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H. W. WILEY, Chief of Bureau.

THE GROWTH OF WHEAT SEEDLINGS AS AFFECTED BY ACID OR ALKALINE CONDITIONS.

BY

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LETTER OF TRANSMITTAL.

U. S. Department of Agriculture,
Bureau of Chemistry,
Washington, D. C., June 12, 1911.

Sir: I have the honor to submit for your approval a manuscript prepared by J. F. Breazeale and J. A. Le Clerc, plant physiological chemists, of this bureau, on the growth of wheat seedlings as affected by acid and alkaline conditions. Although the results herein recorded were obtained from experiments conducted in water cultures, it is believed that their interpretation may be directly applied to practical agriculture. I recommend the publication of this manuscript as Bulletin No. 149 of the Bureau of Chemistry.

Respectfully,

H. W. Wiley,
Chief of Bureau.

Hon. James Wilson,
Secretary of Agriculture.

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INTRODUCTION.

The following physiological study on the effect of the reaction of the culture medium on the growth of wheat seedlings and particularly on the development of the root was undertaken primarily to determine whether or not the results obtained in practical agriculture can be explained in the laboratory from a purely scientific standpoint.

A few years ago Director Thorne, of the Ohio experiment station, called the attention of one of the authors to peculiar conditions existing on certain of his fertilizer experiment plots, to which potassium chlorid and potassium sulphate had been applied annually for the past 12 years. These plots had become so acid that it was found impossible to grow clover on them. Liming one-half of each plot had restored that half to almost its original fertility. This acidity, he said, was due to the selective action of the root, doubtless a correct explanation which will be considered in detail later.

There seems to be a natural tendency for all soils to become acid under continuous culture, due chiefly to one of two processes. The primary cause of this acidity is the decay of organic matter, leaves, stems, etc., which during decomposition develop acid-reacting bodies. If this process is allowed to continue, the reaction will ultimately become alkaline, but under soil conditions, especially if the aeration is poor and the water level high, decay is apt to be checked, leaving the soil in a characteristic acid condition. This phase of soil acidity, which will not be considered in this bulletin, has been studied extensively during the past few years, particularly by the Rhode Island and Ohio experiment stations, and by Mr. Frederick V. Coville[1] in his elaborate investigations on the blueberry. Peat bogs furnish an exaggerated case of acidity, due to organic matter. The secondary cause of soil acidity is the subject of the investigation herein reported.

[1] U. S. Dept. Agr., Bureau of Plant Industry Bul. 193.

EXPERIMENTS WITH NUTRIENT SOLUTIONS AND DISTILLED WATER CULTURES.

DESCRIPTION OF SOLUTIONS AND METHOD OF SOWING.

The following experiments were carried on in nutrient solutions and in distilled water cultures, eliminating the disturbing factors due to the presence of soil grains. For the most part wheat was used on account of the ease in handling the young seedlings. The seed, which was furnished by the Pennsylvania experiment station, was washed with warm water for about six hours and then sprinkled on perforated aluminum disks about 12 inches in diameter. These disks were floated, by means of glass tubes, in shallow pans which held about 3 liters of water. In this way approximately 1,000 seeds were used in each pan. The preliminary washing removed all of the readily soluble salts, the actual amounts so removed, as has been shown by the authors in previous experiments[1] of this kind, being quite large. The distilled water was prepared especially for this purpose and a small amount of carbon black was placed in each pan.

After some preliminary work a set of 13 pans was started, as follows:

Solution 1. Distilled water.

Solution 2. Distilled water + 0.5 gram of calcium carbonate.

Solution 3. 150 parts per million of sodium nitrate.

Solution 4. 150 parts per million of sodium nitrate + 0.5 gram of calcium carbonate.

Solution 5. 150 parts per million of potassium chlorid.

Solution 6. 150 parts per million of potassium chlorid + 0.5 gram of calcium carbonate.

Solution 7. 150 parts per million of potassium sulphate.

Solution 8. 150 parts per million of potassium sulphate + 0.5 gram of calcium carbonate.

Solution 9. 10 parts per million of hydrochloric acid.

Solution 10. 10 parts per million of hydrochloric acid + 0.5 gram of calcium carbonate.

Solution 11. 10 parts per million of sulphuric acid.

Solution 12. 10 parts per million of sulphuric acid + 0.5 gram of calcium carbonate.

Solution 13. 150 parts per million of sodium nitrate + 75 parts per million of potassium sulphate.

FIRST CROP OF SEEDLINGS.

These cultures were started January 24 and grown until February 2. The plants were then harvested, representative samples were selected and photographed, and the others were dried, weighed, and prepared for analysis. The photographs are shown in Plates I and II, the controls being the same in each case. The solutions were

[1] U. S. Dept. Agr., Bureau of Chemistry Bul. 138.

then made up to volume, 500 cc withdrawn for analysis, and the remainder saved in which to grow a second crop.

Reaction of the residual solution.—In Table 1 are shown the reactions and titration data for the 13 solutions after gathering the first crop; no nitrates and only a trace of potash remained in any of the solutions.

TABLE 1.—*Titration of the culture solutions after the first crop was harvested.*

No. of solution.	Original solution.[1]	Reaction upon boiling.	Titration of 100 cc with twentieth-normal sodium hydrate.
			cc.
1	Distilled water	Slightly acid	0.1
2	Distilled water+calcium carbonate	Akaline	
3	Sodium nitrate	do.	
4	Sodium nitrate+calcium carbonate	do.	
5	Potassium chlorid	Acid	.8
6	Potassium chlorid+calcium carbonate	Alkaline	
7	Potassium sulphate	Acid	1.2
8	Potassium sulphate+calcium carbonate	Alkaline	
9	Hydrochloric acid	Acid	.1
10	Hydrochloric acid+calcium carbonate	Alkaline	
11	Sulphuric acid	Acid	.2
12	Sulphuric acid+calcium carbonate	Alkaline	
13	Sodium nitrate+potassium sulphate	do	

[1] See page 6 for amounts of constituents in each solution.

