A COMPARISON OF THE DEFICIENCY EFFECTS OF THE DIFFERENT ESSENTIAL ELEMENTS ON THE GROWTH OF TOBACCO PLANTS IN SOLUTION CULTURES.

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INTRODUCTION

It is of considerable practical as well as theoretical importance to be able to recognize the type of growth produced by plants when the medium,in which, they are growing is deficient in one of the elements essential to normal development. Reduced growth as expressed in total dry matter produced is a measure of development obtained, but the accompanying growth manifestations are of great importance as a means of recognizing the underlying cause of the condition, thus making possible the correction of the trouble when seen under other similar conditions. The literature is well supplied with quantitative data as to the final weights produced when themedium in which plants were allowed to develop is lacking or deficient in an essential element. There is rarely a case, however, where the author has attempted to discuss the gross morphology of the plants in question in the particular experiment. It is also the usual thing to limit the investigation to a single element. In a few cases detailed anatomical studies of such plants have been made which have contributed much to our knowledge along these lines.

There is possibly no plant better suited to a study of this kind than tobacco since it is unusually responsive to all changes in environment. Its large leaf surface affords an excellent opportunity for the appearance of marked manifestations of deficiency or hunger symptoms, making easier their distinction. If the wheat plant, for instance, were used, many changes would pass unnoticed which are perfectly evident where the tobacco plant is the subject of such a study. In a sense, therefore, it may be said that the tobacco plant will magnify the growth manifestations to such an extent that they can be observed with the naked eye in their proper relation. Once the distinctive symptoms for a deficiency of each element are known for one plant species such as the tobacco plant, their recognition in other plants will be relatively simple. Although there may be minor variations in the symptoms shown by different plant species, the characteristic effects are likely to be essentially the same.

The elements which have been studied are as follows: nitrogen, phosphorus, potassium, magnesium, calcium, boron, sulfur, manganese, iron and chlorine. All these elements are now generally admitted to be essential for the growth of all higher plants with the possible exception of chlorine. The tobacco plant when allowed to develop in a media where any one of these elements is deficient, again excepting chlorine, produces a characteristic as well as reduced growth. There are certain similarities between the nutritional deficiency effects produced by the different elements but on close examination there are certain features which serve to distinguish them. A reduction in growth is characteristic where any one element is deficient. Dry weights alone, therefore, fail to present a true picture of the situation. If an element is essential to growth, normal growth is impossible in its absence but actually complete absence is rarely attained. The seed contains small quantities of essential nutrients or if the plants are grown for a time in the presence of all elements, the tendancy is to set up a reserve of those elements which are readily mobile. Also, even the purest chemicals readily obtainable carry small amounts of various elements as impurities. Any experiment of this kind, therefore, must of necessity resolve itself into a study of the growth of the plant under conditions where the element under consideration is more or less deficient but not entirely lacking. Solution cultures were used in this study. This method is almost ideal for such studies since the element can be added or withheld at will and the entire root system of the plant can be transferred bodily at any time in its life cycle to the desired solution. This is not possible where solid media are used.

REVIEW OF LITERATURE

It is not the intention in this paper to attempt a complete review of the literature touching upon this subject but, to endeavor to refer to a few of the outstanding contributions which have added to our knowledge along these lines. Gris (7) in his studies on iron chlorosis of plants (1844-47) was possibly the first to describe a deficiency effect on plants and give its remedy. Salm-Horstmar (13 and 14) was one of the pioneers (1849 and 1851) in this type of study. He used the oat plant which was grown in different solid media particularly charcoal derived from pure sugar and sand, to which certain chemicals were added so as to omit or include the essential elements as desired. This author gives a brief description of the oat plant growing in a media from which the different essential elements were withheld. Maze (8 and 9) in 1914 and 1919 published the results of his studies with maize (corn) grown in water cultures. He does not attempt to describe in detail the symptoms produced when the medium is deficient in an essential element. In 1925 Ginsburg (6) gave the results of his studies on the soybean plant. He reports more or less distinct growth effects for the several ions which he considered. The solutions used in this work did not contain the same parts per million of the ions under investigation and in some cases foreign ions were introduced. In a paper published in 1925 Gericke (5) reports stimulation of growth in wheat plants when some of the ions were removed for a period during growth. While details as to the amount of salts used in preparing the nutrient solutions employed in this work are only briefly stated, apparently this investigator increased one of the ions already present in the solution when another was omitted. In the solution from which phosphorus was omitted, for example, where the greatest stimulation is reported, the nitrate ion was increased. It would appear that the plants might have been stimulated in growth due to the presence of more nitrate and were able to develop for the time under consideration without showing the effects of phosphorus deficiency.

If there is such a thing as stimulation for a temporary deficiency as reported by Gericke (5) certain points must be considered. Among these are, the season of the year when the experiments are conducted and the concentration of the ions in the solutions in question. If earlier stages of the experiments are conducted at a season when light conditions are poor the plants growing in the control solution go through their cycle under these unfavorable conditions. The plants in the solutions lacking a particular ion are delayed in completing their cycle until they are transferred to a complete solution, when more favorable light conditions have developed, stimulation may result as compared with plants in the control solution for the entire period. On the other hand the concentration of a given ion may be unfavorable for growth or the question of total concentration or reaction of the solution which is partially corrected by removing this ion may account for an apparent stimulation due to deficiency. The instance given above, where the nitrate ion is substituted for the phosphate ion in a solution which is low in nitrate, a temporary stimulation would necessarily result since, as shown later in the paper, it is difficult to produce phosphorous deficiency late in growth if the plant is supplied with this ion during its early growth phases. In the light of these considerations it is doubtful if any of these effects can be considered as true stimulations in growth, being due merely to special factors which would hardly operate where proper control of conditions is exercised. Where these factors have been eliminated or properly evaluated as reported in the present paper no consistent stimulation has been found. Russell (12) in a recent edition of his monograph, "Soil condition and plant growth", brings up to date the contributions on this subject.

Studies on the nutritional deficiency effects manifested by the tobacco plant have not been extensive and very few attempts have been made to compare these effects. Wilfarth et al (16) in 1902 reported the effect on the growth of this and other plants when potassium was lacking. Garner et al (4) in 1922 have described the symptoms of magnesium deficiency on tobacco and corn. This same author and his associates (1) have described and illustrated magnesium deficiency on tobacco. Moss et al (11) in 1927 have presented the results of field studies when certain essential elements were absent from the fertilizer mixture. Valleau and Johnson (15) report that "Frenching" of tobacco is due to nitrogen deficiency, but as will be discussed later in this paper under effects of nitrogen deficiency, this trouble has not been observed under conditions of extreme nitrogen shortage. McMurtrey (10) in a paper published in 1929 described the effects of boron deficiency on tobacco and demonstrated the improvement in growth obtained when tobacco is grown in an aerated as contrasted with an unaerated nutrient solution. Garner et al (2) in a recent paper (1930) described and illustrated the effects of calcium deficiency on the growth of tobacco. In a paper published the same year these same authors (3) discuss the effedt of chlorine on the growth of the tobacco plant.

METHODS OF EXPERIMENTATION

The solutions used in these studies were made up on the basis of the complete solution which was prepared so as to contain the approximate proportions of elements which an average of a large number of chemical analyses of the tobacco plants shows, as mentioned in a previous paper (10). In these studies ammonium chloride was added to the control solution used which increased the nitrogen content slightly and added chlorine to the solution used in the previous study. Table 1 shows the volume molecular concentration of chemically pure salts used in preparing the stock solutions. These stock solutions were diluted 20 times with distilled water for growing the plants. The distilled water used was obtained from a tin lined still and stored in 5 gallon glass bottles, until used. The complete or control solution when diluted contained the following elements expressed in round numbers as parts per million; nitrogen (N), 225; phosphorus (P) 65; potassium (K) 125; calcium (Ca) 245; magnesium (Mg) 30; sulfur (S) 20; and chlorine (Cl) 50. Boron (B) 0.5 and manganese (Mn) 1.0 p.p.m. were added to this solution in the form of boric acid (H_3BO_3) and manganese acetate ($Mn(C_2H_3O_2)_2$), respectively, as chemically pure salts. Iron usually in the form of iron citrate (U.S.P.) was added daily to all cultures during the first few weeks and every other day during the last few weeks at the rate of 1 c.c. of a 0.5 per cent solution per liter of culture solution. The form of iron salt used was different with the cultures from which it was desired to withhold manganese. Ferrous sulphate free from this element was substituted for the citrate in this case. The solutions which did not carry one of the ions contained the same parts per million as given for the complete solution for other ions, with only slight variations. √

It is to be seen from table 1 that in order to supply the same quantity of nitrogen it was necessary to substitute some ammonia nitrogen for nitrate nitrogen in certain solutions. While this method of maintaining a constant supply of elements may be open to objection it was considered more satisfactory than introducing a foreign ion or increasing ions already present, as Ginsburg has done (6), or to only increase ions already present as done by Gericke (5). The solution to which no nitrogen was added is open to the objection that it was supplied with calcium as the carbonate, but in order to determine if this solution would give satisfactory growth, with addition of nitrogen, a second control (C^2) was introduced in series 3 with the nitrogen supplied as ammonium nitrate. This control also serves to throw light on whether ammonium nitrate as used in the solution deficient in calcium will produce satisfactory growth with calcium supplied in this form, as well as in the other cases where the ammonia form of nitrogen is substituted for the nitrate form. When properly prepared, the stock solutions of the volume molecular concentration given in the table show little or no precipitate with the exception of the solutions containing calcium carbonate. The necessary precautions are that calcium nitrate be dissolved separately and not added to the other dissolved salts until most of the volume of water has been added. However, as will be shown √

later the heavy precipitate produced by the addition of calcium carbonate does not materially affect the ability of the solution to produce satisfactory growth when all elements are present.

The reaction of these solutions when freshly prepared, as determined by use of the quinhydrone electrode, varied from around 4.0 to 8.0 pH. The solutions designated C^1, S, Fe, B, Mn, Mg and K ranged between 4.0 and 4.5 pH. The solutions to which no chlorine and no calcium were added were between 4.6 and 5.0 pH. The freshly prepared solution containing no added phosphorus showed a pH around 6.0, while the solutions designated C^2 and N ranged between 7.6 and 8.0 pH. The control solutions C^1 and C^2 therefore showed approximately the two extreme pH values. Since growth in these two solutions was normal it would appear that the reaction range of these solutions was satisfactory for growth of the tobacco plant so that the observed effects on growth may be attributed to a deficiency of the ions in question and not to the reaction of the solution.

In preliminary trials in which the weights of plants were not obtained the above solutions, which will be referred to as standard solutions, were compared with solutions made up of three salt combinations, .005 volume molecular concentration, as suggested by Gericke (5). Boron, manganese and iron were supplied as in the standard series, using the three salt control solutions to observe effects when these elements were omitted. In series 2 a comparison was made between the standard group of solutions and a group of solutions devised by Johnston[1] in which the salts used and the parts per million of essential elements varied to some extent from the standard solutions and none of these solutions contained chlorine save the complete (C^3). These solutions also produced the typical growth effects that will be discussed in due course in this paper.

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[1] The solutions referred to were devised by Dr. Earl S. Johnston formerly of the University of Maryland, for deficiency studies with the tomato plant.

The containers used for growing the plants were commercial two-quart glass fruit jars, except that for the plants from which manganese was withheld. In this case two-liter pyrex beakers were substituted. This change was made because it was found in preliminary trials that omitting manganese produced no effects where fruit jars were used as containers. The plants were held in position by paraffined cork stoppers or by paraffined boards with suitable holes, placed on the beakers. It was necessary to stake the plants to hold them upright. Both beakers and jars were wrapped with two thicknesses of heavy wrapping paper to exclude most of the light, thereby preventing growth of algae in the solution. In all cases where yields are reported the cultures were aerated by bubbling with compressed air. The rate during the first four weeks of growth was approximately one liter of air per hour but it was found necessary to double this rate during the last few weeks of growth. If for any reason the bubbling was discontinued during the last week or so of growth the roots at once began to die, resulting in a wilting of the leaves and a drying up of many of the lower leaves. Such plants did not die but were markedly stunted in growth.

In some cases the solutions were renewed, whereas in others there were no renewals. The cultures were made up to the original volume by adding distilled water every few days during the early stages of growth and every second or third day during the later stages. The volume of water necessary in each case was recorded. Leaf counts and measurements of the tops (height) and roots (length) were made at suitable intervals and recorded. It was found difficult to measure the roots accurately during the later stages of growth because they became so tangled and matted.

The Connecticut Broadleaf variety of tobacco was used in these studies. The seeds were sown in a flat of steam sterilized mixture of greenhouse potting soil and after one month the seedlings were potted into thumb pots containing the same soil sterilized in the same manner. After the plants were allowed to develop in these pots for a time, usually one month, the roots were washed free of the soil and they were transferred to the various solutions. Although every effort was made to have the plants free from harmful organisms it was found that in some cases they were attacked by organisms which to some extent interfered with their growth.

In order to overcome this difficulty several disinfectants were tried and silver nitrate, 1 to 1000, was found to be the most satisfactory. The roots were immersed in this solution for five minutes, then the whole plant was immersed for another five minutes, thus giving the roots a ten minute treatment and the tops five minutes. Plants treated in this manner were slow to start growth after putting them into water cultures and especially was this so in the solutions containing no added chlorine. However, such plants eventually outgrew the untreated plants and were relatively free from organisms. The first two series of plants were not given this treatment but the third series was treated in this manner.

The temperature and humidity conditions in the greenhouse where these studies were conducted showed the usual daily fluctuations. It was attempted to hold the night temperatures between 65° and 70°F and the day temperatures between 75° and 80°F.

EXPERIMENTAL DATA

Data are presented for three series of experiments conducted during the season 1929-1930, but this work was based on preliminary studies covering a period of several years. One phase of the work has been reported in a previous paper (10). During the season of 1928-1929 observations were made on cultures grown in the standard series of solutions with and without aeration. The symptoms manifested by plants growing under these two conditions were essentially the same although the plants growing in the unaerated solutions were later in manifesting the characteristic symptoms due to the deficiency of the different elements because of slower growth. The plants were of a much smaller size with roots of such a nature that it was almost impossible to observe any difference in roots from the various solutions with the exception of those grown without added phosphorus in the unaerated cultures. Here the roots were unusually long for an unaerated solution and in fact they were almost as long as those developed by plants in the same solution aerated.

The standard series of solutions were also compared with the three salt solutions used by Gericke (5). These comparisons were made in both aerated and unaerated solutions for which the above observations also held. Here again the symptoms produced were practically identical with the standard series of solutions where the plants were transferred to the solutions lacking the different elements and allowed to grow for the period of the observations.

It appears, therefore, that the effects produced in solutions which are aerated or unaerated are essentially the same. Also that solutions made up of different salt combinations which are lacking the same element produced much the same effects on growth where plants are allowed to develop in them for a considerable period.

The three points taken up in the data presented are: series 1, the effect of the removal of the various ions at different periods during the growth of the tobacco plant; series 2, a comparison of the effects on growth of two solutions each lacking the same ion but made up of different salts supplying the essential elements at different rates; and series 3, the effect on recovery when the different essential elements are supplied after having been withheld for certain periods.

In order to determine the dry weight at the beginning of the experiment a sample of ten plants was taken from the general lot of plants used in each series. The average air dry weight per plant in grams for 10 sample plants taken from each lot used was: series (1) 0.54, series (2) 0.25 and series (3) 0.33. The curves given for series 1 have for their starting point 14.9 cms. as an average for 10 sample plants for height of tops and 9.2 cms. for length of roots. This explains why some of these curves show a downward trend when measured November 9 since some plants were below average.

The data presented in table 2 for series 1 show the average measurements and leaf counts for duplicate cultures at different intervals where the plants are transferred at approximately weekly intervals from a solution containing all the essential elements designated as the control solution (C^1) to the solutions lacking one of them. This table also shows average measurements and leaf counts for duplicate cultures which were allowed to grow in the solutions which were unchanged lacking each of the essential elements as compared with the control solution where all were supplied.

The data presented in table 3 show the average air-dry weights of plants from the same series. The total quantity of water used during the entire period is shown and the amount of water for each gram of air-dry weight. This table also shows the percentages of root, stalk and leaf based on the air-dry weights.

Table 4 gives height of tops, length of roots and leaf counts of plants from series 2 which were grown from January 16 to February 27, 1930. The figures in this table are the averages of five plants for each group. The solutions were not changed during this period.

The figures presented in table 5 give the quantitative data from series 2 consisting of air-dry weights, total quantity of water used, amount of water used per gram of air-dry weight as well as percentages leaf, stalk and root. It is to be seen from these data that solutions lacking the same ions in both groups of solutions have produced practically the same amount of growth with but few exceptions and the decreases in growth where each element is lacking is about in the same proportion.

In all cases when the data from the first two series are not consistent one of the main contributing causes was the fact that parasitic organisms occasionally were accidentally introduced on the plant roots. In an attempt to overcome this objectionalbe feature the plants of series 3 were disinfected with silver nitrate as previously mentioned.

The data presented in Table 6 gives height of tops, length of roots and leaf counts for plants grown from April 1 to May 28, 1930 (series 3), where a study upon the effect on recovery of the plants was made where each essential element was withheld for a certain period. The measurements and leaf counts were made at times when the plants were changed from one solution to the other. All solutions were changed on the dates indicated.

The air-dry weights, total water used, water loss per gram of air-dry weights and percentages of leaf, stalk and root based on air-dry weight (series 3) are given in table 7. The data given in tables 6 and 7 for the group of plants in the incomplete solution and a group of controls similarily placed in the greenhouse represent an average of four plants. The other groups represent an average of three plants. There seems to have been a place effect in the greenhouse so that the averages for control plants are given in groups so as to correspond with the incompletes and the different periods of change. The control solution designated C^1 was compared with a solution C^2 made up as described under methods of experimentation as deriving its calcium from the carbonate and the nitrogen from ammonium nitrate.

INTERPRETATION AND DISCUSSION OF RESULTS

It has been shown by studies in comparatively recent years that the original list of 10 essential elements must be considerably increased if it is to include all elements which are necessary for the normal growth of higher plants. In the older studies on the salts nutrition of plants it was thought that seven elements, namely; nitrogen, phosphorus, potassium, calcium, magnesium, sulfur and iron in suitable combinations were all that need be supplied in nutrient solutions. These conclusions were based upon short time experiments with chemicals possibly containing more impurities than readily available chemicals of today. It has been definitely established that small amounts of boron and manganese must be present if normal growth is to result. It is still an unsettled question as to whether chlorine is essential. The above list of elements were the ones included in this study. When the tobacco plants were allowed to develop for the periods indicated, in a solution supplying these elements, growth was apparently normal. If other elements such as zinc, aluminum, silicon, etc. are necessary as some investigators (8 and 9) have reported the methods used in this study were of such a nature that their effects were not apparently manifested by the growth of the plants when they were not intentionally supplied in the control solution.

Growth in Control Solutions.

All comparisons and discussions of effects on growth produced when the various elements are lacking in a solution are based on the growth secured in the control solution (C^1). Plants grown in the control solution were apparently normal and showed increased dry weights when compared to the plants grown in the incomplete solutions. They were usually the most economical users of water per gram of air-dry weight, as shown by tables 3, 5 and 7. The growth curves (Fig. 1) for height of tops based on data given in Table 2 show the effect of renewing the control solution at different periods during growth. The curves for growth in length of roots are shown in Fig. 2. The growth curves for plants grown in the control solution (C^1) at a different season of the year are shown in Fig. 3 for tops and in Fig. 4 for roots, based on data from Table 6. Here all solutions were renewed at intervals, as shown by the dates when the changes were made. The growth curves for plants grown in a second control solution (C^2), where the source of calcium was calcium carbonate and the nitrogen was ammonium nitrate agree essentially with the curves shown in Figs. 3 and 4 and are for this reason not given. It is evident from a comparison of figures given in Tables 6 and 7 that this solution (C^2) produces almost as good growth as the standard control (C^1). The controls when harvested were usually in full flower and in some instances had set a few seed pods. The roots were abundant, much branched and white to light brown in color. It is evident from a comparison of curves given in Figs. 1, 2, 3 and 4 that the roots make their maximum growth in length before the tops show any considerable elongation.

