{KH}_2\text{PO}_4 \), 0.018; \( \text{Ca(NO}_3\text{)}_2 \), 0.0052; \( \text{MgSO}_4 \), 0.015. Of course these controls, as well as all the experiment solutions, contained a small amount of iron; about 3 mg. of suspended \( \text{FePO}_4 \) was added to each culture jar at the beginning and at every renewal of solution, in the manner followed by Shive.

The 90 different solutions without potassium (all having a total salt content of 0.015 gram-molecule per liter—of all salts taken together—and an osmotic-pressure value of about 1.00 atmosphere) were grouped in six series of fifteen solutions each, each series representing fifteen different sets of proportions of a single set of three salts. There were thus six different sets of salts, all that are logically possible on

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the basis of the five potential ions included. Table I, column 1, shows the six solution types, as characterized by their component salts.

The total volume-molecular concentration of all salts taken together (always 0.015 gram-molecule per liter, as has been said) was considered as divided into seven equal parts, and then fifteen different solutions for any type were so prepared as to apportion the seven units (a unit was 0.00214 gram-molecule in every case, being one-seventh of 0.015 gram-molecule) among the three salts in all possible ways. Table I shows that all six types of solution were alike in that each contained a nitrate salt, a di-hydrogen-phosphate salt and a sulphate salt. The cation proportions differed from type to type but the anion proportions were the same in the corresponding solutions of all types. Of course it is to be noted that, on account of the valences, the $\text{SO}_4^-$ unit is $\text{SO}_4^-$ but that the other two anion units are double, being $(\text{NO}_3^-)_2$ and $(\text{H}_2\text{PO}_4^-)_2$.

The solution designations in table I refer to the salt proportions and to the triangular diagram mentioned above (see also fig. 1); the number following the letter R (for "row") denotes the number of sevenths (of the total molecular concentration) due to the nitrate salt $(\text{NO}_3^-)_2$, the number following the letter S (for "solution") denotes the number of sevenths due to the di-hydrogen-phosphate salt $(\text{H}_2\text{PO}_4^-)_2$, and the number of sevenths due to the sulphate salt $(\text{SO}_4^-)$ is found by subtracting both of the preceding numbers from seven. Thus, solution R2S3 had 2 sevenths of its total volume-molecular concentration due to the $(\text{NO}_3^-)_2$-salt, 3 sevenths due to the $(\text{H}_2\text{PO}_4^-)_2$-salt, and 2 sevenths due to the $(\text{SO}_4^-)$-salt. This interpretation applies to solution R2S3 in every one of the six types. The six types are distinguished by letters (A, B, etc.), and the type of any given solution is indicated by placing the type letter before the salt-proportion formula; thus BR2S3 denotes a solution (see table I) made up of: Mg$(\text{NO}_3^-)_2$, 2 sevenths; Ca$(\text{H}_2\text{PO}_4^-)_2$, 3 sevenths; and Ca$\text{SO}_4$, 2 sevenths.

**Table I.**

Showing the six different solution types and the fifteen different sets of salt proportions of the solutions studied, together with the score values for each solution by each of five different growth criteria, and also the generalized or average score values (representing the combination of all five criteria) for each solution.
### SOME SOLUTION CULTURES OF WHEAT

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Results.

After three weeks in the culture jars the plants of the poorest cultures appeared to be about to die and it was therefore decided to end the experiment, although many cultures still seemed perfectly healthy. Final observations were made on February 20.

No cases of Tottingham's "magnesium injury" were observed in any of these 3-week cultures, although the control solution is known to produce mild forms of this physiological disease under certain climatic conditions. Perhaps the low evaporating power of the air and the weak sunlight of our experiment may explain the freedom of our cultures from any of the recognized symptoms of this disturbance. The best plants of the incomplete solutions would have been considered as very satisfactorily grown but for the presence of the still better control plants. The poorer cultures were characterized by smaller plants, with less sturdy stems and with many leaves that were partly or wholly yellow or even dry. In order to obtain comparative numerical values for the various solutions each culture was given a relative score value, by inspection, for each of five different observational criteria. The plants were not weighed. The five observational criteria employed were: total height (H), leaf condition (L), sturdiness of stems (S), root branching (Rb), and length of main roots (R1). Total height denotes the distance from the seed to the extreme tip of the plant, the leaves being extended upward. Leaf condition takes account of the yellowness of leaves and the amount of dead foliage. By sturdiness of stems is meant mainly the apparent stem diameter at the base of the plantlet. Root branching denotes the frequency of branching of the roots.