Effects of sodium nitrate.—In Plate I, figure *a*, a slight improvement, especially in root development, is noticed in the distilled-water cultures when calcium carbonate is added, but no appreciable difference is seen when the calcium carbonate is added to the sodium nitrate solution. By reference to the analysis of the culture solutions in Table 1, it will be seen that control No. 1, at the close of the experiment, showed, upon boiling, a slight acid reaction. This was probably due either to the exudation by the roots of some acid-reacting body or to the excretion of similar bodies by the seeds themselves. Nos. 2 and 4 were, of course, alkaline because of the presence of the calcium carbonate. The alkalinity of No. 3 was due to the fact that all of the nitrate (NO_3) or acid radical in the sodium nitrate had been removed by the plant, while some of the sodium or alkaline radical, being less rapidly absorbed, remained in the solution, forming, probably, sodium hydroxid. This, in turn, had taken up carbon dioxid and was existing in the solution as sodium bicarbonate.

Relative effects of potassium chlorid and hydrochloric acid.—In Plate I, figure *b*, are shown the relative effects of potassium chlorid and hydrochloric acid (solutions 5 and 6, and 9 and 10). The plants removed practically all of the potash from the potassium chlorid solution, only a trace remaining, while by analysis 38 parts per million of chlorin out of a total of 71 still remained in the solution, thus clearly showing the selective ability which roots possess to take up one part or radical of a salt and to leave the other. All of this chlorin did not exist as hydrochloric acid, for after boiling and titrating with twentieth-normal sodium hydrate, using phenolphthalein as an indicator, a reading equivalent to only 14.6 parts per million of hydrochloric acid was obtained, which, however, is a much larger amount of free acid than was originally present in solutions 9 and 10, where only 10 parts per million of acid were used.

The effects of the strongly acid solutions were markedly shown upon the roots, that is, in the potassium-chlorid solution they showed the same general characteristics as those grown in the hydrochloric acid; they were short, stubby, and often discolored, the tips being enlarged, and many of the roots growing in the shape of a fishhook, a characteristic of roots grown in the presence of some toxic substance. Moore, Roaf, and Knowles,[1] as a result of their investigation, found that the smallest amount of free acid arrests the growth and nuclear divisions at the root tip, causing it to become thicker, while dilute alkali stimulates the tip to excessive nuclear division.

Of the 10 parts per million of hydrochloric acid added to solution 9, only 1.8 parts remained in solution after the first cropping. The remainder was either absorbed by the plants or the carbon black, or was neutralized by the aluminum disk. Both in the case of the potassium chlorid and of the hydrochloric acid, the presence of calcium carbonate overcame the injurious effects of the acids in the solutions. That is, of course, a common observation and hardly requires citations from the literature to substantiate it. Claudel and Crochetelle[2] found that when they used ammonium sulphate, potassium chlorid, or potassium sulphate in amounts varying from 500 to 5,000 parts per million, an injurious action on germination was noted, and that the application of lime neutralized this toxic effect.

The results obtained by the use of lime in the experiments here reported can be explained only by assuming that the lime has been used to neutralize the acids.

Effect of reaction of the solution on weight of roots and tops.— In making the culture medium alkaline, the growth of the root has been most favorably affected. From Table 2 it is seen that in every case where lime was present the weight of the roots was greater than in the corresponding case without lime, and especially was this so where hydrochloric acid and sulphuric acid had been used, with and without lime.

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[1] Effects of Variations in Inorganic Salts and the Reactivity of the External Medium upon the Nutrition, Growth, and Cell Division in Plants and Animals. Biochem. J., 1908, *3:* 279.

[2] Les engrais et la germination. Ann. Agron., 1896, *22:* 131

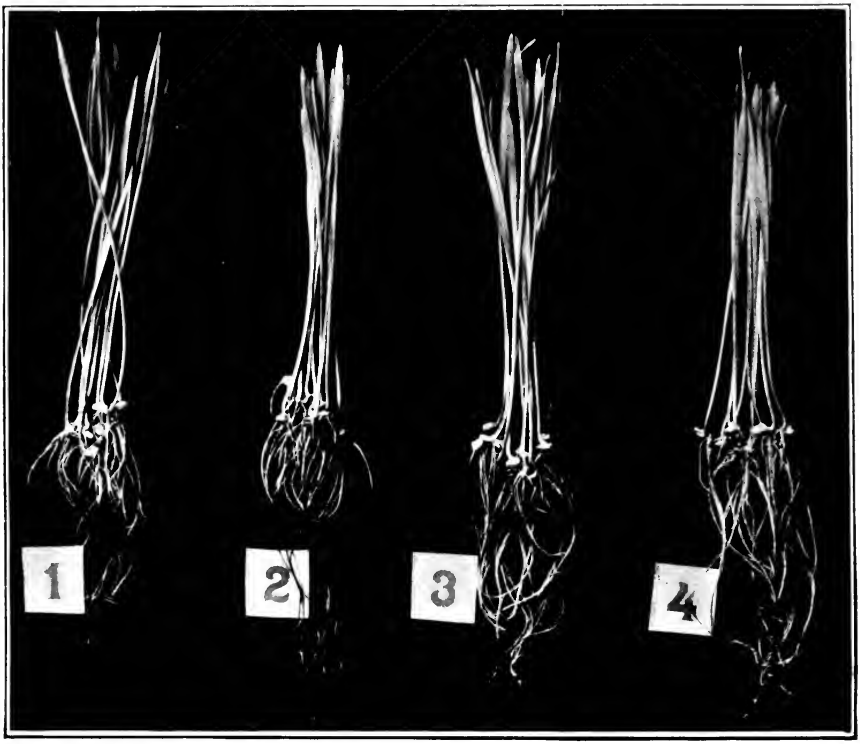

Fig. a.—First crop of plants, grown 9 days in (1) distilled water; (2) distilled water + calcium carbonate; (3) sodium nitrate; (4) sodium nitrate + calcium carbonate.