The curves showing the increase in number of leaves based on the data given in Tables 2 and 6 for the different solutions take essentially the same shape as the height of tops of plants and are therefore not presented.

Nitrogen Deficiency

Quantitative Effects.--The first incomplete solution to be considered is the one to which no nitrogen was added. Where this element was withdrawn at intervals during the growth of the plant the final product was decidedly reduced, as shown by the figures for air-dry weight given in Table 3, and fell off consistently, depending upon the date of withdrawal of nitrogen. The growth curves given in Fig. 5 for height of tops based on data from Table 2 serve to demonstrate how soon this effect manifested itself. Where this element was withdrawn during the late stages of growth the total height was not materially reduced. The root growth curves for these same plants are shown in Fig. 6. If nitrogen was withheld for a considerable period the ability of the plant to recover was not materially interfered with, for when the plants were transferred to a solution where this element was supplied the recovery was rapid and apparently complete, save for the leaves which had dried up. The recovery as indicated by measurements of height of tops plotted as a growth curve is shown in Fig. 7 and length of roots in Fig. 8, based on data from Table 6 for series 3. These curves represent three groups of plants, one of which was held in the no-nitrogen solution for the entire period while the other two groups were transferred to a solution containing this element at two different periods. It appears that where the plants were held in a solution containing no added nitrogen for six weeks they were slower in recovering than where nitrogen was withheld for four weeks, as indicated by their ability to increase in height in a given period.

When nitrogen was withheld or withdrawn in early stages the growth of the roots appears to have been stimulated, as shown in Figs. 6 and 8. This conclusion is substantiated by the percentage of root weight based on total air-dry weight given in Tables 3, 5 and 7, where the root percentage is higher than that of the control. It is evident from the tables that when plants are grown in a solution which contains no added nitrogen they use more water per gram of air-dry weight than plants grown in the control solution although the total quantity is greatly reduced. The percentage of leaf based on the total air-dry weight is higher than from plants grown in the control solution.

Qualitative Effects.--While the graphs and data presented show the measureable effects of a deficiency of this element there are visible phenomena which serve better to accurately identify this condition. When plants are transferred to a solution containing no added nitrogen they lose their normal verdant green color in a few days, followed in a week or ten days by a yellowing of the lower leaves. This yellowing first appears as a lemon to orange yellow color of the lower leaves while the bud leaves tend to retain their normal green color and in no instances have been observed to show Frenching, which has been attributed by Valleau and Johnson (15) to nitrogen deficiency. These yellowed leaves dry up or "Fire" to a light brown color in a few days. The marked effects produced on growth where nitrogen is withheld from the solution is well illustrated in Fig. 9. When plants which have been growing in a solution to which no nitrogen has been added are transferred to one containing nitrogen, the recovery takes place rapidly and completely except in the leaves in which the hunger effects are very pronounced or where drying up has taken place. A deficiency of this element produces characteristic "Firing." Local necrotic spots have not been observed on leaves of plants suffering from nitrogen hunger. If the plants are transferred at a later growth period to a solution containing no added nitrogen they are able to flower and set a few seed pods due to the translocation of the nitrogen from the older leaves, a transfer which results in their yellowing and drying or firing. However, when plants were transferred from the soil to the solution containing no added nitrogen they remained alive but produced no flowers for the periods that they were observed.

The stalks of plants suffering from pronounced nitrogen starvation may become somewhat slender and light green in color, but the tendency is for such plants to hold the rosette form with poorly developed stalks. The roots tend to attain a greater length than in the control solution but there is little or no branching. They are characteristically white in color.

Phosphorus Deficiency

Quantitative Effects.--The solution to which no phosphorus was added produced reductions in growth if the plants were held in such a solution for a considerable length of time, when compared to the growth of plants in the solutions where this element was supplied, as shown by the data (Tables 2-7). The growth curves shown in Fig. 10 for tops and in Fig. 11 for roots, based on data given in Table 2 show the effects on growth where this element was withdrawn at intervals, When this element was withdrawn late during the growth there resulted neither reduction in total dry weight produced or in height of the stalk, nor was there any apparent stimulation in growth as reported by Gericke (5). It is evident from the curves shown in Fig. 12 for tops, based on data given in Table 6 that the ability of the plant to recover is still good after being held in the no phosphorus solution for six weeks. However, plants did not attain as great a height in the same time as those from which this element was withheld for only four weeks. The graph showing the effect on root growth in length from series 3 is given in Fig. 13. It is apparent from this figure and Fig. 11 that when phosphorus is withheld early in growth the root length increases decidedly over the control or where phosphorus is withdrawn later in the growth of the plant. This increase in root growth is substantiated by the high percentage of root in the total air-dry weight shown in Tables 3, 5 and 7. The plants grown in a solution to which no phosphorus is added tend to use a much smaller total quantity of water but the amount of water used per gram of air-dry weight is increased over that used by the control. The percentage of leaf based on dry weight is higher than for plants grown in the control solution.

Qualitative Effects.--The lack of phosphorus is first shown by the tobacco plant in the development of an abnormally dark green color which later develops a brownish cast. The first change in color is apparent in from two to three weeks after the plants have been transferred to the solution to which no phosphorus is added. In about four to five weeks a few of the lower leaves may yellow and begin to dry up. When they have dried up they are a greenish brown or almost black color. Under some conditions and particularly on cultures grown in mid-winter the leaves well up on the plant develop characteristic lesions which are large and seem to lie adjacent to or even cross and include the veins. These spots are dark brown to black in color. They are not abundant on the individual leaf, usually only a few such areas being found on any one leaf. These leaf spots do not always occur on plants grown in a solution containing no added phosphorus and it is impossible at the present time to give the exact conditions for their occurrence. Leaves on plants showing phosphorus hunger are characteristically narrow in proportion to their length.

The tendency is for the plant to be held to the rosette form when phosphorus is withheld early in growth (Fig. 14). The plants did not flower but remained alive under these conditions for the periods observed. Where the phosphorus is withdrawn after stalk formation has begun the stalk formed thereafter is slender and weak. Where phosphorus is withdrawn late during growth the plant seems to be able to complete its normal cycle by flowering and setting seed pods. The roots of plants grown in a solution which receives no added phosphorus present a characteristic appearance. They are unusually long, branched very little and have a reddish brown color. This color however is due to some iron compound precipitated on their surfaces for when the iron was withheld the roots were of a normal white color.

Plants transferred from a solution lacking phosphorus to one containing it show a rapid and complete recovery save for the leaves which have dried up or where spots have developed on the leaves.

Potassium Deficiency

Quantitative Effects.--Tobacco plants grown in a nutrient solution to which no potassium was added gave reductions in growth if the element was withdrawn early in the plants' life cycle (Table 2-7). The graph shown in Fig. 15 constructed from data given in table 2 for tops shows the effect of removal of this element at intervals during the growth of the plant. It is evident that these figures are not entirely consistent which was due in a large measure to fungi introduced on the roots from the soil. It is characteristic that plants grown in media deficient in this element are more susceptible to injury from parasitic organisms (11 and 12). Where this element is withdrawn late in the life cycle there was in some instances no depression in yield. The ability of the plant to recover as indicated by the graphs given in Fig. 16, based on data presented in Table 6, was very good. While the graph showing recovery after the plant was held in a solution without potassium for six weeks does not exactly parallel the recovery after four weeks but approximates it. The curves showing root growth in length of these plants take essentially the same shape as the corresponding curves of the control plants (Figs. 2 and 4) and are, therefore, not presented. The amount of water used per plant is reduced when potassium is withheld early enough to dwarf the plant, but the quantity of water necessary to produce one gram total air-dry weight is materially increased as compared with the control. The percentage of leaf based on the air-dry weight is materially increased over the control.

Qualitative Effects.--The characteristic effects on growth resulting from a deficiency of potassium have received earlier (16) and possibly more attention (11) than any of the other elements. These characteristics will be described again here with an attempt at greater detail for purposes of comparison with other deficiency symptoms when growing conditions are similar for all the plants. The first symptom of potassium deficiency as shown by the tobacco plant is a development of abnormally dark green color with a blush cast, followed characteristically by a chlorosis or yellowish mottling of the lower leaves. This mottling usually appears at the tips and margins of the older leaves and is typically followed by a dying of the tissue within the mottled area thus giving the plant a rusty appearance. These dead areas are characteristically very small at first although they later may enlarge and coalesce until most of the leaf tissue between the principal veins is involved. A typical case of potassium hunger contrasted with the normal plant is shown in Fig. 17. In cultures grown in midwinter these effects do not always take the above described characteristic course in that the final change resulting in a drying up of the tips and margins of the leaves though delayed appear so rapidly that it is impossible to distinguish the intermediate steps. In all cases observed the bud leaves tended to remain normal, while the older leaves showed the characteristic effects and in extreme cases the primary and secondary veins became shriveled and the leaf apparently lost its turgor and hung down against the stalk. The leaves are markedly cupped under at the tips and margins. A few bottom leaves may finally dry up but the spots still persist. When plants that show decided potassium hunger are transferred to a solution containing this element all new growth is normal and all old leaves recover save in the necrotic areas, which results in a decided rim-bound condition on such leaves.

The stalks of plants suffering from extreme potassium hunger after a time show lesions usually just below or around the point where the leaf is attached to the stalk. Where the plant was transferred from the soil to a nutrient solution containing no added potassium the stalk was poorly developed and slender. Such plants were unable to flower and set seed though they did not die during the period of observation. The roots from these plants were relatively long and had very few branches. They manifested a yellowish slimy appearance.

Magnesium Deficiency.

Quantitative Effects.--The effect of a deficiency of magnesium on the growth of the tobacco plant is marked. There resulted a decreased growth when this element was withdrawn at all the periods, as shown by the data presented in Table 3 giving dry weights. The later withdrawals did not cause a marked reduction, however. The growth curves for heights of tops as given in Fig. 18, based on data presented in Table 2, show about the same relations as the final dry weight data. The curves showing the recovery when this element is withheld for different periods is given in Fig. 19 for tops, based on data given in Table 6. It is evident from these curves that the plant recovers rapidly when this element is supplied after it has been withheld for a time. However, the recovery is more rapid at the end of four weeks than after six weeks as indicated by the height attained in a given period. The curves showing root growth in the above cultures take practically the same shape as the control given in Figs.2 and 4 and are for this reason not given.

If this element was withheld early enough in the life cycle to cause a decided reduction in growth the total quantity of water used by the plant was lowered but the amount necessary to produce one gram of total air-dry weight was increased.

Qualitative Effects.—The measureable effects presented above show decided retardation where this element is withheld early in growth. However, these effects are not as characteristic as the appearance of the plants. The plants when transferred to a solution containing no added magnesium in from two to three weeks, began to show a chlorosis or loss of the green color on the lower leaves of the plant between the veins. Here the loss of color is not so characteristically confined to the lower leaves or to the leaf tips and margins as in the previous descriptions (1), (4) and (11), of this deficiency as seen under field conditions. In fact in some instances one or two more mature leaves failed to lose their green color. This loss of green color was first apparent as a light green but later progressed to a stage where the leaf tissue became almost white between the principal veins which tended to retain their normal green color. It is characteristic of these leaves in the later stages to curl upward at the tips and margins. The leaves apparently lose their ability to support themselves and hang down against the stalk due to the principal veins in the last stages becoming shriveled. A typical case of magnesium hunger as contrasted with the normal plant is shown in Fig. 20. All leaves on the plants save the bud leaves may finally become involved but in all cases observed the bud leaves tended to remain normal. Where this element was removed late during growth the plant was able to flower and set seed, but when removed early no flowers or seed were formed resulting in a rosette condition induced by a shortage of this element. Such plants showed an exceptionally high percentage of leaf based on the air-dry weight as compared to all other cultures. Under some conditions the leaves on plants showing magnesia hunger developed large lesions even prior to the appearance of the characteristic chlorosis. This condition seemed to be common on cultures grown in mid winter or when the plants which had been growing vigorously in the control solution were transferred to the solution to which no magnesium was added. Leaves suffering from pronounced magnesium hunger rarely dry up.

When plants which are showing pronounced symptoms of magnesium hunger are transferred to a solution containing this element the new growth produced is normal and the chlorotic leaves recover their normal green color, although the older leaves are very slow in recovering.

The stalks of plants suffering from pronounced magnesium hunger are slender and may show lesions just below or around the point where the leaves are attached. The roots are few in number and show a relatively small number of branches. They are comparatively long and have a slimy appearance.

Calcium Deficiency

Quantitative Effects.--Effects of the lack of calcium as manifested by the growth of the tobacco plant are pronounced. The results of withdrawal of this element is shown by the plants' growth, as illustrated by the graphs given in Fig. 21 for height of tops, based on data given in Table 2. If this element is withdrawn early in growth there is almost no increase in height and the total height reached is in direct proportion to the time of removal. The falling off in total dry weight production as given in Table 3 is also directly dependent upon the extent of the period for which this element was supplied, although the late removal has not reduced the dry weight. The length of the roots is reduced as illustrated by Fig. 22 based on data given in Table 2 according to the time of removal of this element, being shorter where this element was removed at an early growth stage.

The recovery of plants where this element was withheld for different periods is shown in Fig. 23 based on data given in Table 6. When this element is withheld for an extended period the recovery of the plant is slow. The roots are poor as shown in Fig. 24 which may explain the slow recovery.

The percentage of the total dry weight of leaf is fairly high when compared with the control, as shown by the data. The root percentage is also higher than would be expected from the length of the roots. The total amount of water used is reduced where this element is removed early enough to produce marked dwarfing but the amount of water necessary to produce one gram of dry weight is not materially increased over the control.

Qualitative Effects.--Characteristic effects on growth are usually apparent in from ten days to two weeks after this element is removed. If the plants are transferred early the first effect manifests itself as a peculiar hooking downwards of the young leaves making up the bud at their tips. This is followed by the death of the young leaves characteristically at their tips and margins and if growth later takes place the tips and margins are missing, giving the leaves a cut out appearance, which are the symptoms seen under field conditions (2). The plant as a whole shows an abnormally dark green color and some thickening of the leaves as the result of death of the terminal bud. In the later stages all terminal growth is stopped and some necrotic spots and chlorosis may develop on the older leaves, but this is not characteristic. Where the plants are transferred late in the life cycle to a nutrient solution containing no added calcium so that the effects of its absence is not manifested by the plant until the flowering stage, such plants show a drying up of the corollas at their tips so that eventually the pistil protrudes and the calyx lobes may also show necrotic spots. Such plants may set a few seed pods but the tendency is for most of the flowers to shed before seed pods are set. If this element is removed early during growth no flowers are formed due to the death of the terminal buds as shown in Fig. 25 as contrasted with a normal plant.

When such plants are transferred to a nutrient solution in which this element is supplied the recovery is slow and the tendency is for the plant to develop one or more suckers since the apical dominence has been broken up due to the death of the terminal bud. The new growth which is produced for a time may show abnormally shaped leaves but later the leaves produced are of a normal shape.

The stalk growth in length is materially reduced when this element is withdrawn early in the life cycle and when once stopped it is unable to renew its growth by translocation of this element from the older formed parts. Lateral buds may start at the axils of the leaves, but they immediately develop the above described effects and die back. The roots are short and thick and show many branches. They usually show a dirty brown color with more or less decomposition. In some instances plants suffering from extreme calcium hunger were not able to survive for the period of the experiment.

Boron Deficiency

Quantitative Effects.--The effect of boron deficiency on the growth of the tobacco plant has been reported in a previous paper (10). Further studies of the effects of a deficiency of this element on growth were made in this series of experiments along with studies of the other deficiencies to determine where its effects differ or resemble those of the other elements. The graphs based on data from Table 2, presented in Fig. 26 show how soon at different periods in the life cycle the withholding of this element manifests its effect on the growth in height of the plant. The increase in height is in direct proportion to the time of removal. The root growth curves (Fig. 27) based on data from Table 2 show that the length is affected by early removal of this element. The recovery of plants when this element is withheld for a time is shown in Fig. 28 based on data from Table 6. It is evident that the recovery is slow where this element is withheld for four weeks and that where it is withheld for six weeks the plants' ability for recovery as indicated by increase in height in a given period is materially injured. The root growth curve for these same plants is shown in Fig. 29. It appears from this graph that these plants have roots which are considerably shorter than the controls (Figs. 2 and 4).

The percentage of leaf in the total dry weight (Tables 3, 5 and 7) is materially increased when this element is withheld early during growth, while the stalk percentage is decreased without great change in root percentage. The total quantity of water used by the plant is low and the amount per gram of dry weight is even less than for plants grown in the control solution.

Qualitative Effects.--The effects of boron deficiency were usually apparent in a week or ten days after plants were transferred to a nutrient solution lacking this element. The first visible effect was the manifestation of a light green color of the leaves making up the bud with the base of the individual leaf assuming a lighter green than the tip. When this appears the bud has ceased to grow and shows a more or less drawn appearance. This is followed in a day or so by a breaking down of the tissue at the base of the young leaves making up the bud. When this stage does not progress too far and if the young leaves later make some growth they will show distortion due to growth around this injured tissue. The death of the terminal bud (Fig. 30) was the final result of the above described phenomena. This automatic topping causes the individual leaves to thicken and increase in area. When this takes place lateral buds may develop in the axils of the leaves or even on the base of the stalk or the roots but they break down as described above. The leaves remaining on such plants are glabrous and brittle and when broken the vascular tissue shows blackening. The upper leaves of the plant tend to roll in a half circle from the tip toward the base. They are of an unhealthy light green color. Such plants were again (10) observed to emit a faint aromatic odor resembling the tobacco blossom odor. If this element was withdrawn late in the life cycle of the plant so that the shortage was felt at the blossoming stage usually all the flowers were shed and no seed pods set.

If plants suffering from decided boron hunger were transferred to a nutrient solution containing this element they were slow in recovery and due to the destruction of the apical dominance as a result of the death of the terminal bud they developed as a rule more than one sucker. In most cases the growth first produced was of leaves which were abnormal in shape but later leaves produced were normal.

The stalks of plants suffering from boron deficiency were not able to further elongate once the effect of the deficiency was apparent. The roots of plants suffering from boron hunger show many short branches but the primary roots may be relatively long and brownish in color and may show some decomposition. In one or two instances plants suffering from extreme boron hunger did not survive for the period of the experiment but died prematurely.

Sulfur Deficiency

Quantitative Effects.--The effect of a lack of sulfur on the growth of the tobacco plant is illustrated by Fig. 31 based on the data from Table 2 relating to withdrawal of this element at intervals during the growth of the plant. The early withdrawal of this element resulted in decided reductions in height of tops, but very late withdrawals did not always do so. The dry weight figures given in Table 3 take much the same course. These figures are not entirely consistent due to fungi which injured some plants more than others. It was characteristic of the cultures in which this element was withdrawn in this series that a practically pure culture of *Thielavia basicola* developed although the pH of the fresh solution was distinctly acid or about the same as that of the control in which practically no evidence of this organism was seen. It is generally known that this organism thrives in a neutral or alkaline medium but in this case this appears not to be the explanation. In series 3 where this organism was not present, due to disinfection, the growth was materially reduced when this element was withheld. Recovery took place rapidly and completely when it was supplied as shown by the curves given in Fig. 32 based on data from Table 6. The curves showing the root growth resemble so closely the curves for roots given for the controls (Figs. 2 and 4) that it was not considered necessary to give them. The percentage of roots in the total dry weight is higher than for the controls as was also the percentage of leaf. If this element were removed early enough to produce a reduction in growth the total quantity of water necessary for the plant was also reduced but the amount necessary per gram of air-dry weight as compared with the control was not materially changed.