For each of the three criteria referring to tops the plants were classified into three groups. The cultures of the best group were each given the score value 1; those of the medium group, 2; and those of the poorest group, 3. The same plan was followed for the two root criteria, but the roots of certain cultures were so very poor (being all dead or nearly so, and without considerable growth since the plants were placed in the jars) that a fourth group was established in these cases, and the cultures of this group were given the score value 4. The control plants were given the value 1 for every criterion, there being no case where any culture in an incomplete solution surpassed the controls, which were very satisfactorily consistent among themselves.

It is to be noted that unity represents comparative perfection in growth and that greater numerical values (2, 3, 4) represent successive
degree of apparent *poorness*. The physiological worth of any solution, by any criterion, is thus really proportional to the *reciprocal* of the corresponding relative score value. The solutions might be considered as "first class", "second class", etc., in the ordinary sense of these terms.

Table I presents the relative score values for all the ninety solutions without potassium, according to each of the five growth criteria. The table is divided into six parts, each part representing the fifteen different solutions of each type. At the extreme left of each part is shown the designation of the type and the three main salts used, as has been said. In the second column are shown the symbols for the five criteria, as just described. The remaining 15 columns show the values for the fifteen different sets of salt proportions, these being designated by the symbols already explained. At the bottom of each part of the table are shown the average score values, for all five criteria combined.

Since the available data represent only a single trial,—one culture of five plants for each of the ninety solutions,—the following discussion will be confined to a consideration of the average or generalized values. These averages may be taken to represent approximately the relative physiological worths of the respective solutions. They range from 1.4, for the best incomplete solutions, to 3.4, for the poorest. Of course the average for the control solution (with potassium) is 1.0. The averages have been grouped into three classes: values from 1.0 to 1.7, inclusive, are regarded as *good*; those from 1.8 to 2.6 are *medium*, and those from 2.7 to 3.4 are *poor*. Generalized values of the *good* class are shown in table I by black-face type, while those of the *poor* class are shown by Italic type. Table II presents a summary of the solutions of the *good* and of the *poor* class. In the *good* class the three very best solutions (1.4) are shown by black-face type (these are just alike in their scores by all criteria) and those that have a score of more than 2 by any one criterion are shown by Italic type. It is seen that all but the three best (11 out of 14) are alike in having the generalized value of 1.6, and all of these are to be considered as closely approaching the three best (1.4), those indicated by Italics being not as promising as the others (but see also the footnotes of the table).
Taking everything into account, the 14 good solutions may be arranged as follows:—First, and best AR2S1, ER3S1, and ER4S1 (these being practically alike in physiological worth). Second, AR1S1, AR1S2, BR4S1, BR5S1, CR1S1, CR3S1 and ER5S1 (these being practically alike). Third, FR5S1 Fourth, ER1S1. Fifth, and worst (for the good class), AR3S1 and DR1S1.

In the poor class the three very poorest solutions (3.4) are shown

<table>
<thead>
<tr>
<th>Solution</th>
<th>Average value</th>
<th>Salts used</th>
<th>Solution</th>
<th>Average value</th>
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<sup>a</sup> These solutions show score values of either 1 or 2 by every criterion. They are to be regarded as the best of those having the generalized value 1.6.

<sup>b</sup> Solution FR5S1, although graded as 3 by root branching, is graded as 1 by sturdiness of stems, the only case in the entire series where the stems were equal to those of the controls. It must be regarded as a promising solution.

<sup>c</sup> Solution ER1S1 has a better grade than solution FR5S1 by leaf condition, but the former is worse by sturdiness of stems (see table 1); otherwise the score values are alike for these two.
in table II by black-face type. None of these has any score value of 1 by any criterion. Those shown by Italic type all have the score value 2 by some criterion and thus may approach the medium class. All 19 solutions of the poor class are surely of very low physiological worth.

It appears that the most obvious outcome of this experiment is the fact that some of these solutions without any potassium did give very good growth of the plantlets and that the best of these are to be considered as ten-fourteenths (or five-sevenths) as good as the control solution, which is one of the very best solutions for young wheat plants thus far described. This ratio, ten-fourteenths, is of course the ratio of the physiological worth of the three best incomplete solutions (1.4) to that of the control solution (1.0). As has been said, the physiological worths of the solutions are to be considered as proportional to the reciprocals of their generalized score values. The generalized score value for the best solutions without potassium is 1.4, and that for the controls is 1.0, so that we have the expression

$$\frac{1}{1.4} \div \frac{1}{1.0}$$

to represent the ratio of their physiological worths, the valuation of this expression being $\frac{1.0}{1.4} \div \frac{10}{14} = \frac{5}{7}$, or 0.714.