Fig. b.—First crop of plants, grown 9 days in (1) distilled water; (2) distilled water + calcium carbonate; (3) sol. 5, potassium chlorid; (4) sol. 6, potassium chlorid + calcium carbonate; (5) sol. 9, hydrochloric acid; (6) sol. 10, hydrochloric acid + calcium carbonate.

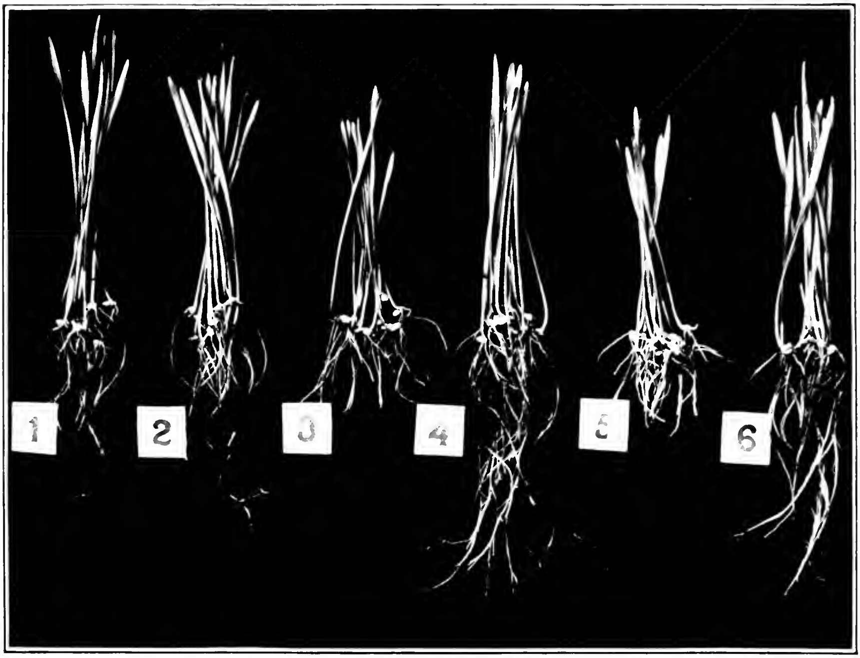

Fig. a.—First crop of plants, grown 9 days in (1) distilled water; (2) distilled water + calcium carbonate; (3) sol. 7, potassium sulphate; (4) sol. 8, potassium sulphate + calcium carbonate; (5) sol. 11, sulphuric acid; (6) sol. 12, sulphuric acid + calcium carbonate.

Fig. b.—First crop of plants, grown 9 days in (1) distilled water; (2) sol. 3, sodium nitrate; (3) sol. 7, potassium sulphate; (4) sol. 13, sodium nitrate + potassium sulphate.

TABLE 2.—*Dry weight of first crop of plants.*

No. of solution.	Original solution.	100 tops.	100 roots.	100 whole plants.
		Grams.	*Grams.*	*Grams.*
1	Distilled water	1.013	0.575	2.041
2	Distilled water+calcium carbonate	.953	.704	2.176
3	Sodium nitrate	1.012	.625	2.090
4	Sodium nitrate+calcium carbonate	.932	.673	2.135
5	Potassium chlorid	1.088	.466	2.213
6	Potassium chlorid+calcium carbonate	1.013	.639	2.247
7	Potassium sulphate	1.055	.457	2.342
8	Potassium sulphate+calcium carbonate	.933	.672	2.288
9	Hydrochloric acid	.870	.320	2.103
10	Hydrochloric acid+calcium carbonate	.888	.577	2.185
11	Sulphuric acid	.914	.392	1.910
12	Sulphuric acid+calcium carbonate	1.063	.682	2.092
13	Sodium nitrate+potassium sulphate	.878	.528	2.055

The following tabulation shows the increase in weight of one hundred roots in each case when lime was added:

Solution.	Gram.	Solution.	Gram.
Distilled water	0.129	Potassium sulphate	0.215
Sodium nitrate	.048	Hydrochloric acid	.257
Potassium chlorid	.173	Sulphuric acid	.290

These figures indicate that the least increase was found in the sodium nitrate solution. This is explained by Table 1, which shows that even when sodium nitrate was used alone the solution was alkaline at the end of the experiment, and therefore the further use of calcium carbonate simply acted as a stimulant to a very slight extent.

The weight of the tops, or rather of the stems grown in solutions with and without lime, show no such marked difference, indicating that the appearance of the stems of young wheat seedlings is not always a criterion of the vigor of the plant and therefore of the probable yield of the mature crop. In other words, the root system may be a better indicator as to the probable success of a crop than the appearance of the portion above ground.

The effects on the root development, due to the acidity, are always easily noticeable in water-culture experiments such as these, but in field tests the results of applications of single fertilizers, for example, potassium chlorid, potassium sulphate, ammonium chlorid, or ammonium sulphate, are not necessarily apparent in so short a time, due to the fact that there may be many substances in soils which neutralize the acid thus formed.