Qualitative Effects.--The typical effect on growth produced when sulfur was deficient manifests itself first as a light green color of the younger leaves on the plant. The older leaves retained their normal green color, (Fig. 33), but the younger leaves were of a light green color and the veins were characteristically lighter color than the inter-vein areas of the leaf. This effect became apparent in from two to three weeks after transferring into the solution which contained no added sulfur.. If the transfer were made late or just prior to the flowering stage such plants were able to flower and set seed although the quantity produced was reduced. If the plants were held in a solution containing no added sulfur from an early period in their life cycle they were unable to flower during the period of observation. However, if such plants were transferred to a nutrient solution containing sulfur they showed almost immediate recovery and no harmful effects from having been held in a solution deficient in this element for four to six weeks.

The stalks of such plants show no striking abnormalities save possibly a lighter green color. The roots however are characteristic in their appearance. They are abundant and much branched and are typically of a white color if no parasites are present. Plants from which sulfur was withheld early in growth tended to hold the rosette condition and were unable to flower or set seed although they were able to remain alive for the period of observation.

Iron Deficiency

Quantitative Effects.--The growth curves presented in Fig. 34 based on data given in Table 2 represent the effects on increase in height when iron was removed at intervals during the growth of the plant. When this element was withheld early in growth there was a marked reduction in height, although later removals do not always appear to reduce the final height. The roots were shorter where iron was withheld early during growth than in the control solution as shown by Fig. 35, based on data from Table 2. The results in this case were not entirely consistent which appeared to be due to parasitic organisms being accidentally introduced in some instances and possibly causing more damage because of the absence of iron salts which are known to have mild fungicidal properties.

The recovery of plants grown without iron for a time and then supplied with this element is shown in Fig. 36 for height of tops and in Fig. 37 for length of roots, based on data from Table 6. It is evident that the recovery after six weeks is just as rapid as after four weeks as indicated by the heights attained in a given period.

The total amount of water used was decreased when this element was withheld early enough to produce any considerable dwarfing of the plant but the amount of water, necessary per gram of total dry weights was considerably increased as compared to the control. The percentage of leaf in the total dry weight was increased.

Qualitative Effects.--The typical chlorosis caused by a deficiency of iron was one of the first deficiency diseases of plants to be recognized (7). In fact the term chlorosis has been used so frequently in this connection that iron deficiency and chlorosis in plants have often been treated as synonomous terms. This chlorosis is characteristic and manifests itself first on the young leaves making up the bud. These leaves first lose their green color between the veins and are light green to white in color (Fig. 38). The lower leaves on the plant will be of a normal green color and the veins of the younger leaves tend to retain their green color. However, the leaves making up the bud may eventually become perfectly white in color. This chlorosis usually develops in from three to four weeks when iron is withheld during the early growth of the plants. If the iron were withheld after one month such plants rarely showed chlorosis but flowered and set seed normally. These chlorotic leaves usually show no lesions but under some conditions when exposed to bright sunlight and dry air they tend to dry up.

If plants which show pronounced symptoms of iron hunger were transferred to a solution where this element was supplied they tended to assume their normal green color. All the growth produced following the transfer will be normal although some of the older chlorotic leaves may not develop a green color and in this case a chlorotic leaf may be seen on the lower part of the plant.

It is possible by withholding iron to prevent any considerable stalk development and prevent the plant from flowering. The roots on such plants are relatively short and have many short branches. Such plants remained alive for the period of the experiment.

Manganese Deficiency

Quantitative Effects.--The effects of a shortage of manganese on height of plants is shown in Fig. 39, based on data taken from Table 2. When this element was withheld early in the life cycle of the plant a reduction in total height resulted. The root growth was also affected as shown by Fig. 40 for the same plants. The recovery of plants is shown in Fig. 41 based on data from Table 6 giving the increase in height. The curve showing the root length takes much the same shape as that for plants grown in the control solution as shown in Fig. 4. The dry weight data given in Tables 3, 5 and 7 show practically the same trends as the height of tops. The total amount of water necessary per plant does not seem to have been decreased by withholding manganese even though the growth was reduced. This has necessarily resulted in a higher water requirement per gram of dry weight. This effect agrees with Maze (8) who reports increased water consumption per gram of air-dry weight produced when this element was withheld. The percentage of leaf in the total air-dry weight was increased when manganese was withheld.

Qualitative Effects.--The characteristic effects which resulted from a deficiency of this element were slow in manifesting themselves. It usually requires from four to five weeks for them to become apparent. It was possibly for this reason that no reduction in growth resulted where plants which had grown in a solution containing no added manganese for one month were then transferred to one containing the element (Table 6). The typical effects (Fig. 42) which occur as a result of a deficiency of this element manifest themselves as a chlorosis which was apparent on the younger leaves of the plant. This chlorosis gives the leaf a checkered appearance due to the chlorosis only taking place between the veins and following out the minutest branches of the vascular system. In the later stages small necrotic spots develop on the chlorotic leaves which dry to a white or brownish color. If plants manifesting these symptoms were transferred to a solution containing this element they recovered from the chlorosis but the necrotic spots were still evident on the leaves.

The stalks of plants suffering from pronounced manganese hunger were slender. Although such plants flowered the quantity of seed produced was small or none at all. The roots of such plants were as a rule not abundant nor did they show many branches but they were relatively long.

Chlorine Deficiency.

The effect of chlorine on growth has so far shown nothing typical. In some instances the growth seems to have been reduced when it has been withheld (Tables 2-7). It is possible that the failure of the chlorine to produce marked effects was due to the fact that the experiments were conducted in the city of Washington where considerable soft coal was burned in a nearby industrial plant which supplied the surrounding air with enough chlorine gas so that the acute effects of its absence were not apparent.

Comparison of Deficiency Effects

Quantitative Effects.--It is evident from the foregoing discussion of the effects of the several deficiencies that there are points in which they resemble one another. They all produce reductions in growth as illustrated by the total dry matter produced (Tables 3, 5 and 7). The growth curves from series 3 (Fig. 43), based on data from Table 6 show the typical reductions in growth of height of tops when the several elements are deficient as compared with growth obtained in the controls. The effects on root growth are shown in Fig. 44 for the same plants. In this case some stimulation of root growth appears to have taken place when certain elements are withheld. This effect is also apparent in Fig. 45, where the percentages of root, stalk and leaf are shown on the basis of averages for the three series grown in the standard solutions. Here the longest root gives the highest percentage of root based on the air-dry weight. Although a long root did not always mean a high percentage of root based on dry weight as, for example, the plants which showed magnesium deficiency had a relatively long root but showed the lowest percentage of root. The plants suffering from magnesium and potassium hunger showed a relatively high percentage of leaf. It was characteristic of those cultures which showed a high water loss per gram of air-dry weight to show a high percentage of leaf, although there are two outstanding exceptions to this rule. The cultures which suffered from manganese hunger and gave the highest water loss and the one suffering from boron hunger and showing the least loss of water per gram of air-dry weight, were both relatively high in leaf percentage, though they were neither the highest nor the lowest in percentage of leaf.

Qualitative Effects.--There are two points of similarity in symptoms produced which enables one to make two classifications which serve for the broader distinctions. The first group including nitrogen, phosphorus, potassium and magnesium characteristically manifests deficiency effects on the older growth. The second group including calcium, boron, sulfur, iron and manganese typically shows deficiency effects on the new growth. It appears from this classification that the elements making up the first group are more mobile than are those making up the second group.

The first group may be further subdivided into those elements which manifest their deficiency effects as a general dwarfing, with yellowing followed by drying up of the lower leaves including nitrogen or phosphorus, and those causing local effects such as chlorosis of the lower leaves, namely potassium or magnesium. The general effects including the decided dwarfing resulting from shortages of nitrogen and phosphorus may be distinguished one from the other on the basis of the general appearance of the plant. Plants suffering from nitrogen hunger show an abnormally light green color while those suffering from phosphorus hunger show an abnormally dark green color. In both cases there is more or less yellowing and firing or drying up of the lower leaves but this effect is usually more pronounced with nitrogen deficiency. However, the leaves after drying up show differences in color, those from plants suffering from a shortage of nitrogen showing a light brown as contrasted with those from plants suffering from phosphorus hunger which show a greenish brown to black color. The stalk is slender and short in extreme cases where both are deficient. If either of these elements is removed late during growth flowering and setting of seed takes place although the number of seed set may be reduced. The roots resemble each other in that they are relatively long and little branched but where the plant is suffering from nitrogen hunger they are white in color and where phosphorus is withheld they are of reddish brown color.

The local effects manifesting themselves on the lower or older leaves as mottling or chlorosis are characteristically due to potassium or magnesium hunger which may be distinguished by the fact that with the former the mottled areas usually surround small necrotic spots or specks which are located at the tips and margins of the individual leaf and with the latter the chlorotic areas do not characteristically show necrotic areas and if necrotic areas are present they are large and are not at the tips and margins of the leaf. In the case of potassium hunger the plant is of a bluish green color save in the mottled areas between the veins which have a yellowish cast while due to the necrotic spots drying up, the plant shows a rusty appearance, with the leaves cupping under due to the rimbound condition caused by the dead tissue at the tip and margins of the leaf around which the living portions of the leaf attempt to grow but are distorted by dead tissue. A contrast to this is evident in plants suffering from a shortage of magnesium which are of a normal green save in the chlorotic areas between the principal veins which are light green to almost white in color. In this instance the leaves turn up or cup up at the tips and margins. If either element is withheld the veins tend to retain their green color. The veins of the leaves in extreme cases where either element is deficient become shriveled and allow the leaves to hang down against the stalk. The stalks are slender and extreme cases show lesions just below or around where the leaves are attached. The root conditions resemble each other in showing few branches and a slimy appearance but the color is yellowish with plants where potassium is deficient and colorless where magnesium hunger is pronounced.

The second group may be subdivided into those elements whose shortage does not cause the death of the terminal bud but induces chlorotic effects on the young leaves including iron, manganese or sulfur and those causing death of the terminal bud preceded by characteristic steps as shown by a deficiency of calcium and boron. Where death of the terminal bud does not take place chlorotic effects are apparent on the young leaves which show distinguishing characteristics. A deficiency of iron or manganese is apparent as a chlorosis of the younger leaves but the veins tend to retain their green color as contrasted with a deficiency of sulfur where the veins appear of a lighter green than the tissue between the veins. Iron chlorosis appears as a loss of the green color between the veins with the principal veins tending to retain the green color but in some cases the entire leaf may be white although no necrotic spots are typically evident.

While in the case of manganese chlorosis the minutest veins tend to retain their green color, thus resulting in a checkered appearance of the leaf and in no instance have perfectly white leaves been seen. The leaves also typically show small necrotic spots distributed over the leaf surface. The stalk is short and slender in all cases of decided deficiency. The roots differ in appearance, those from plants suffering from iron hunger are of a brown color showing many short branches on a relatively short primary root, those from a plant suffering from sulfur hunger are white in color and characteristically abundant and much branched while those from a plant showing manganese hunger are not especially characteristic save that they are not quite so abundant.

Those effects classed under the second group having as their final result the death of the terminal bud which is preceded by characteristic steps include calcium and boron deficiency symptoms. The effects of the former are to be distinguished from those of the latter by a peculiar hooking of the young leaves making up the bud, where about one third of the leaf from the tip hooks sharply downward. This is followed by death of the tips and margins of these young leaves so that in later growth the tips and margins are missing or have a cut out appearance. The first signs of boron deficiency, on the contrary, show a light green color of the bud leaves characteristically at the base of the individual leaf, where decomposition takes place to a greater or less extent. When the decomposition does not involve all the tissue and later growth takes place, these leaves show distortion at their base due to growth around the injured areas. If the breakdown of the tissue at the base of the young leaf is complete the tip may remain alive and green for sometime. The final result is the death of the terminal bud with calcium or boron hunger. With calcium lacking such plants take on an abnormally dark green color as contrasted with effects of a lack of boron, where the plant shows an unhealthy light green color, with leaves which are glabrous, stiff and brittle. The stalk and roots do not show any especially distinct characteristics which serve to contrast the one against the other. The stalks die back in both cases and the roots are short and much branched, with a dirty brown color showing more or less decomposition.

The foregoing effects are typically illustrated in Plate 1. It is evident from the preceding discussions that a key can be made which may be of service in quickly identifying these effects, as follows:

Decreased growth. More or less localized effects causal parasites absent.	Group 1. General on whole plant or Localized effects on older or lower leaves of plant.	General on whole plant - Also yellowing and drying up or "Firing" of lower leaves.	Nitrogen	Plant light green. Lower leaves yellow and dry up to a light brown color. Stalk slender and short. Roots long with few lateral branches, white in color.
			Phosphorus	Plant dark green. Lower leaves may yellow and dry up to a greenish brown to black color. Stalk slender and short. Roots long with few lateral branches, reddish brown color.
		Local - Occurring as mottling or chlorosis with or without necrotic spotting of lower leaves. Little or no drying up of lower leaves	Potassium	Lower leaves mottled with necrotic spots at tips and margins, with tips and margins tucked or cupped under. Stalk slender, necrotic areas in extreme cases. Roots long with few lateral branches and of a yellowish slimy appearance.
			Magnesium	Lower leaves chlorotic and typically show no spots. Tips and margins turned or cupped upward. Stalk slender, necrotic areas in extreme cases. Roots long with few lateral branches and slimy in appearance.
	Group 2. Localized effects on newer or bud leaves of plant	Terminal bud remains alive, chlorosis of newer or bud leaves with or without necrotic spots, veins light or dark green.	Iron	Young leaves chlorotic, typically show no spots, veins typically green, that is, principal ones. Stalk slender and short. Roots short with abundant short laterals brown in color.
			Manganese	Young leaves chlorotic with necrotic spots scattered over leaf. Smallest veins tend to remain green producing a checking effect on leaf. Stalk slender. Roots not so abundant and brownish in color.
			Sulphur	Young leaves light green, no necrotic spots. Veins lighter green than inter vein tissue. Stalk short and slender. Roots white, abundant and much branched.
		Terminal bud dies, which is preceded by peculiar distortions at the tips or base of young leaves making up bud.	Calcium	Young leaves making up terminal bud first typically hooked, then die back at tips and margins so that later growth of such leaves shows a cut out appearance at tips and margins. Stalk finally dies back at terminal bud. Roots short much branched, dark brown in color with more or less decomposition.
			Boron	Young leaves making up terminal bud first light green at base, then more or less breakdown takes place at base of young leaf, and if later growth follows leaf shows twisted growth. Stalk finally dies back at terminal bud. Roots show many short laterals, brown color with some decomposition.

* Symptoms under these conditions are similar to those observed in the field on the tobacco plant, except for iron and manganese deficiency which have not been seen on tobacco in the field.

General Discussion

The characteristic effects, since they are growth phenomena, produced by the deficiency of the various essential elements are modified to a certain extent by other conditions affecting growth, particularly the unfavorable light conditions prevailing at this latitude in mid-winter. It is to be recognized also that growth manifestations are altered to some extent by conditions prevailing in the greenhouse but that basically the characteristic symptoms will be found to be essentially the same.

The questions as to whether the effect on growth produced as a result of the shortage of a certain element is caused by the necessity of the given element for certain metabolic processes or because it antagonizes another element is often difficult to determine. In some instances both seem to be in operation but after all this is an academic question which will not be considered in this paper. The initial effects produced when an element is withheld are as a rule the ones which are most typical and serve best to distinguish one deficiency from another.

It is well to call attention here to the fact that the evidence given in Tables 2-7 and the curves presented in the various figures show that plants are much slower in manifesting deficiency effects when an element is removed than they are in showing recovery when the element is supplied. This result may be considered as a buffer effect of the plant which enables it to survive under unfavorable environments. Such a condition is particularly favorable from a practical point of view because through this response the plant is enabled to take advantage of favorable conditions rapidly and is slow in responding to unfavorable conditions of nutrient supply.

A point which may be mentioned here is the effect on growth when more than one of the essential elements are lacking. While not a great deal of work has been conducted in a study of the possibility of combining these effects, it appears from the limited studies made that the effect of the absence of one element usually dominates the others and only one is evident. When two or more èlements are withheld there may be more dwarfing than where only one is deficient, yet the outstanding symptoms will be only those of one element. For example, when boron is deficient it dominates all other deficiencies and the symptoms shown by the plant may be modified slightly but are essentially those of boron deficiency.

SUMMARY

The distinctive deficiency effects of N, P, K, Mg, Ca, B, S, Fe and Mn on the tobacco plant as produced in a series of nutrient solutions so devised as to enable each essential element to be withheld as desired without changing the amounts of other elements present are described and illustrated. A reduction in growth results when any essential element is withheld but on close examination typical symptoms which serve to distinguish one from the other are evident on the root, stem, or leaf or the plant as a whole.

Typically a deficiency of nitrogen is shown by the plant as a whole assuming a light green color, with more or less yellowing and drying up or firing of the lower leaves to a light brown color. The roots are long, little branched and white in color. While a shortage of phosphorus, on the contrary produces a plant which is dark green in color and may show some yellowing and drying up of the lower leaves to a greenish brown color. The roots of such plants are long, little branched and reddish brown in color, due to the presence of iron compounds on their surface.

Potassium and magnesium hunger, contrasted with nitrogen and phosphorus hunger show localized effects with chlorosis of the lower leaves as the dominant characteristic. Typical potassium hunger is distinguished from magnesium hunger by the small necrotic spots or specks at the tip and margins of the chlorotic leaves which usually do not occur in the case of the latter. The chlorotic areas in the case of potassium hunger are of a yellowish color while with magnesium they are pale green or white, with the principal veins tending to retain the green color in both cases. The leaves turn or tuck under at the tips and margins with potassium deficiency and tend to turn or cup up in the case of magnesium hunger.

As contrasted with the deficiencies given above, which are general or occur on the older or lower leaves, those occurring typically on the new growth or bud leaves are: iron, manganese, sulfur, calcium and boron. Deficiency of iron, manganese or sulfur does not result in the death of the terminal bud while lack of calcium or boron produces death of the terminal bud as the final result. The first three deficiencies produce chlorosis of the younger leaves, each of a characteristic type. Iron chlorosis and manganese chlorosis resemble each other in that the veins tend to retain their green color but in the case of manganese deficiency a necrotic spotting occurs scattered over the leaf while no necrotic spots occur with iron deficiency. The chlorosis resulting from sulfur deficiency differs from that just described in that the veins are of a lighter green color than the tissue between the veins. In the case of sulfur hunger the roots are typical, being unusually abundant and white in color while with iron and manganese shortage they are not so abundant nor white in color.

Calcium and boron differ from each other in that the initial effects of their shortage produce different symptoms. A shortage of calcium first becomes apparent as a peculiar hooking downward of the tip of the young leaves of the bud, followed by the death of the young leaves at their tip and margins and, if later growth takes place, the tips and margins show a cut out appearance. In contrast with this effect, a shortage of boron produces a light green color at the base of the young leaves of the bud, followed by their breakdown which, if not too severe is followed by later growth, thus causing the young leaves to become distorted or twisted at their bases. In most cases of boron deficiency the tip of the leaf usually remains alive for sometime after the base has broken down.

The foregoing contrasts have served as a basis for the construction of a key which may help in quickly identifying by comparison the contrasting deficiency effects for each of the essential elements studied. It is characteristic that all the described deficiency effects are relatively slower in their development than is the recovery of the plant when the elements are supplied.