To give the reader a mental picture of what has been regarded as good growth in the preceding discussion, we may take advantage of the fact that the score values for the criterion of height (H) were originally derived from actual measurements, recorded in centimeters. The tallest plants of the entire series were in a control culture and this culture showed an average height of 44.5 cm. The average height of all the control plants was 40.8 cm. and the average height for the three best cultures without potassium (AR2S1, ER3S1 and ER4S1) was 39.9 cm. By the criterion of height alone these three best incomplete solutions are almost as good (39.9 : 40.8 = 0.98) as the controls. Of course the score values obtained for these three solutions by means of the other plant criteria that were used, also take part in the generalized value (1.4), which, as has been said, is only five-sevenths as large as that for the control solution (1.0).

Many nutrient solutions have been put forward in the literature as suitable for green plants. Thirteen of these were simultaneously compared by SHIVE (1916), using young wheat plants. SHINE's table XIV shows the comparative values that he obtained, ranging from 1.00 (SACHS' and SCHIMPER's solutions) to 1.74 (SHIVE's R5C2—1.75 atm.). Every one of these solutions contains all of the chemical elements generally regarded as essential in the medium for ordinary
plants, with the single exception of Schreiner and Skinner's solution, which lacks magnesium. Although the growth criteria used by Shive were not the same as those employed in the present study, it is nevertheless interesting to determine about where on Shive's scale of comparative values the three very best solutions without potassium may be inserted. This may be done in a roughly approximate way by considering that Shive's best solution had a value of 1.74 on his scale and that Morita's three best solutions (without potassium) are classed as five-sevenths as good as Shive's best by the present test. Now, five-sevenths of 1.74 is 1.24, which may be regarded as the approximate value, on the Shive scale, for each of Morita's three best solutions. Examining Shive's list, we find that Morita's three best solutions (1.24) apparently lie between Tollens' solution (1.23) and Schreiner and Skinner's solution (1.26). In a similar manner it may be calculated that Morita's solution FR581 (1.08) lies between Detmer's solution (1.03) and Tollens' solution (1.23). Other solutions of the present series may be located on Shive's scale in a like way.

It therefore seems probable that, for the first three weeks of growth of this wheat, after germination to a height of 3 cm., it is possible to obtain better development with a solution in which no potassium is used (but in which the salts are employed in proper proportions) than can be obtained from any one of several of the poorer complete solutions that have been employed by physiologists (Sachs, Schimper, Detmer, Tollens—see Shive's paper, 1916). The three best incomplete solutions of the present study seem to be each about equal in physiological value to Tollens' complete solution and to Schreiner and Skinner's incomplete solution (without magnesium). The last-mentioned writers appear to have regarded their solution as a sort of standard for comparison, and they used young wheat plants, so that it is particularly important to emphasize that as good growth of these plants may be expected from either of Morita's three best solutions as from Schreiner and Skinner's solution.

It is of course improbable that any solution treatment not involving potassium may be found that will produce good growth to maturity, but such an assumption cannot be seriously adopted without very much more comprehensive experimental study than has ever yet been attempted. The outcome of the present preliminary investigation once more emphasizes the fact that salt proportions and total concentration must be carefully considered whenever the problems of the mineral nutrition of plants are dealt with. The experiments com-
monly set up for elementary students of plant physiology, to show the
effect of the omission of one or another of the essential chemical
elements, must be regarded as quite worthless. For such demo-
strations it is logically essential that the incomplete solution used be
the very best one possible without the omitted element. The further
development of physiology and fertilizer practice in agriculture requires
that the sort of work here preliminarily presented should be carried
much further. A next step along the path of this study might well be
to carry out experiments similar to those here described, including only
the solutions characterized as belonging in the good class, and to
continue the cultures until the best ones show marked injury or cessa-
tion of growth. It would be desirable, furthermore, to test these sets
of salt proportions with total volume-molecular concentrations different
from the one used in our series; it seems, especially, that more dilute
solutions might have greater physiological worths than any tested by
us. It would also be desirable to renew the solutions in the cultures
at much more frequent intervals, or, better still, to arrange the cultures
so that the solutions would be constantly renewed.