Relative effects of potassium sulphate and sulphuric acid.—In Plate II, figure *a*, are shown in a similar way the comparative effects of potassium sulphate and sulphuric acid. With the potassium sulphate the plants removed all of the potash, but left 57 out of a total of 82 parts per million of sulphate in solution. This solution showed on analysis 29.4 parts per million of sulphuric acid, an amount more than twice as large as that originally present in solution 11, thus again showing the extent to which the selective action of roots for one radical of a salt may be carried. Leclerc du Sablon [1] put forth the theory that such useful ions as potassium (K), phosphorus (PO_4), nitrogen (NO_3), and iodin (I) combine with the organic substance of the plant, thus relieving the osmotic pressure within the plant and permitting a still larger quantity of these ions to be absorbed. On the other hand, such ions as chlorin (Cl) and sodium (Na) do not form this organic combination, the result being that the pressure inside the plant soon equals that outside, and the plant is, therefore, satisfied with a relatively small amount of them.

Of the 10 parts per million of sulphuric acid present in solution 11, all but 4.9 parts per million disappeared. The appearance of the plant roots in the potassium sulphate solution was even worse than that of those grown in potassium chlorid. Maze[2] obtained results which may be similarly interpreted in his experiments in growing corn in water cultures. He found that when ammonium sulphate was used the crop was not so well developed as when ammonium chlorid was applied. Calcium carbonate overcame the injurious effects in these as in the preceding cultures, thus again showing how beneficial it is to the crop to maintain the alkalinity of the culture medium.

The effect of sodium nitrate and potassium sulphate separately and in combination.—In Plate II, figure *b*, are shown the cultures of sodium nitrate (alkaline reacting), potassium sulphate (acid reacting), and a mixture of the two. The mixture was prepared so as to become alkaline and produce good plants, and it did so. In this case the nitrate of the sodium nitrate and the potassium of the potassium sulphate were drawn up into the plant, while the sodium left in solution from the sodium nitrate combined with the sulphate from the potassium sulphate to form sodium sulphate, with a sufficient excess of sodium to make the solution alkaline.

Discussion of data obtained on the first crop.—All of the culture solutions to which no sulphate was added; that is, the sodium nitrate, the hydrochloric acid, and the distilled water cultures, contained a small amount of SO_4, due probably to its excretion from the seed. In solutions 7 and 8, however, containing 150 parts per million of potassium sulphate, the amounts of SO_4 were noticeably large, 57 out of the 87 parts per million being found in the solution. This was about 6 times more than was found in the sulphate-free solutions and would seem to indicate that the plant at this stage does not

[1] Dégagement d'eau par les plantes, Rev. gén. Bot., 1909, *21:* 295.
[2] Compt. rend., 1911, *152:* 783.

require much more than 25 to 30 parts per million of SO_4, since a much larger amount was at their disposition during the whole period without any larger amount being absorbed. These two solutions, Nos. 7 and 8, containing 87 parts per million of SO_4 and 63 parts per million of potash, respectively, show very clearly to what extent selective action is practiced by the roots. At the end of the experiment all of the potash had been taken up by the plant, while only 30 parts per million of SO_4 were thus absorbed.

Solutions 5 and 6 show the same selective process going on in the case of potassium chlorid. These solutions contained at the beginning of the experiment 79 parts per million of the potash ion and 71 parts per million of the chlorid ion. At the end of the experiment no potash was found in the solution, indicating that the plant had absorbed the whole of this element, while 35 to 38 parts per million of chlorid were still present. These results are at variance with those obtained by J. de Rufz de Lavison,[1] who, after growing the young seedling five days in twentieth-normal potassium-chlorid solution, found that the concentration of the solution was about equal to that originally used. The probable reason for such a deduction is that a potassium-chlorid solution of twentieth-normal strength is equivalent to 3,700 parts per million, a solution so strong that even if the plant did exercise a normal selective action of 30 to 50 parts per million, it would be most difficult to detect such a change in a solution of the concentration mentioned.

The pans containing (1) the control, (2) the potassium-sulphate solution, and (3) the potassium sulphate with calcium carbonate, as given in Plate VIII, figure *a*, show that the differences in the development of the roots are marked and that the few plants selected for the plates previously shown were not exceptions to the rule. In every case the plants grown in the presence of lime presented a healthier and more vigorous appearance than those grown in the corresponding solutions without lime.

While the tops of the plants grown in the culture solutions containing calcium carbonate were larger and presented a much better appearance than the others, yet their dry weight was not necessarily greater; on the other hand, the dry weight of the roots was increased in every case by the addition of calcium carbonate.

Although the original seeds and the seedlings all contained sulphur in organic combination, yet no weighable amount of inorganic sulphate was found in the ash of the plants, except in those to which sulphate or sulphuric acid had been added.

In the solutions to which calcium carbonate had been added the carbon dioxid which was given off by the roots combined with the

[1] Du rôle électif de la racine dans l'absorption des sels. Comp. rend., 1910, *151:* 675.

calcium carbonate and brought a relatively high amount of lime into solution as calcium bicarbonate, making the solutions distinctly alkaline.

SECOND CROP OF SEEDLINGS.

Reaction of residual solution and weight of crop.—After the first crop of seedlings was removed from the pans, more seeds that had been thoroughly washed were sprinkled on the aluminum disks and allowed to germinate and grow as a second crop for five days. Samples were then photographed, as shown in Plates III and IV. The solutions were again made up to their original volumes and titrated with the results given in Table 3.