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Table 1.-Volume - molecular concentrations of chemically pure salts used in preparing stock solutions

Solutions containing	Solution designation	C. P. Salts												
		$Ca(NO_3)_2$	$CaH_4(PO_4)_2$	$CaCl_2$	$CaCO_3$	KNO_3	KH_2PO_4	K_2HPO_4	$Mg(NO_3)_2$	$MgSO_4$	$MgCl_2$	NH_4NO_3	$(NH_4)_2SO_4$	NH_4Cl
ll elements	C^1	0.1235	----	----	----	0.0217	0.0422	----	0.0124	0.0125	----	----	----	0.028
ll elements	C^2	----	0.0052	----	0.1180	----	----	0.0320	----	0.0125	0.0140	0.1600	----	----
o added nitrogen	N	----	0.0052	----	0.1180	----	----	0.0320	----	0.0125	0.0140	----	----	----
o added phosphorus	P	0.1026	----	0.0141	----	0.0637	----	----	0.0124	0.0125	----	0.0140	----	----
o added potassium	K	0.1044	0.0211	----	----	----	----	----	0.0124	0.0125	----	0.0298	----	0.0280
o added calcium	Ca	----	----	----	----	0.0217	0.0422	----	0.0124	0.0125	----	0.1242	----	0.0280
o added magnesium	Mg	0.1235	----	----	----	0.0217	0.0422	----	----	----	----	----	0.0125	0.0280
o added sulphur	S	0.1235	----	----	----	0.0217	0.0422	----	0.0124	----	0.0140	0.0140	----	----
o added chlorine	Cl	0.1235	----	----	----	0.0217	0.0422	----	0.0124	0.0125	----	0.0140	----	----
o added boron	B	0.1235	----	----	----	0.0217	0.0422	----	0.0124	0.0125	----	----	----	0.0280
o added manganese	Mn	.0.1235	----	----	----	0.0217	0.0422	----	0.0124	0.0125	----	----	----	0.0280
o added iron	Fe	0.1235	----	----	----	0.0217	0.0422	----	0.0124	0.0125	----	----	----	0.0280

different essential elements at intervals during growth for period from Nov. 1, 1929 to Jan. 2, 1930 (Series 1)

Treatment		Length of Roots (cms.)						Height of stalk (cms.)								Number of leaves					
Elements omitted	Date trans. to solution indicated from control (C^1)	Nov. 9	Nov. 16	Nov. 23	Nov. 30	Dec. 6	Jan. 2	Nov. 9	Nov. 16	Nov. 23	Nov. 30	Dec. 6	Dec. 13	Dec. 26	Jan. 2	Nov. 16	Nov. 23	Nov. 30	Dec. 6	Dec. 13	Jan. 2
N	Nov 1	14.0	37.5	42.5	49.0	54.5	60.0	10.5	10.5	11.5	12.5	13.5	16.0	19.0	23.0	5.5	7.5	7.5	8.5	10.5	15.0
N	Nov 9	14.0	37.5	51.5	57.0	65.0	75.0	7.0	11.0	12.5	15.0	16.0	20.5	26.5	33.0	7.0	8.5	9.5	10.5	11.0	16.0
N	Nov. 15	16.5	31.0	33.0	41.5	36.5	50.0	7.0	10.5	17.5	23.0	26.5	31.5	52.5	61.5	7.5	10.5	11.5	12.5	14.0	21.0
N	Nov. 22	14.5	36.5	51.0	53.0	44.5	59.0	9.0	13.5	21.5	35.5	46.0	72.0	89.0	90.0	8.0	11.0	13.0	14.0	20.5	21.0
N	Nov. 29	16.0	35.5	39.5	50.5	51.5	55.0	6.0	10.0	21.0	32.0	42.5	67.0	92.0	95.0	8.0	11.5	13.5	15.5	20.0	23.0
P	Nov. 1	16.0	37.5	49.0	68.0	75.0	60.0	11.0	12.0	14.0	14.5	18.0	20.0	24.5	29.0	7.0	8.5	9.5	10.0	10.0	15.0
P	Nov. 9	13.0	32.5	45.0	56.5	42.5	57.5	7.0	11.5	17.0	22.0	27.5	39.0	58.0	69.0	7.5	9.5	11.0	12.0	13.5	13.5
P	Nov. 15	12.5	26.0	32.5	30.5	33.5	42.5	8.5	12.0	18.5	25.0	32.0	50.5	81.0	93.5	8.0	11.5	12.5	14.0	15.5	22.5
P	Nov. 22	13.5	32.5	32.5	33.0	31.5	32.5	10.0	13.0	19.0	28.0	38.5	60.5	88.0	92.0	8.0	11.5	13.0	15.0	16.5	20.0
P	Nov. 29	12.0	32.0	32.0	33.0	34.0	31.5	7.0	10.5	20.5	30.0	40.0	65.0	103.5	106.0	8.0	12.0	14.0	16.0	18.5	23.0
K	Nov. 1	13.0	31.5	43.5	41.5	38.5	37.5	11.5	14.0	19.5	25.0	32.5	49.5	69.5	83.5	8.0	10.0	12.0	14.0	17.0	23.5
K	Nov. 9	11.5	28.0	41.5	51.5	40.0	36.5	9.0	12.0	18.0	25.0	33.0	46.5	62.0	74.0	7.5	10.5	12.0	13.5	16.5	22.5
K	Nov. 15	13.5	30.5	44.0	37.5	35.5	39.0	11.0	15.0	23.5	35.5	50.0	78.5	99.0	101.0	8.0	10.5	12.5	14.5	18.5	22.5
K	Nov. 22	15.0	28.5	41.0	43.5	37.0	44.0	10.5	14.5	24.0	36.0	53.0	88.0	110.0	111.0	8.0	11.5	13.5	15.5	19.5	21.5
K	Nov. 29	13.0	25.0	33.5	34.5	33.0	35.0	8.5	13.5	21.0	29.5	41.0	64.0	79.0	81.0	8.5	11.5	13.0	14.5	16.5	19.5
Ca	Nov. 1	14.0	18.5	24.0	26.5	27.0	24.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	6.5	6.5	6.5	6.5	6.5	7.5
Ca	Nov. 9	13.5	18.5	23.5	25.5	26.0	32.5	10.0	12.0	12.0	12.0	13.0	13.5	13.0	13.0	7.5	8.0	8.0	8.0	8.0	8.5
Ca	Nov. 15	13.5	30.5	36.5	38.5	32.5	37.5	9.5	14.0	22.0	26.5	32.0	34.0	35.0	35.0	7.5	10.5	11.0	12.0	12.0	11.5
Ca	Nov. 22	12.5	23.0	26.0	26.5	28.5	33.5	9.5	13.5	18.5	24.0	31.0	42.5	54.0	57.5	7.5	10.0	12.0	14.0	16.0	18.5
Ca	Nov. 29	13.5	33.0	45.0	45.0	46.5	42.5	9.5	13.0	23.5	40.0	56.0	91.0	104.0	105.0	8.0	11.0	13.0	16.0	19.0	21.0
Mg	Nov. 1	13.0	30.0	38.0	43.5	35.0	32.5	9.0	11.0	13.0	14.5	16.0	17.5	20.5	21.0	7.5	9.5	10.5	12.0	13.5	18.0
Mg	Nov. 9	12.5	28.0	41.5	46.5	45.0	42.5	9.5	14.5	23.0	28.0	33.5	45.5	53.0	55.5	8.0	11.0	13.0	14.0	17.0	19.5
Mg	Nov. 15	16.0	22.0	30.0	30.0	31.5	38.5	10.0	13.0	19.0	27.0	36.0	43.0	63.5	67.5	8.0	10.5	12.5	14.0	17.0	20.5
Mg	Nov. 22	13.5	32.0	39.5	37.5	39.0	35.0	9.5	13.5	23.0	33.5	49.0	74.0	93.5	96.5	8.5	11.5	13.5	15.5	18.5	21.5
Mg	Nov. 29	15.0	36.0	30.0	35.5	36.5	34.5	9.0	14.0	18.5	27.5	37.5	64.0	94.0	97.5	9.0	10.5	12.5	15.0	18.0	21.5
None (C^1)	Nov. 1	14.5	26.0	36.5	37.0	37.0	37.5	11.0	15.5	23.5	34.0	45.0	71.0	95.0	105.0	8.0	11.0	12.5	14.5	17.5	23.0
None (C^1)	Nov. 9	14.5	30.5	42.0	45.5	46.5	48.5	11.0	15.5	25.0	38.5	51.5	81.5	105.0	106.0	8.0	12.0	13.0	15.5	18.5	23.0
None (C^1)	Nov. 15	15.0	31.0	41.5	44.5	47.5	45.0	8.5	13.0	22.5	38.5	56.0	86.5	104.5	105.0	8.5	11.5	13.5	15.5	19.0	22.5
None (C^1)	Nov. 22	16.0	32.5	41.5	44.0	35.0	37.0	8.5	12.5	23.0	37.5	61.5	96.0	107.5	110.0	8.0	11.0	14.0	16.0	19.0	20.0
None (C^1)	Nov. 29	13.0	30.5	43.5	42.0	37.5	32.5	6.5	11.5	20.0	33.5	45.5	74.0	101.5	102.5	8.0	11.0	12.5	14.5	17.5	22.0
B	Nov. 1	14.0	15.0	15.5	17.0	17.0	19.5	8.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	8.0	8.0	8.0	8.0	8.0	8.5
B	Nov. 9	12.5	24.5	25.0	25.0	25.0	25.0	12.0	15.0	17.0	17.5	17.5	17.5	17.5	17.5	8.0	9.5	10.0	10.0	10.0	10.5
B	Nov. 15	20.0	29.0	33.0	33.5	33.0	35.5	10.0	14.5	23.0	27.0	27.0	27.0	27.0	27.0	9.0	12.0	13.0	13.0	13.0	14.5
B	Nov. 22	13.5	30.5	43.0	49.5	47.5	44.0	10.0	14.0	22.5	29.0	31.5	33.0	32.5	32.5	7.5	10.5	12.5	13.0	14.0	15.5
B	Nov. 29	13.5	31.0	42.5	50.0	41.0	30.5	9.0	14.0	24.0	36.0	48.0	62.5	66.0	67.0	8.0	11.0	12.5	14.5	16.5	18.5
S	Nov. 1	12.0	31.5	43.0	46.5	43.0	35.5	11.0	14.5	20.0	25.5	30.5	45.5	57.5	60.0	8.5	11.0	11.5	12.5	14.5	16.5
S	Nov. 9	15.0	27.0	35.0	47.0	47.5	39.0	11.0	15.0	23.0	34.0	44.0	60.0	62.5	64.0	8.0	11.0	12.5	14.0	16.0	17.5
S	Nov. 15	12.5	29.5	42.5	45.0	41.0	36.5	10.5	14.5	22.5	34.5	44.5	60.5	67.0	74.0	8.0	11.5	13.5	15.0	16.5	20.0
S	Nov. 22	15.0	29.5	45.0	40.5	40.5	41.0	10.0	15.0	25.0	41.0	61.5	89.0	98.0	99.5	8.0	11.5	13.5	16.0	18.5	20.5
S	Nov. 29	11.5	30.0	33.0	41.5	45.0	40.0	8.0	12.5	22.5	36.5	48.0	69.0	82.5	83.5	7.5	10.5	13.0	14.0	17.0	20.5
Mn	Nov. 1	16.0	25.5	32.0	32.5	30.5	35.5	9.5	13.5	21.5	33.5	45.0	65.0	81.5	83.5	8.0	11.5	13.5	14.5	17.5	20.0
Mn	Nov. 9	13.5	21.5	26.0	27.0	27.5	30.0	9.0	12.5	17.0	25.5	34.0	50.5	73.0	85.0	7.5	10.5	13.5	14.0	17.0	22.5
Mn	Nov. 15	12.0	18.5	29.5	33.5	34.5	39.0	7.5	11.5	15.0	26.0	38.0	65.5	102.5	106.5	7.0	11.0	13.0	15.0	18.0	21.0
Mn	Nov. 22	13.0	29.5	43.0	47.5	47.5	55.0	7.0	10.5	17.5	31.5	50.0	85.0	123.5	125.0	8.0	12.0	14.0	16.0	19.0	22.5
Mn	Nov. 29	14.0	28.0	34.0	40.5	40.0	35.0	7.0	10.5	17.5	27.5	39.5	67.0	103.5	111.0	7.0	10.0	12.0	14.0	17.5	23.0
Fe	Nov. 1	12.0	25.5	31.0	31.5	32.0	32.0	9.0	11.5	17.0	22.0	27.0	35.0	41.5	44.5	8.0	11.0	12.0	14.5	16.0	21.0
Fe	Nov. 9	14.0	30.0	31.0	27.5	29.5	29.5	10.5	15.0	20.0	27.5	34.5	55.0	75.0	85.0	7.5	11.5	12.0	14.0	17.0	23.0
Fe	Nov. 15	13.0	27.0	37.0	32.5	35.0	35.5	11.0	15.5	22.5	34.5	51.0	82.0	103.5	106.5	8.0	11.0	13.5	15.5	18.5	23.0
Fe	Nov. 22	11.0	25.5	36.5	35.5	36.5	34.0	8.0	12.0	18.0	27.5	38.5	57.5	78.5	84.0	7.5	10.5	12.5	14.5	17.0	22.0
Fe	Nov. 29	14.0	29.0	48.5	56.0	44.5	49.5	10.0	14.0	22.5	37.0	50.0	81.0	107.5	112.5	8.0	11.0	13.0	15.0	18.5	21.5
Cl	Nov. 1	14.0	33.0	51.0	54.5	54.5	59.0	9.0	13.0	22.5	38.5	51.0	82.0	101.0	101.0	7.5	10.5	13.0	15.0	17.5	21.0
Cl	Nov. 9	17.0	30.5	34.0	35.0	37.0	37.5	9.0	12.5	21.0	32.5	47.5	75.0	99.5	100.5	8.5	12.0	14.0	15.5	18.5	21.5
Cl	Nov. 15	15.0	30.5	40.5	42.5	42.5	40.0	6.5	12.5	22.0	35.5	49.0	79.0	98.5	101.0	9.0	12.0	14.0	16.0	19.5	22.0
Cl	Nov. 22	15.0	33.0	34.5	32.5	32.5	32.5	9.0	14.0	21.5	30.0	46.5	80.0	110.0	110.0	8.5	11.5	13.5	15.0	18.0	21.0
Cl	Nov. 29	13.5	30.0	35.0	35.0	35.0	32.5	6.5	10.5	17.5	28.0	41.0	73.0	103.5	106.5	8.0	10.5	12.5	14.5	18.0	21.0

intervals during growth for period from Nov. 1, 1929 to Jan. 2, 1930 (Series 1)

Treatment	Date transferred into solution indicated from Control (C^1)	Air-dry weight (grams)				Water used (cc)		Percentages based on air-dry weight		
		Leaf	Stalk	Root	Total	Total for period	Amt. per gram air-dry wt.	Leaf	Stalk	Root
No added nitrogen	Nov. 1	1.13	0.40	0.35	1.88	910	484	60.1	21.3	18.6
" " "	" 9	1.60	0.85	0.65	3.10	1608	519	51.6	27.4	21.0
" " "	" 15	2.33	1.55	0.80	4.68	2350	502	49.8	33.1	17.1
" " "	" 22	4.48	4.43	1.08	9.99	5280	529	44.8	44.4	10.8
" " "	" 29	5.35	5.58	2.03	12.96	6518	503	41.3	43.1	15.6
No added phosphorus	Nov. 1	2.35	0.88	0.85	4.08	1840	451	57.6	21.6	20.8
" " "	" 9	4.10	2.30	1.13	7.53	3335	443	54.4	30.6	15.0
" " "	" 15	6.15	3.98	1.63	11.76	4683	398	52.3	33.8	13.9
" " "	" 22	6.40	5.00	1.65	13.05	5758	441	49.0	38.3	12.7
" " "	" 29	8.50	7.15	2.25	17.90	6810	380	47.5	39.9	12.6
No added potassium	Nov. 1	6.13	3.15	1.25	10.53	4993	474	58.2	29.9	11.9
" " "	" 9	5.33	2.98	1.05	9.36	4770	510	57.0	31.8	11.2
" " "	" 15	6.40	5.80	1.48	13.68	6418	469	46.8	42.4	10.8
" " "	" 22	8.05	7.30	1.98	17.33	7693	444	46.5	42.1	11.4
" " "	" 29	5.30	4.60	1.63	11.53	4763	413	46.0	39.9	14.1
No added calcium	Nov. 1	2.48	0.80	0.45	3.73	1723	462	66.5	21.5	12.0
" " "	" 9	3.70	1.80	0.95	6.45	3180	493	57.4	27.9	14.7
" " "	" 15	5.55	2.93	1.25	9.73	4683	481	57.0	30.1	12.9
" " "	" 22	5.70	4.08	1.80	11.58	4523	391	49.2	35.2	15.6
" " "	" 29	7.85	7.03	2.43	17.31	7143	413	45.3	40.6	14.0
No added magnesium	Nov. 1	4.08	0.45	0.53	5.06	2780	549	80.6	8.9	10.5
" " "	" 9	6.33	1.83	0.83	8.99	4780	532	70.4	20.4	9.2
" " "	" 15	6.83	2.50	1.20	10.53	5333	506	64.9	23.7	11.4
" " "	" 22	7.43	6.25	1.75	15.43	6785	440	48.1	40.5	11.4
" " "	" 29	7.18	5.80	1.98	14.96	7103	475	48.0	38.8	13.2
Control (C^1)	Nov. 1	6.23	5.55	1.53	13.31	5125	385	46.8	41.7	11.5
"	" 9	6.60	5.80	1.70	14.10	6678	474	46.8	41.1	12.1
"	" 15	7.05	7.13	1.63	15.81	6873	435	44.6	45.1	10.3
"	" 22	6.98	8.33	1.98	17.29	7428	430	40.4	48.2	11.4
"	" 29	7.85	7.00	2.35	17.20	6235	363	45.6	40.7	13.7
No added boron	Nov. 1	4.50	0.55	0.93	5.98	2190	366	75.3	9.2	15.5
" " "	" 9	4.65	1.05	0.80	6.50	2695	415	71.5	16.2	12.3
" " "	" 15	6.60	2.05	1.18	9.83	3786	385	67.1	20.9	12.0
" " "	" 22	6.60	2.43	1.25	10.28	3945	384	64.2	23.6	12.2
" " "	" 29	5.10	3.90	1.38	10.38	4088	394	49.1	37.6	13.3
No added sulphur	Nov. 1	3.70	2.73	1.25	7.68	2963	386	48.2	35.5	16.3
" " "	" 9	3.68	3.65	1.05	8.38	3408	407	43.9	43.6	12.5
" " "	" 15	4.28	4.10	1.30	9.68	4048	418	44.2	42.4	13.4
" " "	" 22	7.60	8.33	1.90	17.83	6798	381	42.6	46.7	10.6
" " "	" 29	5.35	5.15	1.20	11.70	4055	347	45.7	44.0	10.3
No added manganese	Nov. 1	5.78	3.73	1.38	10.89	6050	556	53.1	34.3	12.6
" " "	" 9	5.65	3.68	1.35	10.68	4225	396	52.9	34.5	12.6
" " "	" 15	7.15	5.90	1.80	14.85	7480	504	48.2	39.7	12.1
" " "	" 22	8.88	8.48	1.90	19.26	9710	504	46.1	44.0	9.9
" " "	" 29	8.13	7.45	2.05	17.63	7150	406	46.1	42.3	11.6
No added iron	Nov. 1	3.95	2.20	0.80	6.95	3350	482	56.8	31.7	11.5
" " "	" 9	5.40	4.33	1.20	10.93	4455	408	49.4	39.6	11.0
" " "	" 15	7.30	7.53	1.70	16.53	7615	461	44.2	45.5	10.3
" " "	" 22	5.90	4.90	1.30	12.10	5050	417	48.8	40.5	11.7
" " "	" 29	9.25	8.75	2.15	20.15	9028	448	45.9	43.4	10.7
No added chlorine	Nov. 1	7.30	6.23	1.95	15.48	7643	494	47.2	40.2	12.6
" " "	" 9	6.03	5.68	1.60	13.31	6598	496	45.3	42.7	12.0
" " "	" 15	7.10	6.53	1.58	15.21	6775	445	46.7	42.9	10.4
" " "	" 22	8.15	7.35	2.10	17.60	7370	419	46.3	41.8	11.9
" " "	" 29	7.65	7.63	2.03	17.31	6895	398	44.2	44.1	11.7

Table 4.-Average measurements and leaf counts at intervals on tobacco plants grown in nutrient solutions with and without the addition of the different essential elements in a comparison of two groups of solutions of varying composition for the period from Jan. 16 to Feb. 28, 1930 (Series 2)