A rather thorough study of physiological balance in this series of
solutions was originally contemplated, but the fact that the work had
to be discontinued at the end of the single preliminary series makes it
undesirable to attempt a detailed discussion of the relations between
the salts used and salt proportions, on the one hand, and the growth
values, on the other. The numerical data obtained are very consistent
among themselves in many ways, however, and some of the most
striking observations in this connection may be added.

All of the plant data presented in table 1 were placed upon
triangular diagrams of the form used in planning the solutions, and
these were inspected for relationships between growth and salts and
salt proportions. Only the six diagrams for generalized score values
(averages, table 1) will be considered here. These six diagrams are
shown in figure 1. In studying these it is to be remembered that any
set of salt proportions represents exactly the same proportions of the
atomic groups \( \text{NO}_3^- \), \( \text{H}_3\text{PO}_4^- \), and \( \text{SO}_4^- \) on all six diagrams. A given
set of salt proportions differs from one solution type to another only
(1) in the proportions of Ca and Mg, and (2) in the way these two
potential cations were combined with the three potential anions in the
salts used. On the diagram of figure 1 the three very best solutions
(generalized score, 1.4) are each shown by a heavy circle. The remain-
ing solutions of the good class as above characterized (1.6) are shown
by lighter circles, those designated by Italic type in table II having a
vertical diameter drawn within the circle. The solutions of the medium class are shown by small dots. The three very poorest solutions (3.4) are each denoted by a heavy triangle, and the remaining ones of the poor class as above characterized are shown by lighter triangles, those indicated by Italic type in table II having a vertical line through the triangle.

A comparison of the diagrams strongly suggests that the better solutions are generally characterized by low relative partial concentrations of the atomic group \((\text{H}_2\text{P}O_4)_2\), while the poorer solutions have high relative partial concentrations of this atomic group. Solutions of the good class are shown on the left margin of the diagram in every case but one (AR1S2). Solutions of the poor class are never shown on the left margin and every diagram shows one or more poor solutions among the three that are nearest to the angle at the right of the diagram.

There are, of course, a number of discrepancies among the six diagrams (fig. 1), but these cannot be interpreted from the single series of cultures for which we have data; they may or may not be important. But it does seem to be very strongly suggested that there is no marked relation between the salts used in these incomplete solutions and the physiological worths of the solutions; in other words, the Mg: Ca-ratio is not itself apparently influential in determining whether a solution is good or poor. The results indicate clearly that the relative partial concentration of the di-hydrogen-phosphate is the controlling condition encountered here. No matter what may be the proportions of nitrate and sulphate, the solutions are generally good with low and poor with high phosphate concentrations. No ratio value appears as a controlling condition.

It seems probable that this state of affairs may not be primarily related to the atomic group \(\text{PO}_4\), but may depend upon the hydrogen-ion concentration in the solution; for the more \(\text{H}_2\text{PO}_4\) there is in unit volume of the solution the greater should be its \(P_H\)-value. This matter was not directly studied, but may readily be taken up by any investigator at any time, since our solutions have been described so that they may be easily reproduced. The importance of hydrogen-ion concentration is receiving attention from many physiologists. When further tests are to be made along this line it would be well to plan for sets of salt proportions lying outside of our diagram and at its left, thus including some solutions with less than one-seventh of their total salt content due to the \((\text{H}_2\text{PO}_4)_2\)-salt. These would have lower values of \(P_H\), as would also the more dilute solutions already suggested.
as promising.

In conclusion, it may be stated that a 3-salt solution without potassium may produce very satisfactory growth of very young wheat plants if the other essential elements are all present and if the partial concentration of the di-hydrogen-phosphate salt is very low, as compared with the partial concentration of the nitrate and sulphate salts combined. It would be valuable to know what would be the effect of substituting other phosphate salts, such as the mono-hydrogen-phosphates, etc., in place of the di-hydrogen forms employed in the preliminary experiment here described.

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Legend for figure 1.

Diagrams showing good and poor solutions of each of the six types. Good solutions are denoted by circles, poor ones by triangles. Each angle of the triangle represents a solution having five-sevenths of its concentration due to one salt and one-seventh to each of the other salts. The salt named at any angle is the one that predominates in the solution represented by that angle. Note the similarity of all six diagrams and that good growth usually corresponds to low partial concentration of \((\text{H}_2\text{PO}_4)_2\), while high partial concentrations of this atomic group generally correspond to poor growth.
Fig. 1.