TABLE 3.—*Titration of culture solutions after harvesting the second crop of seedlings.*

No. of solution.	Original treatment.[1]	Reaction upon boiling.	Titration of 100 cc with twentieth-normal sodium hydrate.
			cc.
1	Distilled water	Acid	0.3
2	Distilled water+calcium carbonate	Alkaline	
3	Sodium nitrate	Acid	.7
4	Sodium nitrate+calcium carbonate	Alkaline	
5	Potassium chlorid	Acid	3.3
6	Potassium chlorid+calcium carbonate	Alkaline	
7	Potassium sulphate	Acid	1.5
8	Potassium sulphate+calcium carbonate	Alkaline	
9	Hydrochloric acid	Acid	.5
10	Hydrochloric acid+calcium carbonate	Alkaline	
11	Sulphuric acid	Acid	.6
12	Sulphuric acid+calcium carbonate	Alkaline	
13	Sodium nitrate+potassium sulphate	Acid	.5

[1] For full description of solutions, see p. 6.

The plants were dried and weighed as in the case of the first crop, the results being shown in Table 4.

TABLE 4.—*Weight of second crop of plants.*

No. of solution.	Original treatment.	Green weight of 100 tops.	Dry weight.		
			100 tops.	100 roots.	100 residual seeds.
		Grams.	*Grams.*	*Gram.*	*Gram.*
1	Distilled water	7.04	1.51	0.499	0.500
2	Distilled water+calcium carbonate	9.25	1.86	.770	.298
3	Sodium nitrate	9.00	1.80	.564	.398
4	Sodium nitrate+calcium carbonate	10.62	1.98	.728	.270
5	Potassium chlorid	6,14	1.49	.434	.616
6	Potassium chlorid+calcium carbonate	9.78	1.89	.700	.390
7	Potassium sulphate	5.62	1.40	.446	.772
8	Potassium sulphate+calcium carbonate	9.22	1.94	.698	.332
9	Hydrochloric acid		1.21	.338	.378
10	Hydrochloric acid+calcium carbonate	10.54	2.09	.734	.380
11	Sulphuric acid	7.08	1.50	.518	.362
12	Sulphuric acid+calcium carbonate	9.64	1.62	.652	.314
13	Sodium nitrate+potassium sulphate	9.12	1.76	.574	.376

Fig. a.—Second crop of plants, grown 5 days in residual solutions (1) distilled water; (2) distilled water + calcium carbonate; (3) sodium nitrate; (4) sodium nitrate + calcium carbonate.

Fig. b.—Second crop, grown 5 days in residual solutions (1) distilled water; (2) distilled water + calcium carbonate; (3) sol. 5, potassium chlorid; (4) sol. 6, potassium chlorid + calcium carbonate; (5) sol. 9, hydrochloric acid; (6) sol. 10, hydrochloric acid + calcium carbonate.

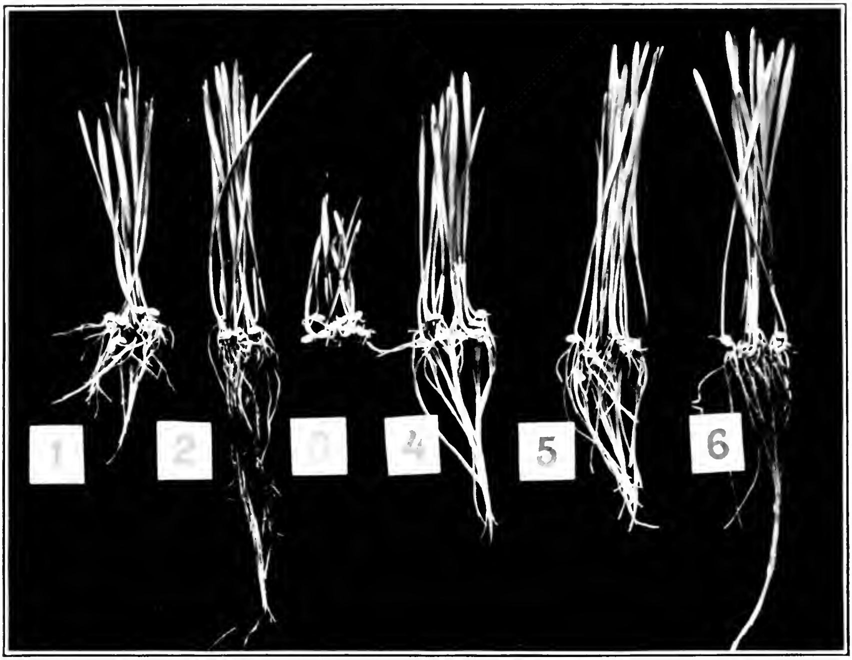

Fig. a.—Second crop of plants, grown 5 days in residual solutions (1) distilled water; (2) distilled water + calcium carbonate; (3) sol. 7, potassium sulphate; (4) sol. 8, potassium sulphate + calcium carbonate; (5) sol. 11, sulphuric acid; (6) sol. 12, sulphuric acid + calcium carbonite.

Fig. b.—Second crop of plants, grown 5 days in residual solutions (1) distilled water; (2) sol. 3, sodium nitrate; (3) sol. 7, potassium sulphate; (4) sol. 13, sodium nitrate and potassium sulphate.

Effects of sodium nitrate.—By reference to Plate III, a marked difference will be noted between the distilled water control and the distilled water with calcium carbonate, a difference much greater than was shown in growing the first crop (see Plates I and II). It will also be noticed from Table 3 that the acidity of the solution has increased threefold since the first cropping. Solution 3, Table 3, containing sodium nitrate, which was alkaline after the first cropping, has now also become acid. The sodium evidently either was absorbed by the plant or was neutralized by some organic acid. Solutions 2 and 4, of course, remained alkaline.

Relative effects of potassium chlorid and hydrochloric acid.—In Plate III, figure *b*, the relative effects of potassium chlorid and hydrochloric acid are again shown. The plants grown in the potassium chlorid solution, which, when the second crop was sown, contained no potash but a considerable amount of acid, made practically no root growth and a very poor leaf development. On the other hand, the plants grown in the hydrochloric-acid solution which contained only one-eighth as much acid made a much better growth both in roots and tops.