Standard group of solutions

Elements omitted	Length of Roots (cms.)				Height of stalk (cms.)				Number of leaves			
	Jan. 18	Jan. 29	Feb. 13	Feb. 27	Jan. 18	Jan. 29	Feb. 13	Feb. 27	Jan. 18	Jan. 29	Feb. 13	Feb. 27
N	12.0	17.8	24.2	30.6	2.8	3.0	3.0	3.4	4.2	5.6	7.2	8.6
P	10.6	21.4	34.6	39.4	2.4	2.8	4.8	5.0	4.4	6.0	8.2	9.4
K	12.2	18.4	40.2	36.8	2.8	3.4	6.2	9.2	3.8	6.0	10.4	14.4
Ca	12.6	10.6	11.0	12.0	3.4	3.8	3.0	3.0	4.2	6.2	6.2	6.2
Mg	10.2	17.4	39.4	42.2	2.8	3.4	4.4	4.8	3.6	6.2	10.0	13.4
None (C^{1})	9.8	21.6	36.8	35.6	3.0	4.2	19.8	61.2	4.2	7.4	13.0	19.6
B	8.2	17.0	25.0	25.4	2.4	2.8	6.2	6.2	4.0	6.6	9.4	9.8
S	11.8	18.6	29.6	30.0	3.0	3.8	7.0	7.6	3.8	7.0	9.8	10.6
Mn	10.0	13.2	19.4	24.2	2.2	2.2	3.4	6.6	3.4	5.6	7.8	13.0
Fe	8.8	13.0	22.8	25.0	2.2	2.4	5.8	10.0	3.8	6.6	10.8	14.2
Cl	9.0	14.8	36.4	33.6	2.4	2.6	12.6	47.0	3.2	5.6	11.0	17.8

Solutions used for comparison with standard group

N	10.6	21.6	22.4	30.6	3.0	3.0	3.0	3.2	4.4	6.8	7.2	8.2
P	9.6	23.6	34.6	34.2	2.4	3.0	4.8	5.2	4.2	5.8	8.6	9.8
K	10.8	17.2	36.8	36.0	2.6	3.6	6.6	10.4	3.8	6.2	10.6	14.4
Ca	10.4	10.4	10.4	10.4	3.2	3.2	2.4	2.4	3.8	5.6	5.0	5.4
Mg	10.8	18.2	37.6	35.8	2.4	2.8	4.0	5.0	3.0	6.2	10.4	13.4
None (C^{3})	10.2	23.6	36.2	34.4	3.2	5.2	21.2	56.8	4.6	8.2	12.4	16.4
B	9.6	14.2	20.8	21.0	2.2	3.2	4.4	4.4	3.8	7.0	8.8	9.2
S	10.6	17.0	32.8	32.0	2.6	3.6	6.6	7.4	4.0	7.0	9.8	11.4
Mn	10.0	12.8	24.6	32.4	2.4	2.6	6.8	20.6	3.6	6.0	9.2	14.6
Fe	11.4	14.0	19.8	21.8	2.6	3.2	5.4	8.6	3.8	6.8	10.0	12.6
Cl	10.4	15.0	30.4	28.8	2.2	2.8	8.6	29.6	3.4	5.8	9.8	15.2

Table 5.-Average air-dry weight, water used and percentage leaf, stalk and root for tobacco plants grown in nutrient solutions with and without the addition of the different essential elements in a comparison of two groups of solutions of varying composition for the period from Jan. 16 to Feb. 28, 1930 (Series 2)

Standard group of solutions

Treatment	Air-dry weight (grams)				Water used (cc)		Percentages based on air-dry weight		
	Leaf	Stalk	Root	Total	Total for period	Amt. per gram air-dry wt.	Leaf	Stalk	Root
No added nitrogen	0.39	0.09	0.09	0.57	328	575	68.4	15.8	15.8
No added phosphorus	0.91	0.15	0.27	1.33	570	429	68.4	11.3	20.3
No added potassium	3.34	0.38	0.39	4.11	2200	535	81.3	9.2	9.5
No added calcium	0.73	0.20	0.21	1.14	446	391	64.0	17.6	18.4
No added magnesium	2.66	0.09	0.16	2.91	1277	439	91.4	3.1	5.5
Control (C^1)	7.88	6.35	1.78	16.01	5011	313	49.2	39.7	11.1
No added boron	3.04	0.46	0.34	3.84	1170	305	79.2	12.0	8.8
No added sulphur	1.32	0.50	0.41	2.23	678	304	59.2	22.4	18.4
No added manganese	2.08	0.35	0.37	2.80	1661	593	74.3	12.5	13.2
No added iron	2.29	0.67	0.48	3.44	1114	324	66.6	19.5	13.9
No added chlorine	7.06	5.06	1.61	13.73	4222	308	51.4	36.9	11.7

Solutions used for comparison with standard group

Treatment	Leaf	Stalk	Root	Total	Total for period	Amt. per gram air-dry wt.	Leaf	Stalk	Root
No added nitrogen	0.42	0.11	0.15	0.68	380	559	61.8	16.2	22.0
No added phosphorus	1.07	0.20	0.28	1.55	658	425	69.0	12.9	18.1
No added potassium	3.39	0.40	0.44	4.23	2190	518	80.1	9.5	10.4
No added calcium	0.64	0.16	0.21	1.01	379	375	63.4	15.8	20.8
No added magnesium	2.45	0.07	0.11	2.63	1281	487	93.1	2.7	4.2
Control (C^3)	4.23	4.57	1.09	9.89	3393	343	42.8	46.2	11.0
No added boron	2.74	0.34	0.25	3.33	1019	306	82.3	10.2	7.5
No added sulphur	1.42	0.40	0.48	2.30	737	320	61.7	17.4	20.9
No added manganese	4.04	1.63	0.89	6.56	3355	511	61.6	24.8	13.6
No added iron	1.70	0.48	0.32	2.50	953	381	68.0	19.2	12.8
No added chlorine	3.46	2.46	0.84	6.76	2263	335	51.2	36.4	12.4

Table 6.-Average measurements and leaf counts at intervals on tobacco plants grown in nutrient solutions with and without the different essential elements supplied at intervals, showing recovery during period from Apr. 1 to May 28, 1930 (Series 3)

Treatment		Length of Roots (cms.)				Height of Stalk (cms.)				Number of leaves			
Elements omitted	Date transferred to Control (C^1) from solution indicated	Apr. 1	May 1	May 14	May 28	Apr. 1	May 1	May 14	May 28	Apr. 1	May 1	May 14	May 28
N	----	11.8	15.5	29.0	41.3	2.0	2.0	3.3	3.3	4.0	6.0	6.5	6.8
N	May 14	10.0	12.3	22.7	35.0	2.0	2.0	3.0	5.3	4.0	6.3	6.3	9.7
N	May 1	10.3	10.3	36.0	39.3	2.0	2.0	8.7	46.7	3.3	4.7	9.7	15.7
P	----	11.8	43.8	51.3	54.0	2.3	2.5	3.5	4.3	4.0	6.8	8.0	8.5
P	May 14	12.0	45.3	60.3	60.3	2.0	2.3	3.3	8.0	3.3	6.7	7.0	10.3
P	May 1	10.0	40.0	48.0	50.7	2.3	3.3	22.0	75.0	3.7	7.7	13.0	19.3
K	----	8.5	42.0	39.5	38.3	2.0	5.8	10.8	14.5	3.8	10.3	13.3	15.3
K	May 14	11.0	40.3	36.0	39.7	2.0	6.7	12.0	27.3	4.3	10.7	13.3	18.0
K	May 1	9.3	33.3	36.3	37.3	2.0	5.0	26.7	81.7	4.3	10.0	14.7	20.3
Ca	----	11.5	12.8	17.3	20.5	2.3	2.3	2.0	2.0	4.3	4.3	4.3	4.3
Ca	May 14	12.7	15.0	17.3	17.3	2.0	2.0	2.0	2.0	4.7	4.3	4.3	4.3
Ca	May 1	10.0	17.0	42.0	46.0	2.3	2.0	12.0	47.7	4.0	4.0	9.0	15.0
Mg	----	12.0	46.8	43.8	46.3	2.3	5.8	8.5	10.3	4.0	11.8	14.8	18.3
Mg	May 14	9.0	44.3	45.0	45.0	2.3	5.0	7.3	13.3	4.3	11.7	14.7	19.7
Mg	May 1	11.3	37.7	36.0	36.7	2.0	3.0	18.0	63.3	4.3	10.3	16.0	20.0
None (C^1)	Apr. 1	13.3	42.0	38.8	38.8	2.0	20.0	67.5	120.5	4.3	13.0	19.5	21.0
None (C^1)	Apr. 1	11.3	38.7	39.3	39.3	2.0	24.7	83.7	132.3	4.0	13.3	20.0	21.0
None (C^1)	Apr. 1	10.3	40.0	38.3	38.3	2.0	24.7	87.0	126.0	4.0	12.7	20.0	20.3
B	----	11.0	26.8	26.0	26.0	2.0	2.0	3.3	3.3	4.0	4.8	6.5	8.5
B	May 14	11.0	29.0	28.0	28.0	2.0	2.0	4.0	5.5	4.0	4.0	5.5	7.0
B	May 1	9.7	18.3	32.3	32.3	2.0	2.0	5.7	23.3	4.0	4.0	6.7	10.0
S	----	11.0	39.5	33.3	33.3	2.0	4.3	9.0	13.5	4.0	9.8	12.5	15.3
S	May 14	9.7	35.0	30.0	37.0	2.3	5.0	11.0	32.0	4.0	10.0	13.0	17.7
S	May 1	10.3	38.0	35.3	35.3	2.0	5.7	38.3	106.7	4.0	10.7	16.3	22.0
Mn	----	10.3	42.5	36.5	36.5	2.8	12.3	40.5	72.3	4.3	11.3	15.5	20.3
Mn	May 14	11.7	39.0	31.7	31.7	2.0	9.7	40.3	81.7	4.0	11.0	16.0	20.7
Mn	May 1	11.7	38.3	36.0	36.0	2.0	9.7	50.7	123.7	3.7	11.0	17.0	21.7
Fe	----	10.3	15.5	24.3	24.3	2.0	2.8	7.3	15.3	4.0	7.3	12.3	15.3
Fe	May 14	9.7	13.7	26.7	26.7	2.0	3.0	11.3	30.3	3.7	8.0	12.3	16.7
Fe	May 1	10.0	18.7	40.0	40.0	2.0	2.3	17.7	62.7	3.7	7.7	14.3	18.0
None (C^2)	----	10.5	38.3	35.5	35.5	2.3	13.8	57.3	122.5	4.0	11.5	17.8	21.3
None (C^2)	----	8.3	37.3	33.3	33.3	2.3	10.3	49.3	113.7	4.0	10.0	15.7	20.7
None (C^2)	----	8.3	35.0	35.7	35.6	2.3	15.7	58.3	109.7	4.0	11.0	17.3	20.7
C1	----	10.5	38.0	34.0	34.0	2.0	5.8	43.3	106.3	4.0	9.5	15.8	20.8

Table 7.-Average air-dry weight, water used and percentage leaf, stalk and root for tobacco plants grown in nutrient solutions with and without the different essential elements supplied at intervals, showing recovery during period from Apr. 1 to May 28, 1930 (Series 3)

Treatment	Date transferred to the Control (C^1) solution	Air-dry weight (grams)				Water used (cc)		Percentages based on air-dry weight		
		Leaf	Stalk	Root	Total	Total for period	Amt. per gram air-dry wt.	Leaf	Stalk	Root
No added nitrogen	----	0.85	0.16	0.30	1.31	641	489	64.9	12.2	22.9
" " "	May 14	1.92	0.23	0.35	2.50	1091	436	76.8	9.2	14.0
" " "	May 1	11.40	4.43	2.50	18.33	7191	392	62.2	24.2	13.6
No added phosphorus	----	1.35	0.16	0.55	2.06	1165	566	65.5	7.8	26.7
" " "	May 14	3.07	0.33	0.77	4.17	1830	439	73.6	7.9	18.5
" " "	Mev 1	14.08	8.25	4.23	26.56	10873	409	53.0	31.1	15.9
No added potessium	----	5.55	0.43	0.56	6.54	4170	638	84.9	6.6	8.5
" " "	May 14	8.83	1.57	1.60	12.00	5372	448	73.6	13.1	13.3
" " "	May 1	16.17	8.35	4.88	29.40	10884	370	55.0	28.4	16.6
No added calcium	----	1.35	0.19	0.47	2.01	872	434	67.2	9.4	23.4
" " "	May 14	1.55	0.20	0.66	2.41	1030	448	64.3	8.3	27.4
" " "	May 1	11.50	5.65	2.81	19.96	7002	351	57.6	28.3	14.1
No added magnesium	----	5.93	0.35	0.42	6.70	3818	570	88.5	5.2	6.3
" " "	May 14	6.38	0.65	0.83	7.86	4024	512	81.2	8.3	10.5
" " "	May 1	15.48	6.75	3.92	26.15	9433	361	59.2	25.8	15.0
Control (C^1)	Apr. 1	16.51	17.63	6.36	40.50	14931	369	40.8	43.5	15.7
"	Apr. 1	15.72	19.15	6.80	41.67	15206	365	37.7	46.0	16.3
"	Apr. 1	18.17	21.20	7.45	46.82	17140	366	38.8	45.3	15.9
No added boron	----	3.75	0.69	0.65	5.09	1780	350	73.7	13.5	12.8
" " "	May 14	3.20	0.68	0.60	4.48	1637	365	71.4	15.2	13.4
" " "	May 1	6.08	2.18	1.27	9.53	3378	354	63.8	22.9	13.3
No added sulphur	----	8.04	1.89	3.50	13.43	5310	395	59.9	14.1	26.0
" " "	May 14	9.22	3.23	3.50	15.95	7070	443	57.8	20.3	21.9
" " "	May 1	16.52	12.51	5.52	34.55	13900	402	47.8	36.2	16.0
No added mengenese	----	12.51	5.63	2.27	20.41	12581	616	61.3	27.6	11.1
" " "	May 14	14.52	7.50	3.28	25.30	13543	535	57.4	29.6	13.0
" " "	May 1	21.90	16.17	7.10	45.17	16227	359	48.5	35.8	15.7
No added iron	----	4.27	1.09	0.80	6.16	2762	448	69.3	17.7	13.0
" " "	May 14	7.57	3.03	1.98	12.58	4780	380	60.2	24.1	15.7
" " "	May 1	11.92	7.08	2.82	21.82	7749	355	54.6	32.5	12.9
Control (C^2)	Apr. 1	15.32	17.79	5.64	38.75	14590	377	39.5	45.9	14.6
"	Apr. 1	15.10	15.30	5.75	36.15	13688	379	41.8	42.3	15.9
"	Apr. 1	15.61	15.42	6.20	37.23	14285	384	41.9	41.4	16.7
No added chlorine	----	14.29	10.80	4.90	29.99	11680	389	47.7	36.0	16.3

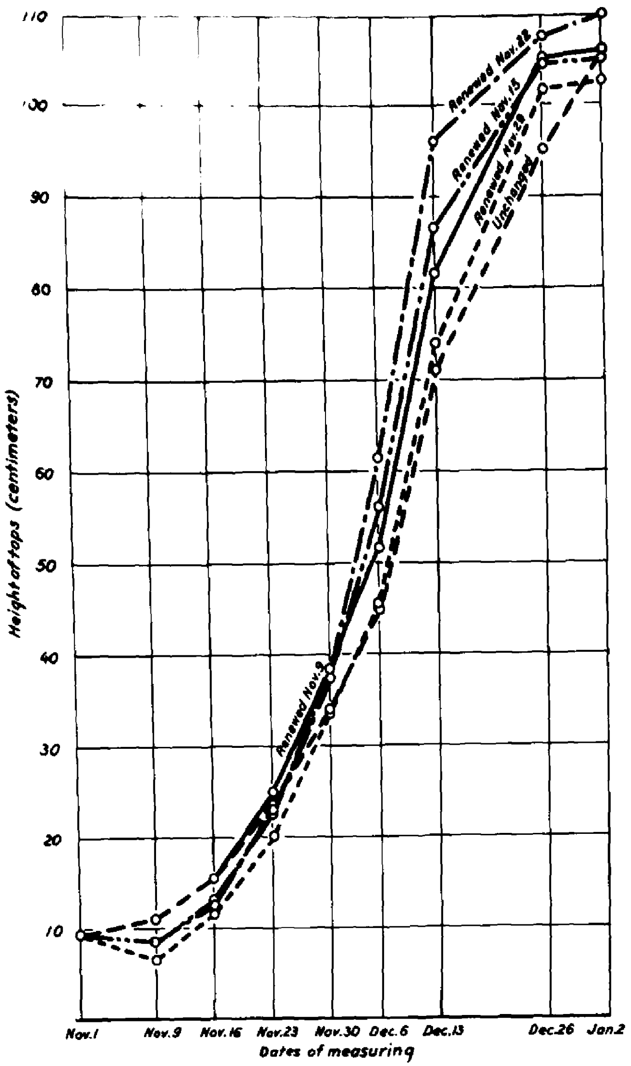

Fig.1-Growth in height of plants in control solution (C^1) unchanged and renewed at intervals, (table 2).

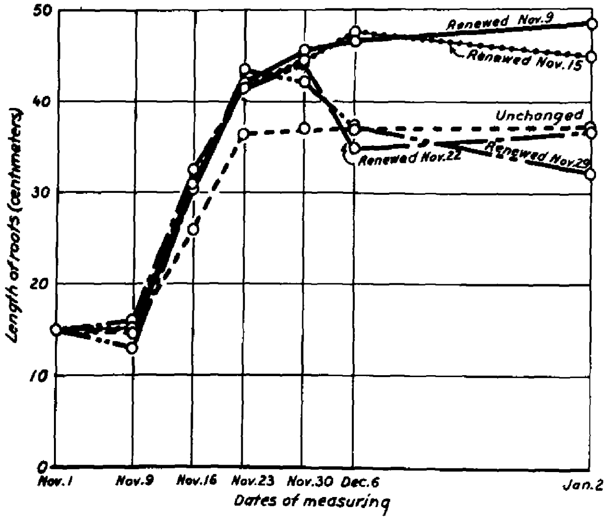

Fig. 2-Growth in length of roots of plants in control solution (C^1) unchanged and renewed at intervals, (table 2).

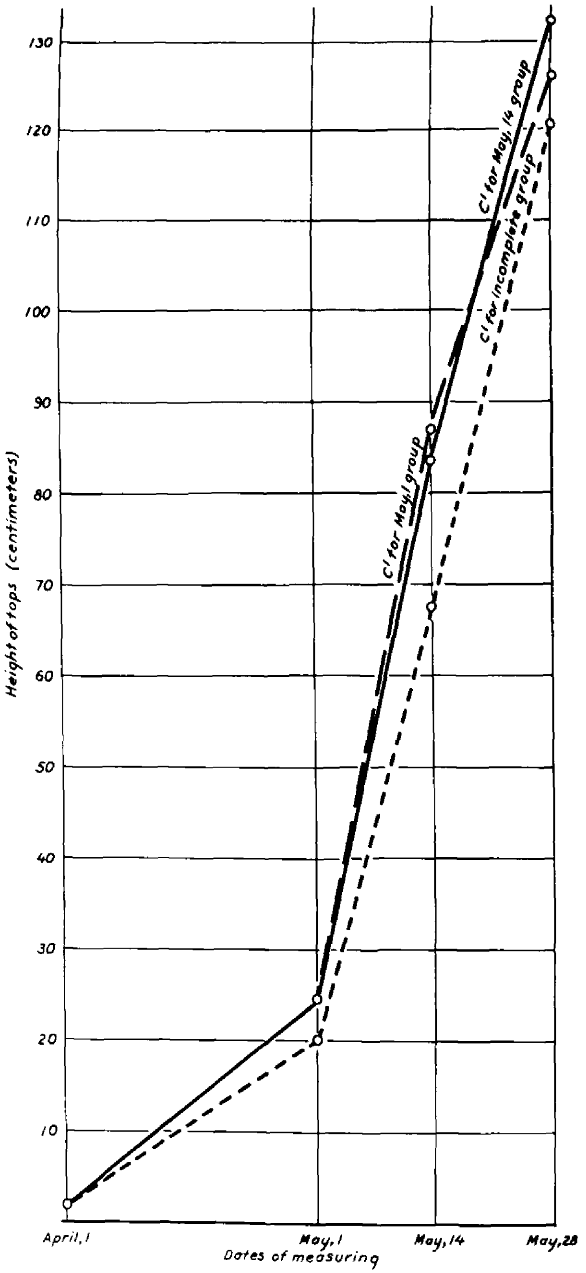

Fig. 3.-Growth in height of plants in control solution (C^1) for different periods of change located on tables in line with cultures changed as indicated and in incomplete solutions (table 6).