Relative effects of potassium sulphate, sodium nitrate, and sulphuric acid.—In Plate IV, figure *a*, are shown the residual effects of the potassium sulphate and sulphuric acid. What has just been said of the potassium-chlorid plants and the hydrochloric-acid plants is in the main true of the potassium-sulphate plants and the sulphuric-acid plants also. Figure *b* illustrates the residual effect of sodium nitrate and potassium sulphate used singly and in combination.

COMPARISON OF THE FIRST AND SECOND CROPS.

A striking difference will be noticed between the plants grown in the potash solutions in the first and second crops, when no calcium carbonate was present. The plants in the first crop had practically as much acidity to contend with during the latter days of their growth as the plants of the second crop had during the first few days of their growth, yet the first crop was much better than the second crop. This difference was not due to the fact that the second crop was deficient in potash, for the control pans containing calcium carbonate but no potash gave excellent plants. It is to be noted that the first crop had to contend only with a gradually increasing amount of acidity due to the absorption of potash from the solution in which it was growing, and it was therefore able to accommodate itself and to endure much more acidity than if it had been placed in the stronger acid solution at first, as was done in the case of the second crop. It has been shown by Mr. Jensen, of the Bureau of Plant Industry, in a piece of unpublished work, that the enzymic activity of a wheat seedling is greatest during the first few days of its growth, this being especially true of the oxydases and peroxydases of the root tip. These enzyms are particularly sensitive to acids, and their destruction would mean a cessation of growth. The first crop had evidently passed the critical period with reference to this enzymic activity before the acidity of the solution had developed to such a degree as to prohibit it. When the second crop was placed in the solution the acidity was high enough to practically prohibit the action of the enzyms and the plants were unable to tide over this critical period. The effect of toxic bodies upon the oxydases and peroxydases, that are so active during the first few days of a plant's growth, is an important factor both in agricultural practice and in scientific research and one that is often overlooked.

Many substances that are classified as plant stimulants or depressants no doubt derive their reputation in a great measure from their effect upon the enzyms. Their beneficial or injurious effects would only be noticed during the first few days of the plant's growth when its enzymic activity is so pronounced.

It will be noticed in the case of the second crop that the alkalinity of the solution increased both the green and the dry weight of the tops and the dry weight of the roots. In the case of the residual seeds that were removed from the plants the reverse is true. The presence of an acid in the solution prevented the food material that was stored up in the seed from being transported into the plant. The residual seeds were therefore much lighter when calcium carbonate was present than when it was absent.

After the second crop had been grown in the solutions described for five days the plants were harvested, separated into tops, roots, and residual seeds, and each part dried and weighed separately. The respective solutions were likewise all tested for acidity and the presence of nitrates and potash. Tables 3 and 4 (see page 12) show the results obtained, and a comparison with Tables 1 and 2 (pp. 7 and 9), respectively, will bring out some interesting changes in the residual solution. After the first cropping solution 1 was slightly acid, but after harvesting the second crop it was three times as acid. Solutions 3 and 13 after the first cropping were alkaline, but after the second one both solutions had become quite acid. Analysis of solution 3 showed that while at the beginning there were 40.5 parts per million of sodium (Na), after gathering the second crop only 8 parts per million remained in solution. The difference shows the probable amount of sodium absorbed by the two crops. Not only was the amount thus reduced from 40.5 to 8 parts per million, but the presence of this small amount of sodium seemed to stimulate an acid excretion on the part of the plants to such an extent that the alkaline solution was not only neutralized but was made even more acid than the distilled water culture. On testing for chlorin, after the second cropping, it was shown that only mere traces of that element were found in any of the solutions except Nos. 5 and 6, in which potassium chlorid was used. Even in solutions 9 and 10, to which 10 parts per million of hydrochloric acid were originally added, only traces of chlorin were found. The amounts of chlorin found in solutions 5 and 6 after the second cropping were approximately 5 parts per million on an average, or about one-seventh as much as was present after the first crop was grown. In a similar test for sulphuric acid in the various solutions it was shown that they all contained appreciable amounts, but that solutions 7, 8, and 13, which had been treated with potassium sulphate, contained about two to three times as much sulphuric acid as the others. This acid was apparently either not absorbed to the extent that the chlorin was or else was excreted by the roots in a larger quantity.

The weights of the roots in both crops and of the stems in the second one, when grown with lime, were much greater than when grown without it. The weight of the residual seed, on the other hand, was greater in the unlimed solutions, thus indicating that in an alkaline medium the process of translocation of the seed constituents goes on more readily and completely than under the influence of an acid reaction.

EXPERIMENTS USING ALUMINUM AND FERRIC HYDROXIDS TO REDUCE ACIDITY OF SOLUTION.

A second series of experiments was made, using aluminum hydrate instead of calcium carbonate to keep the solutions from becoming acid. This aluminum hydrate was prepared from aluminum sulphate by precipitation with ammonium hydrate and was washed free from impurities. It was not allowed to dry, but was added as a thick cream. Carbon black was kept in all of the cultures as in the calcium carbonate series. Plate V shows the effect of the aluminum hydrate used instead of lime in the solutions containing potassium chlorid, hydrochloric acid, potassium sulphate, and sulphuric acid. The results after the plant had grown five days indicate that many substances, which are capable of neutralizing the acid of the culture medium and of keeping it alkaline, may be of benefit to the seedling.

In Plate VI, figure *a*, is shown the relative effect of the addition of aluminum hydrate to solutions containing 150 parts per million of sodium nitrate and 10 parts per million of sodium hydrate. There is no difference between the two crops, and the aluminum hydrate failed to produce any effect upon either. This indicates that, at this stage of growth at least, the reaction of the solution is of more importance than the added plant foods.