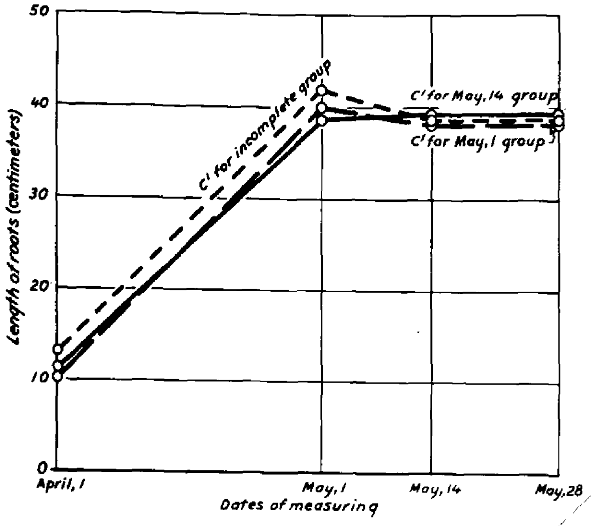

Fig. 4.-Growth in length of roots of plants in control solution (C^1) for different periods of change located on tables in line with cultures changed as indicated and in incomplete solutions (table 6).

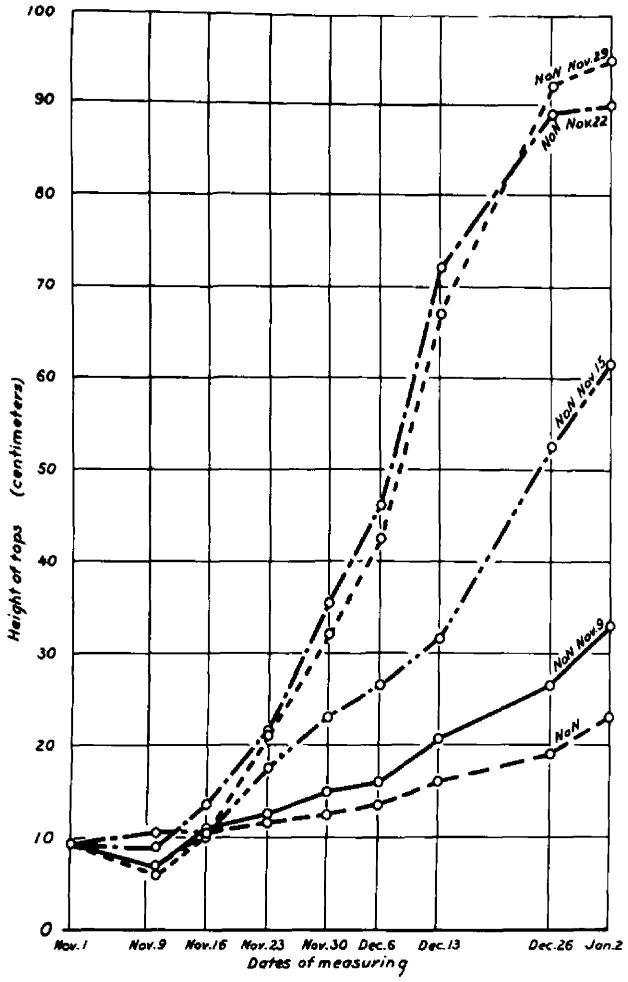

Fig. 5.-Growth in height of plants in solutions with nitrogen (N) withdrawn at intervals compared with no nitrogen for entire period (table 2).

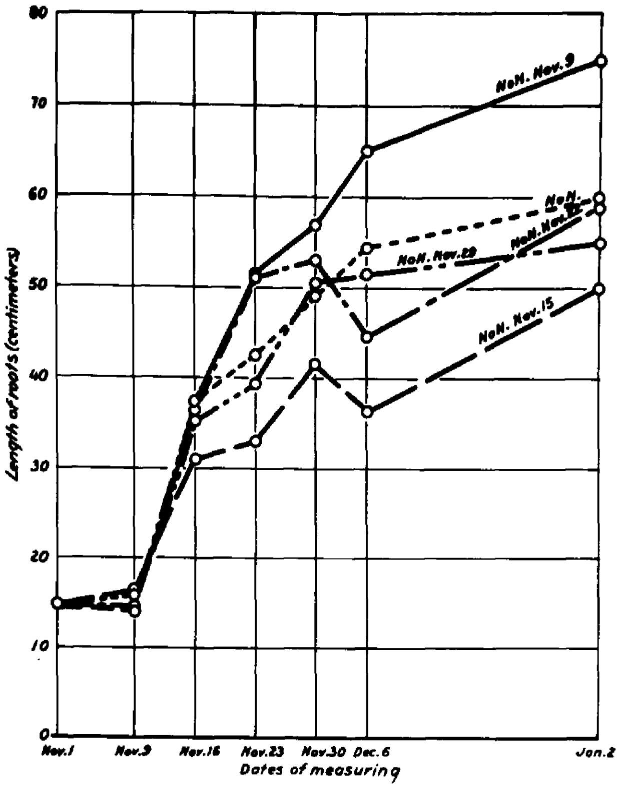

Fig. 6.-Growth in length of roots of plants in solutions with nitrogen (N) withdrawn at intervals compared with no nitrogen for entire period (table 2).

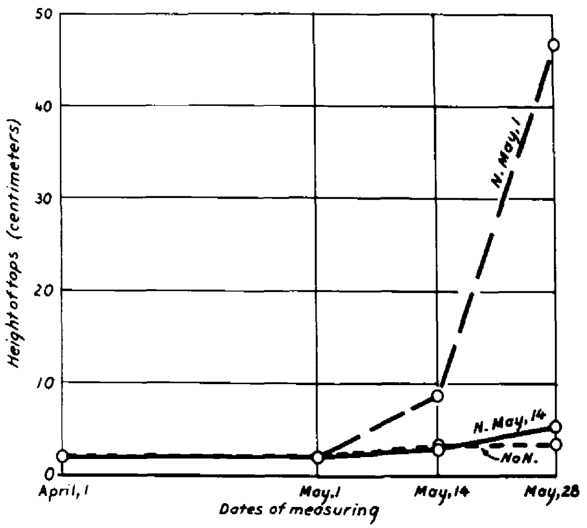

Fig. 7.-Growth in height of plants in solutions with nitrogen (N) supplied at different periods compared with no nitrogen (table 6).

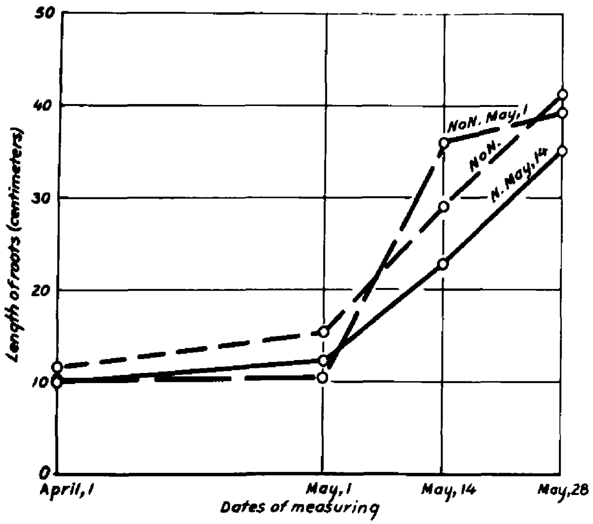

Fig. 8.-Growth in length of roots of plants in solutions with nitrogen (N) supplied at different periods compared with no nitrogen (table 6).

Figure 9.-Tobacco plants placed in culture solutions Apr. 1, 1930, series 3, (photographed May 15, 1930; scale shown in inches): 1, no nitrogen added; 6, nitrogen added.

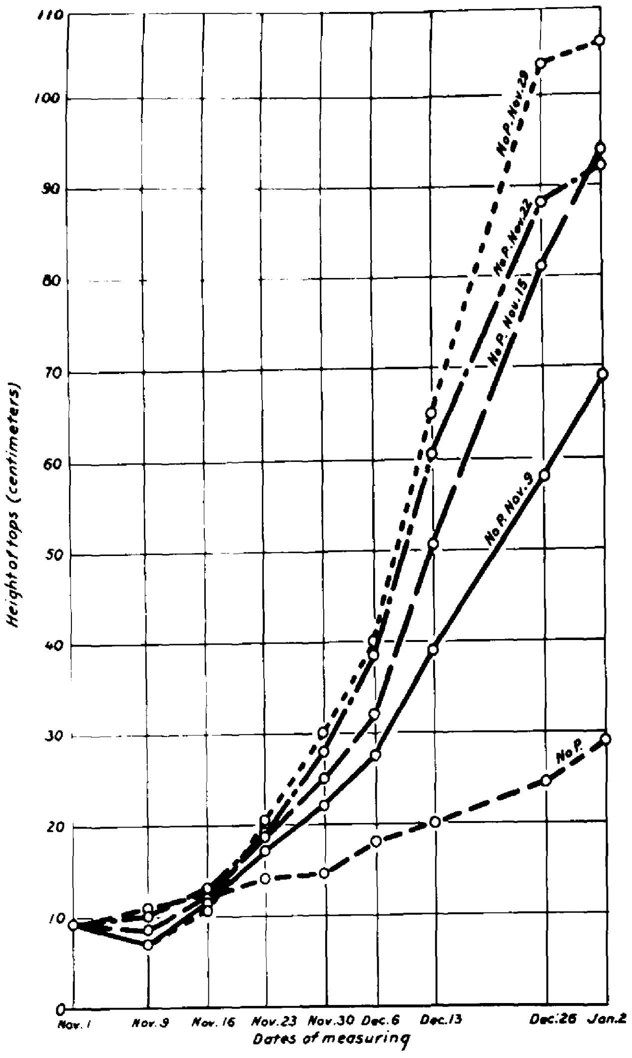

Fig. 10.-Growth in height of plants in solutions with phosphorus (P) withdrawn at intervals compared with no phosphorus for entire period (table 2).

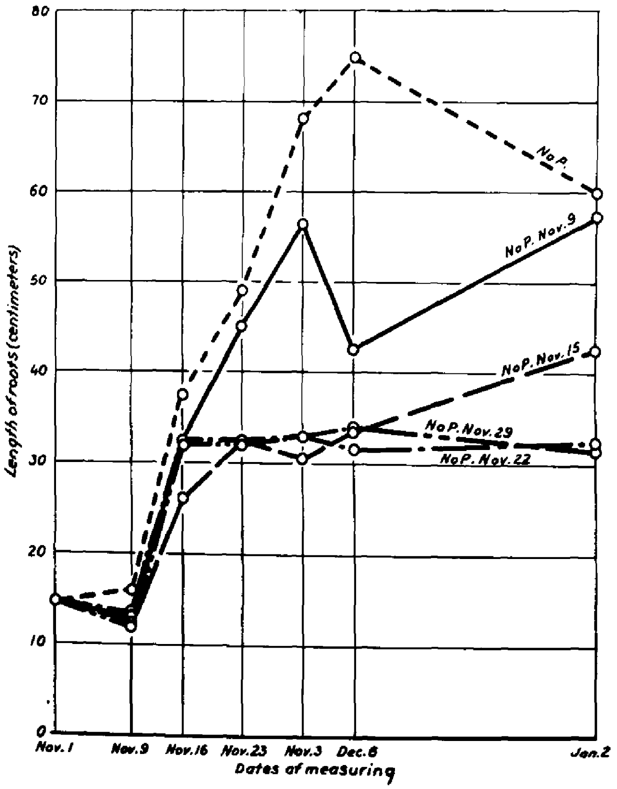

Fig. 11.-Growth in length of roots of plants in solutions with phosphorus (P) withdrawn at intervals compared with no phosphorus for entire period (table 2).

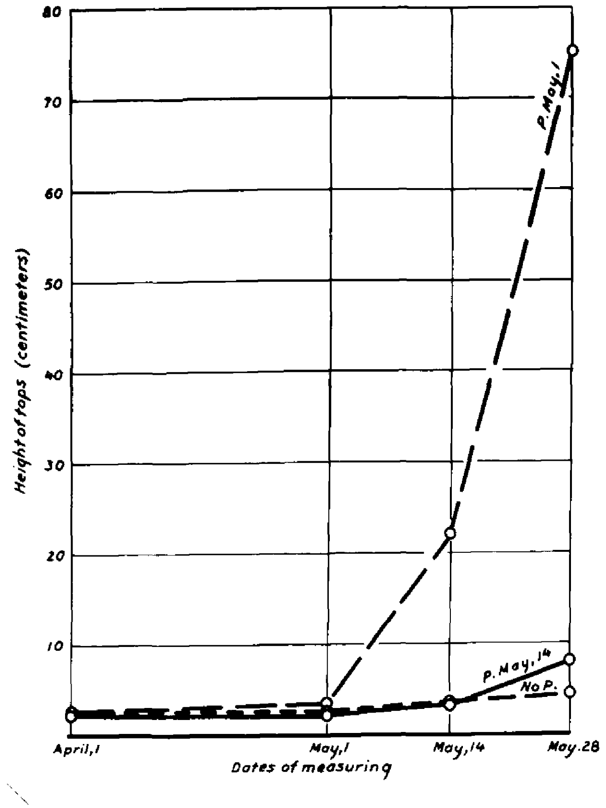

Fig. 12.-Growth in height of plants in solutions with phosphorus (P) supplied at different periods compared with no phosphorus (table 6).

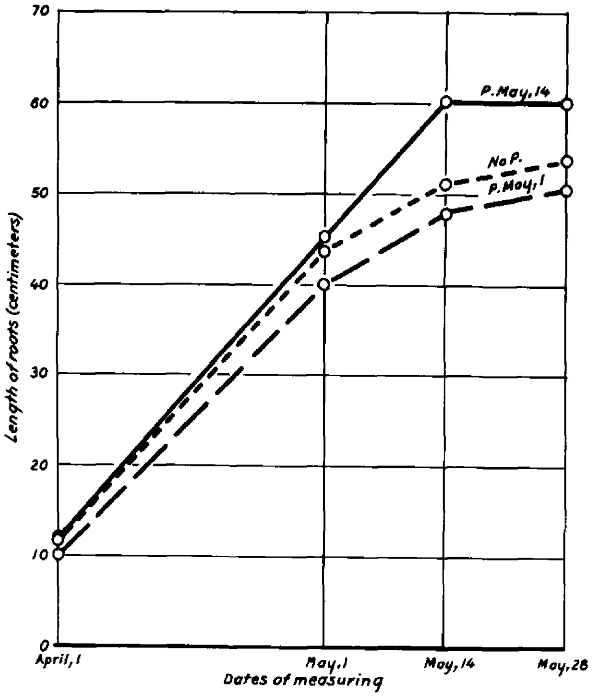

Fig. 13.-Growth in length of roots of plants in solutions with phosphorus (P) supplied at different periods compared with no phosphorus (table 6).

Figure 14.-Tobacco plants placed in culture solutions Apr. 1, 1930, series 3, (photographed May 15, 1930; scale in inches): 2, no phosphorus added; 6, phosphorus added.

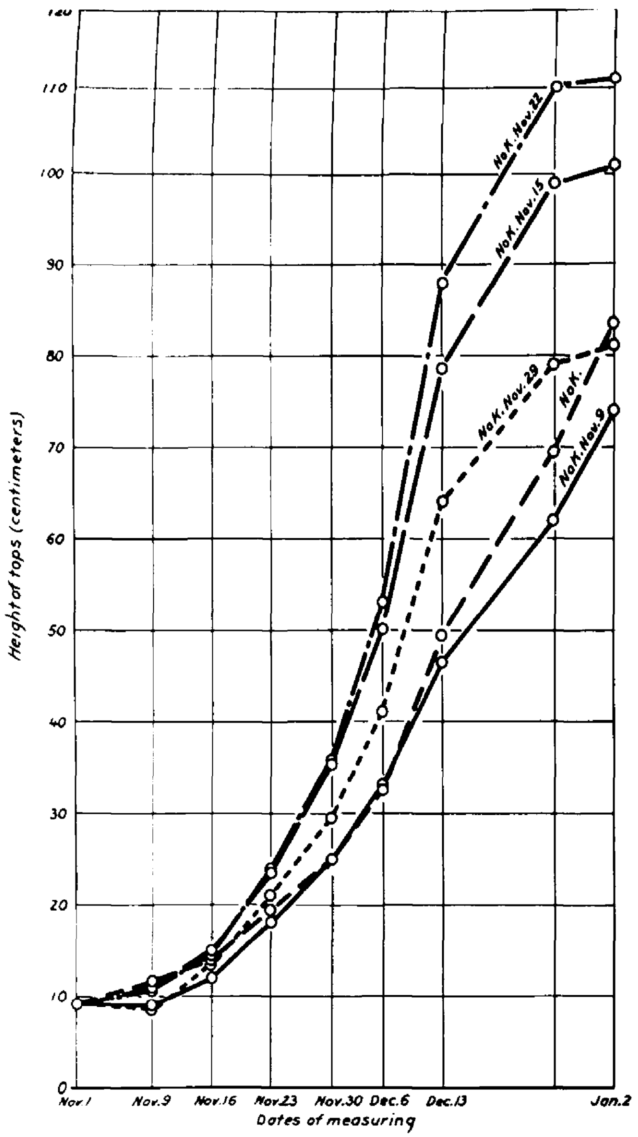

Fig. 15.-Growth in height of plants in solutions with potassium (K) withdrawn at intervals compared with no potassium for entire period (table 2).

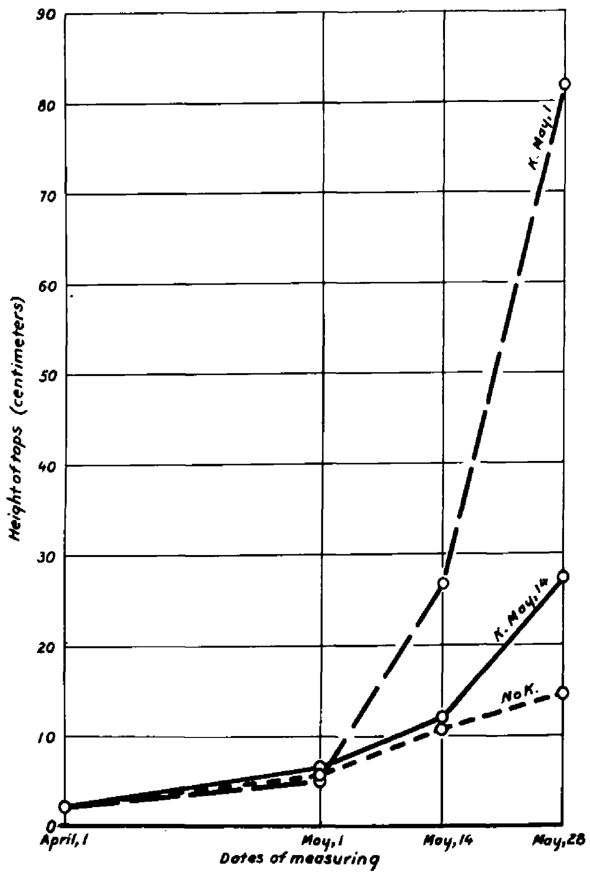

Fig. 16.-Growth in height of plants in solutions with potassium (K) supplied at different periods compared with no potassium (table 6).

Figure 17.-Tobacco plants placed in culture solutions Apr. 1, 1930, series 3, (photographed May 15, 1930; scale in inches): 3, no potassium added; 6, potassium added.