Plants were withdrawn from these pans and arranged as in figure *b* to show the effect of the potassium nitrate. This salt gave an alkaline reaction to the solution and produced excellent plants. The "fishhooks" on the roots of the potassium sulphate plants are seen in this plate also (No. 4).

The experiment with aluminum hydrate was repeated with ferric hydrate. This was prepared from ferric chlorid by precipitation with ammonium hydrate and was also washed free from all impurities in order to insure freedom from chlorin and ammonium. A blank culture solution prepared with the ferric hydrate contained less than 0.5 part per million of ammonium. The 5-day-old plants are shown in Plate VII, and when compared with the preceding plates show that the same general characteristics prevail whether calcium carbonate, aluminum hydrate, or ferric hydrate is used to keep down the acidity.

EXPERIMENTS USING CLOVER AND TIMOTHY WITH WHEAT.

Another experiment was made with clover and timothy, using calcium carbonate to neutralize the acidity. The small seeds were sprinkled upon pieces of bolting cloth of a large mesh, placed on the aluminum disks, and grown with some wheat seedlings. It was found impossible to obtain satisfactory photographs of the timothy plants, but both the timothy and the clover behaved in the same way as did the wheat plants, and were even more sensitive to the acids. A few of the clover plants are shown in Plate VIII, figure *b*.

Both with the wheat and the clover cultures the effect of potassium chlorid was not so harmful as that of potassium sulphate. In nearly every case a much better root development was obtained in the potassium chlorid solutions.

While it is a well-known fact that the presence of certain solids by their absorptive action stimulate the growth of seedlings in water culture, the objection to the presence of a solid (calcium carbonate, ferric hydrate, or aluminum hydrate) in one-half of the cultures is overcome by the fact that another solid, carbon black, existed in all alike, and that this solid has as great an absorptive power as either of the others.

It is also clearly evident that a salt, potassium sulphate for example, is not taken into the plant as such, that is, as the molecule (K_2SO_4), but rather as an ion (K). When the potassium sulphate (K_2SO_4) is applied to the soil as a fertilizer it goes into solution and dissociates—that is, splits apart into two radicals, K and SO_4. The potassium is taken up as the ion, while for the time being the SO_4 radical remains in solution and combines with the water to form

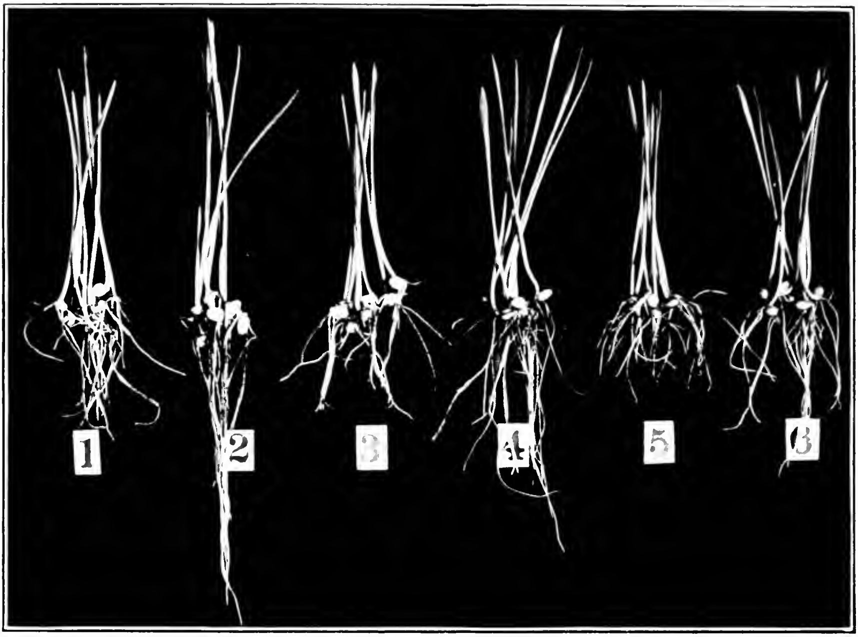

Fig. a.—Crop grown 5 days in (1) distilled water; (2) distilled water + aluminum hydrate; (3) potassium chlorid; (4) potassium chlorid + aluminum hydrate; (5) hydrochloric acid; (6) hydrochloric acid + aluminum hydrate.

Fig. b.—Crop grown 5 days in (1) distilled water; (2) distilled water + aluminum hydrate; (3) potassium sulphate; (4) potassium sulphate + aluminum hydrate; (5) sulphuric acid.

Fig. a.—Crop grown 5 days in (1) distilled water; (2) distilled water + aluminum hydrate; (3) sodium nitrate; (4) sodium nitrate + aluminum hydrate; (5) sodium hydrate; (6) sodium hydrate + aluminum hydrate.