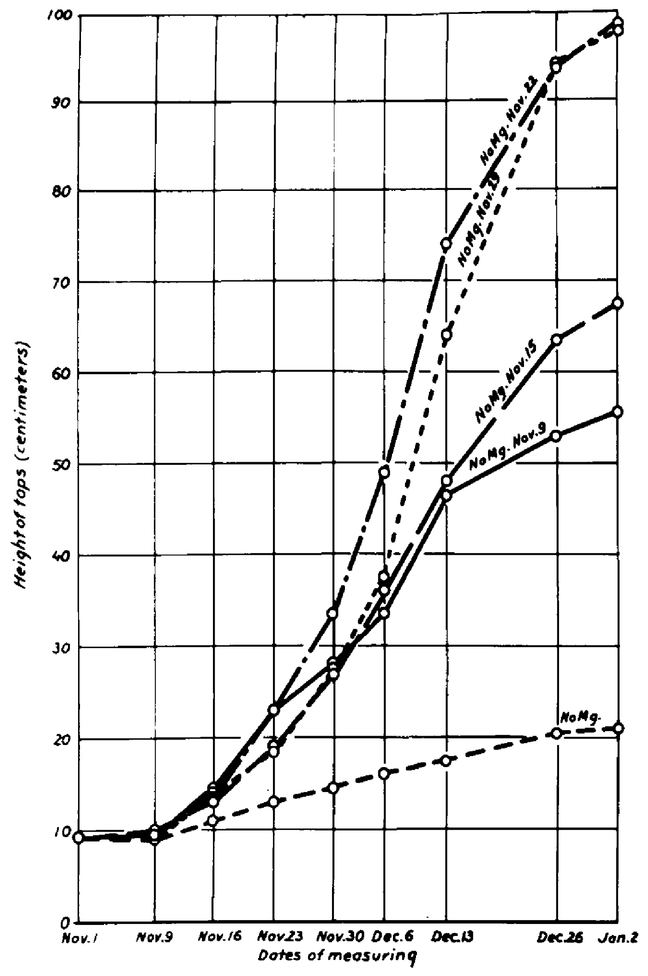

Fig. 18.-Growth in height of plants in solutions with magnesium (Mg) withdrawn at intervals compared with no magnesium for entire period (table 2).

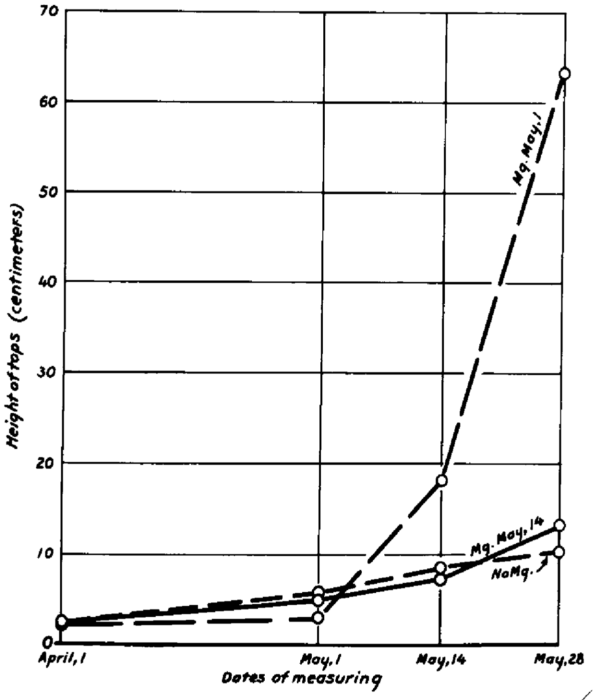

Fig. 19.-Growth in height of plants in solutions with magnesium (Mg) supplied at different periods compared with no magnesium (table 6).

Figure 20.-Tobacco plants placed in culture solutions Apr. 1, 1930, series 3, (photographed May 15, 1930; scale in inches): 5, no magnesium added; 6, magnesium added.

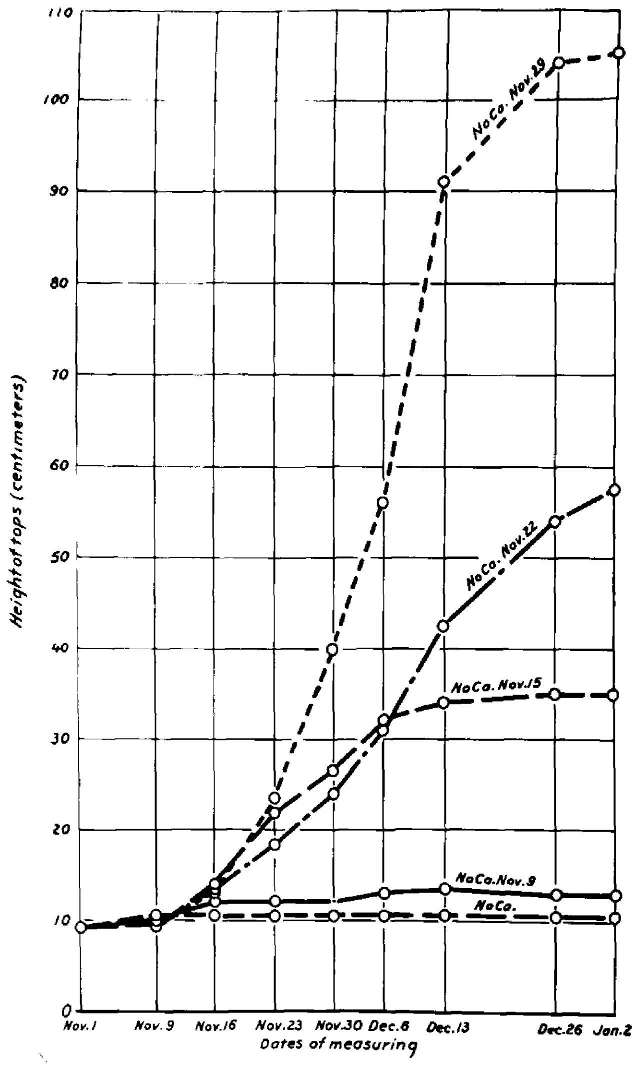

Fig. 21.-Growth in height of plants in solutions with calcium (Ca) withdrawn at intervals compared with no calcium for entire period (table 2).

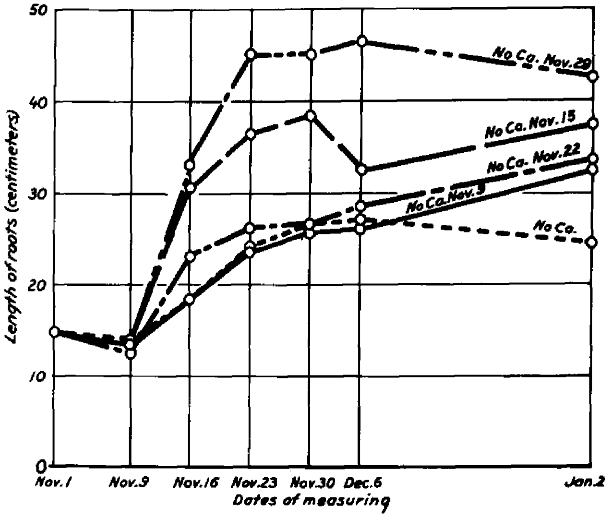

Fig. 22.-Growth in length of roots of plants in solutions with calcium (Ca) withdrawn at intervals compared with no calcium for entire period (table 2).

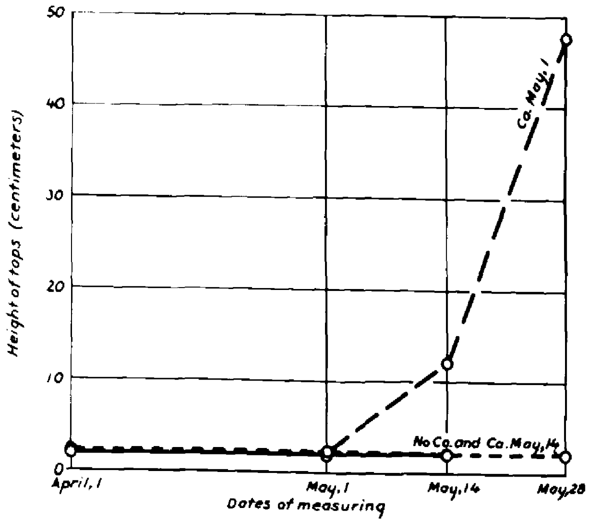

Fig. 23.-Growth in height of plants in solutions with calcium (Ca) supplied at different periods compared with no calcium (table 6).

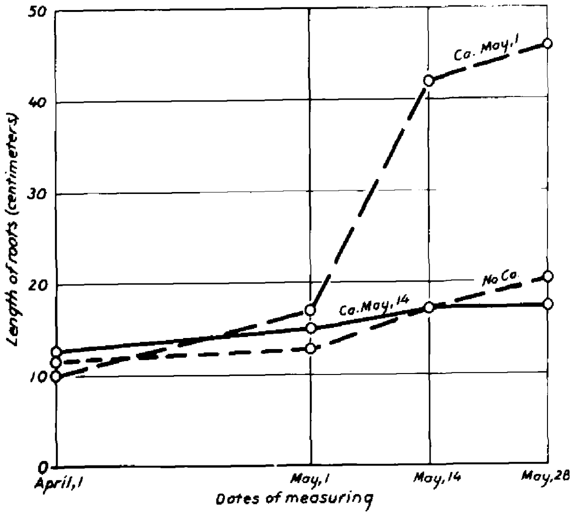

Fig. 24.-Growth in length of roots of plants in solutions with calcium (Ca) supplied at different periods compared with no calcium (table 6).

Figure 25.-Tobacco plants placed in culture solutions Apr. 1, 1930, series 3, (photographed May 15, 1930; scale in inches): 4, no calcium added; 6, calcium added.

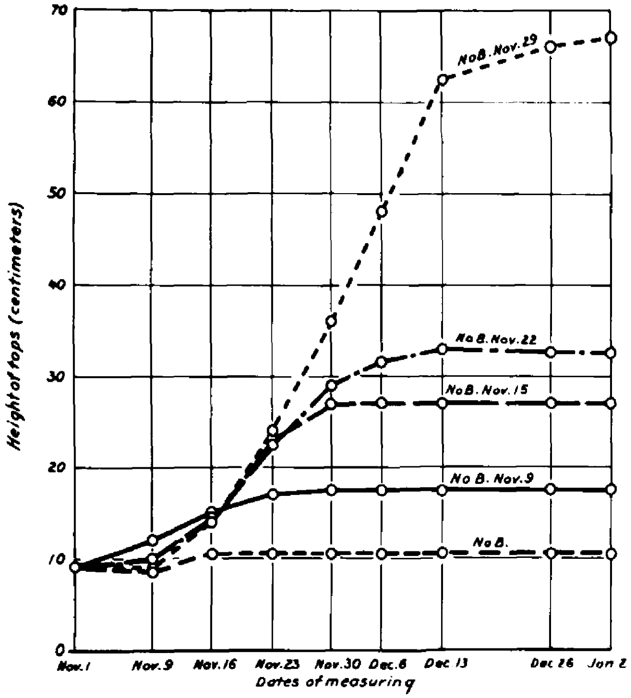

Fig. 26.-Growth in height of plants in solutions with boron (B) withdrawn at intervals compared with no boron for entire period (table 2).

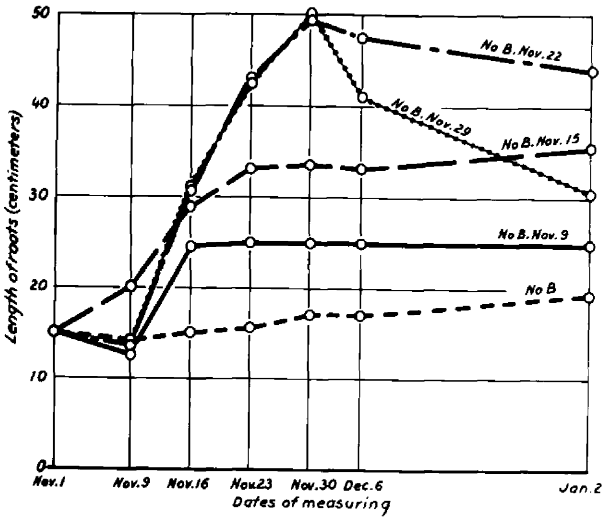

Fig. 27.-Growth in length of roots of plants in solutions with boron (B) withdrawn at intervals compared with no boron for entire period (table 2).

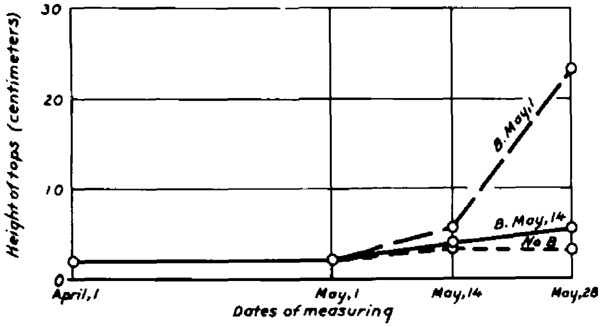

Fig. 28.-Growth in height of plants in solutions with boron (B) supplied at different periods compared with no boron (table 6).

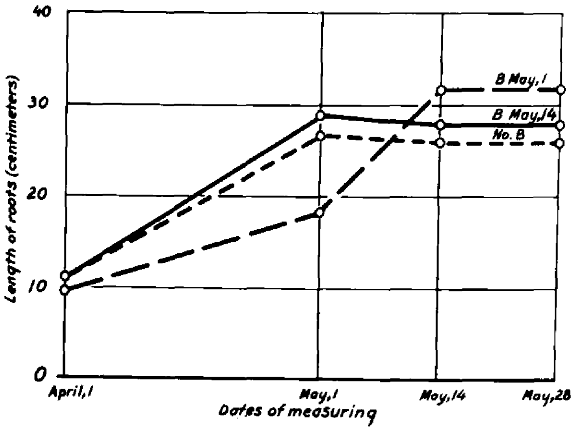

Fig. 29.-Growth in length of roots of plants in solutions with boron supplied at different periods compared with no boron (table 6).

Figure 30.-Tobacco plants placed in culture solutions Apr. 1, 1930, series 3. (photographed May 15, 1930; scale in inches): 7, no boron added; 6, boron added.

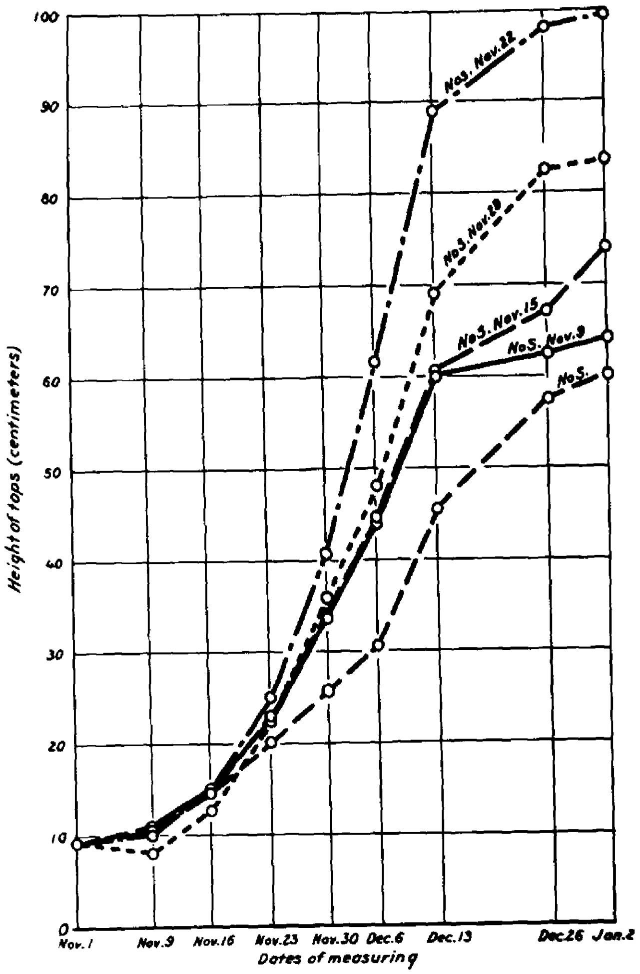

Fig. 31.-Growth in height of plants in solutions with sulfur (S) withdrawn at intervals compared with no sulfur for entire period (table 2).

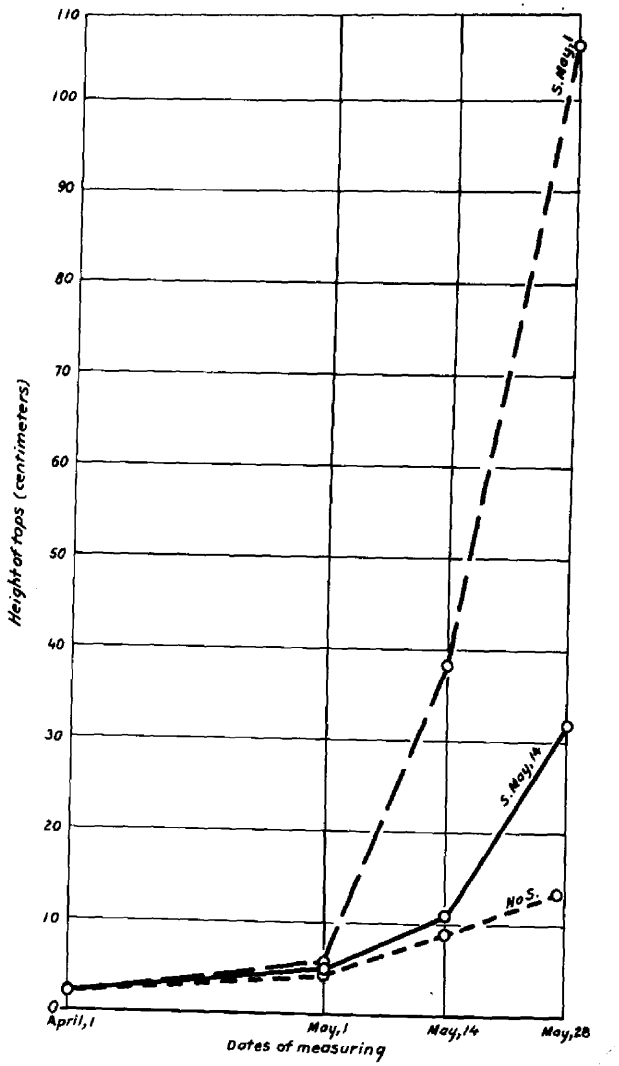

Fig. 32.-Growth in height of plants in solutions with sulfur (S) supplied at different periods compared with no sulfur (table 6).

Figure 33.-Tobacco plants placed in culture solutions Apr. 1, 1930, series 3, (photographed May 15, 1930; scale in inches): 8, no sulfur added; 6, sulfur added.

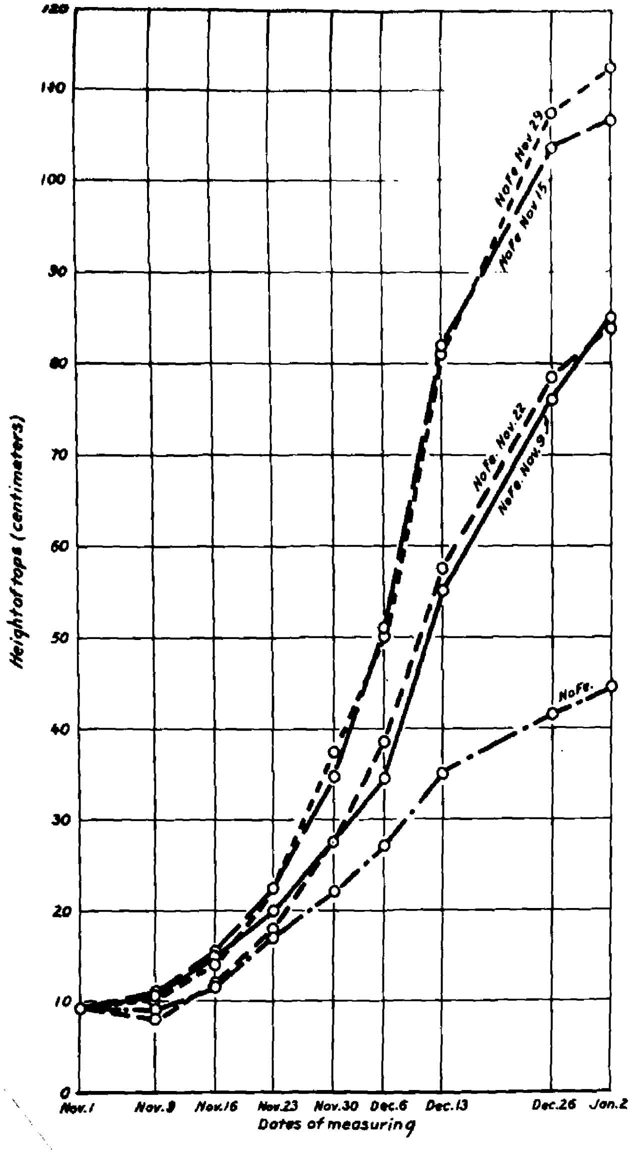

Fig. 34.-Growth in height of plants in solutions with iron (Fe) withdrawn at intervals compared with no iron for entire period (table 2).

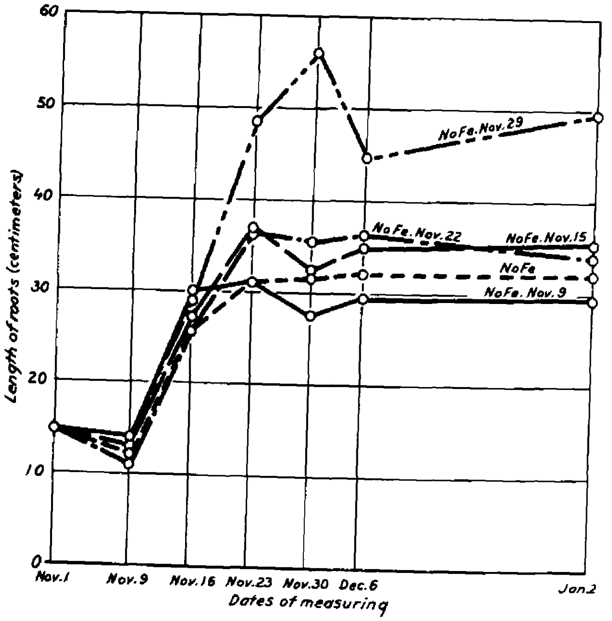

Fig. 35.-Growth in length of roots of plants in solutions with iron (Fe) withdrawn at intervals compared with no iron for entire period (table 2).

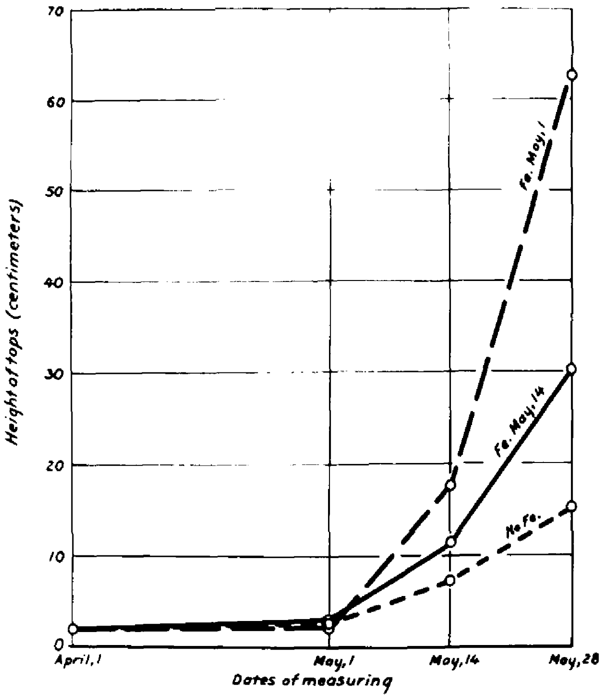

Fig. 36.-Growth in height of plants in solutions with iron (Fe) supplied at different periods compared with no iron (table 6).

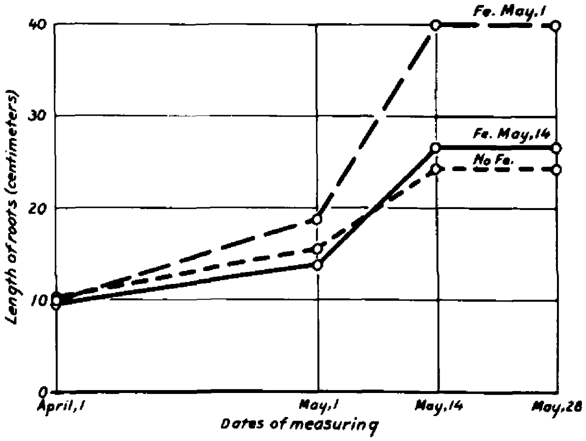

Fig. 37.-Growth in length of roots of plants in solutions with iron (Fe) supplied at different periods compared with no iron (table 6).

Figure 38.-Tobacco plants placed in culture solutions Apr. 1, 1930, series 3, (photographed May 15, 1930; scale in inches): 10, no iron added; 6, iron added.

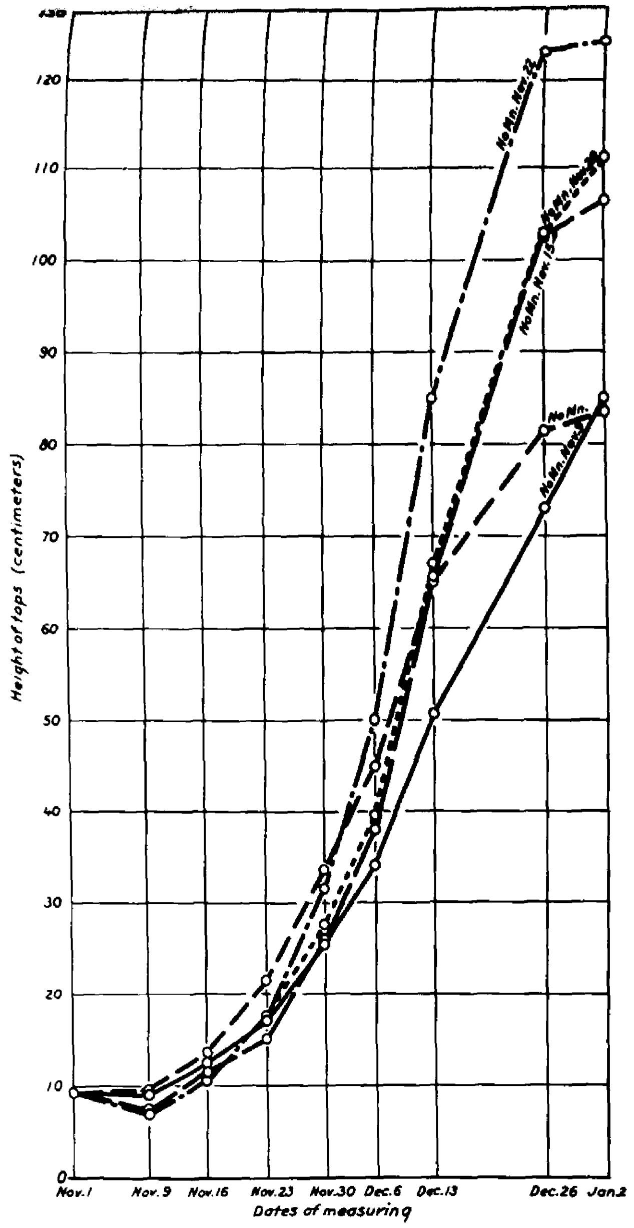

Fig. 39.-Growth in height of plants in solutions with manganese (Mn) withdrawn at intervals compared with no manganese for entire period (table 2).

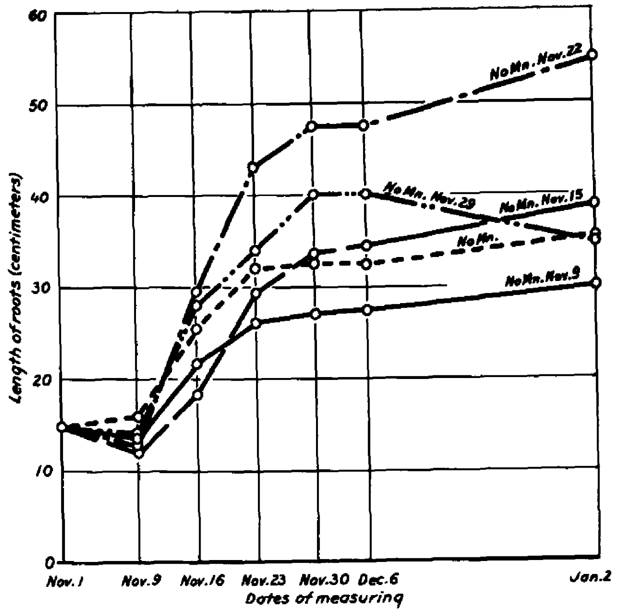

Fig. 40.-Growth in length of roots of plants in solutions with manganese (Mn) withdrawn at intervals compared with no manganese for entire period (table 2).

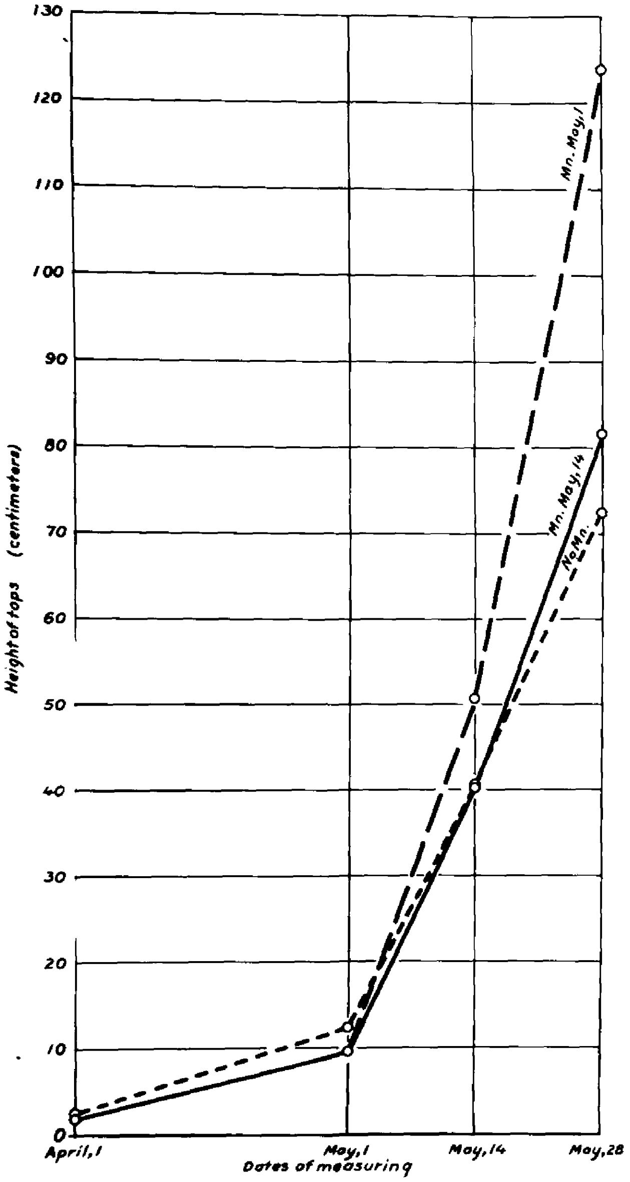

Fig. 41.-Growth in height of plants in solutions with manganese (Mn) supplied at different periods compared with no manganese (table 6).

Figure 42.-Tobacco plants placed in culture solutions Apr. 1, 1930, series 3, (photographed May 15, 1930; scale in inches): 9, no manganese added; 6, manganese added.

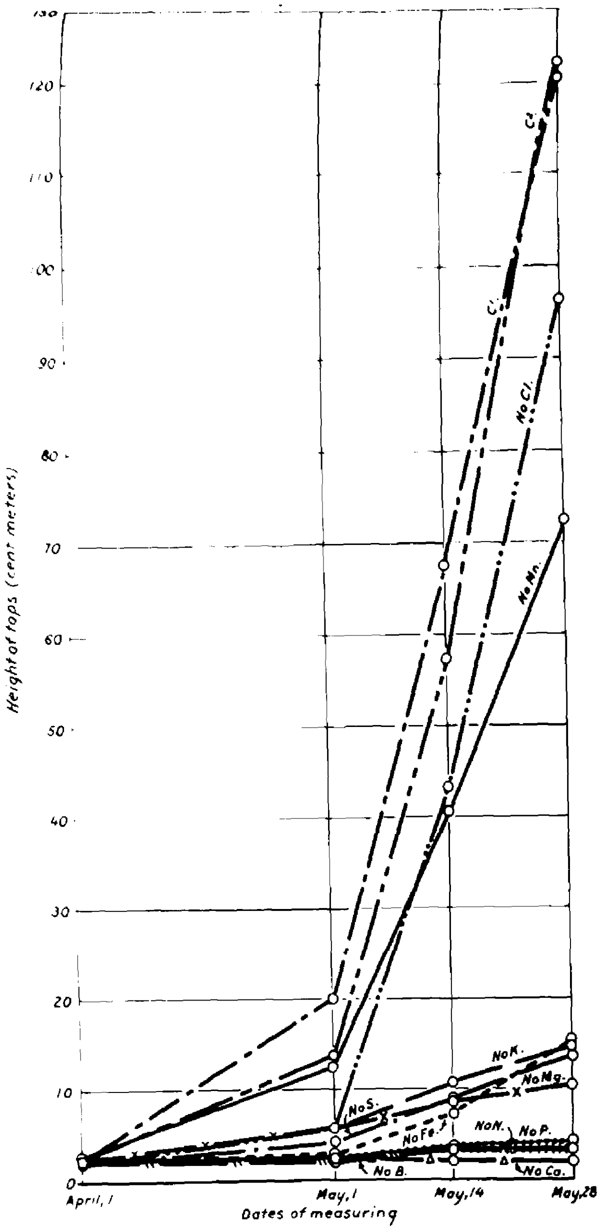

Fig. 43.-Growth in height of plants in control solutions (C^1) and (C^2) compared with solutions deficient in the different essential elements (table 6).

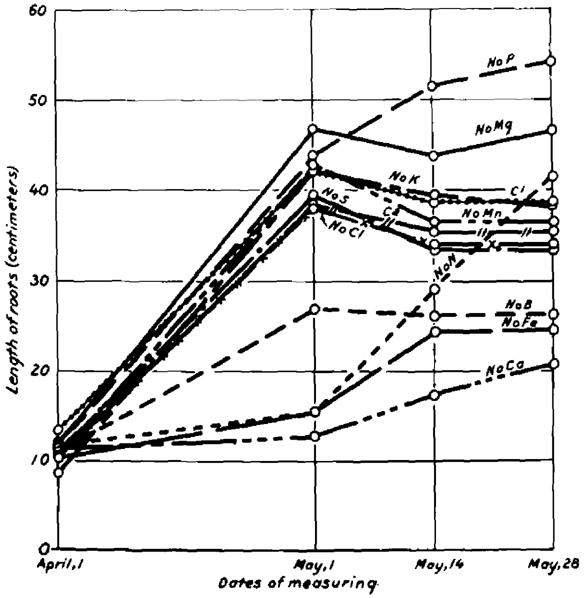

Fig. 44.-Growth in length of roots of plants in control solutions (C^1) and (C^2) compared with the solutions deficient in the different essential elements (table 6).

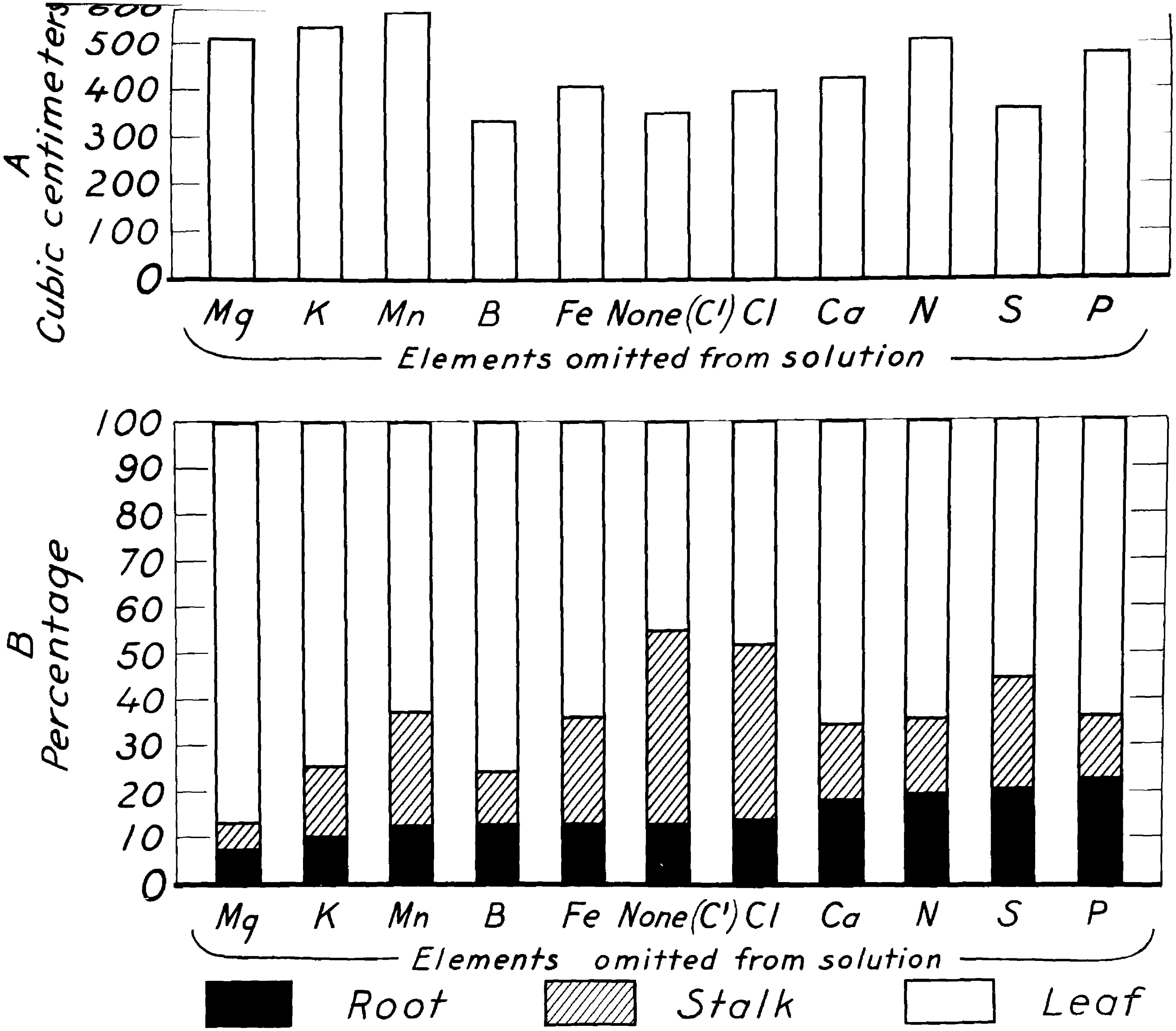

Fig. 45.-A-Average cubic centimeters of water transpired per gram of total air dry weight of plants from series 1, 2 and 3 grown in standard group of solutions. B-Average percentages of leaf, stalk and root in total air dry weight of plants grown in standard group of solutions from series 1, 2 and 3.

Plate 1.-Tobacco plants placed in culture solutions Apr. 1, 1930, series 3, (photographed May 15, 1930; scale shown in inches): 1, no nitrogen added; 2, no phosphorus added; 3, no potassium added; 4, no calcium added: 5, no magnesium added; 7, no boron added; 8, no sulfur added; 9, no manganese added; 10, no iron added; 6, above elements all added.