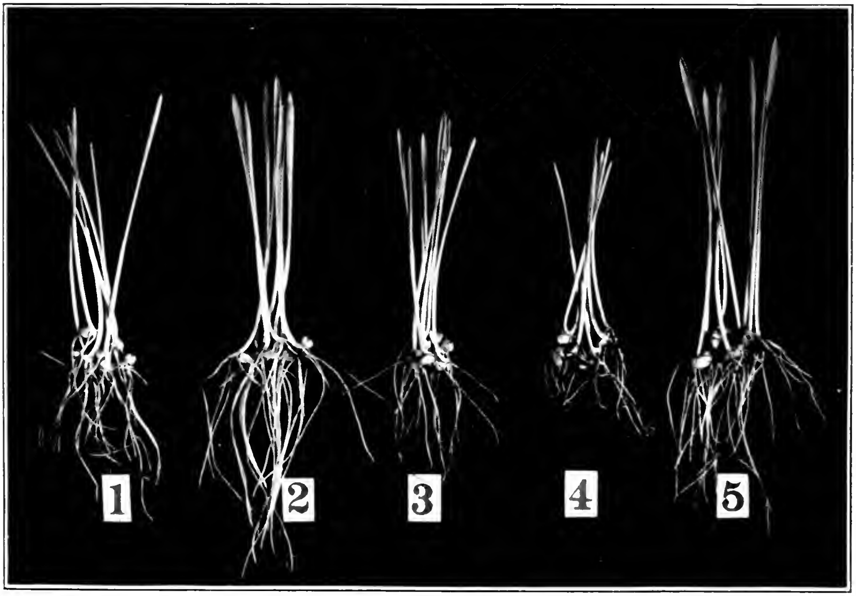

Fig. b.—Crop grown 5 days in (1) distilled water; (2) sodium nitrate; (3) potassium chlorid; (4) potassium sulphate; (5) potassium nitrate.

Fig. a.—Crop grown 5 days in (1) distilled water; (2) distilled water + ferric hydrate; (3) potassium chlorid; (4) potassium chlorid + ferric hydrate; (5) hydrochloric acid; (6) hydrochloric acid + ferric hydrate.

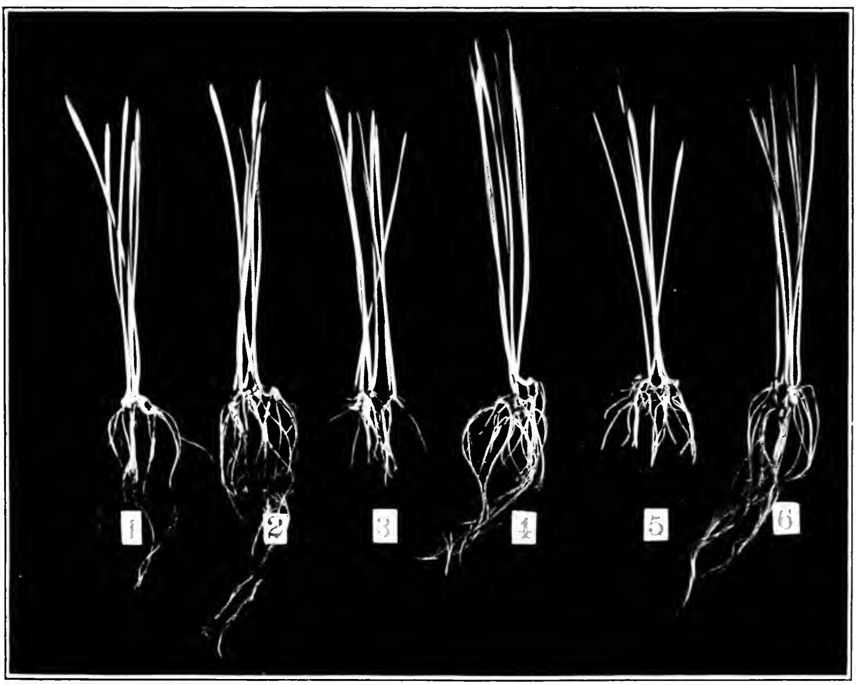

Fig. b.—Crop grown 5 days in (1) distilled water; (2) distilled water + ferric hydrate; (3) potassium sulphate; (4) potassium sulphate + ferric hydrate; (5) sulphuric acid; (6) sulphuric acid + ferric hydrate.

Fig. a.—Comparison of entire pan of wheat plants grown in (1) distilled water; (2) potassium sulphate; and (3) potassium sulphate + calcium carbonate.

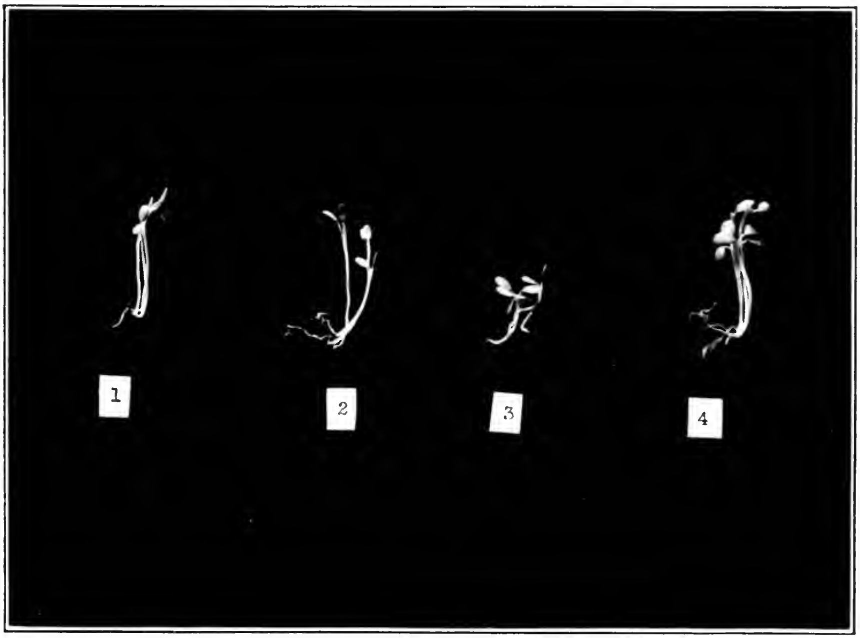

Fig. b.—Clover plants grown with wheat in (1) distilled water; (2) distilled water + calcium carbonate; (3) potassium sulphate; (4) potassium sulphate + calcium carbonate.

sulphuric acid.[1] This is a great secondary source of soil acidity and clearly illustrates the faculty of selective absorption by the plant.

CONCLUSIONS.

The agricultural significance of the physiological study described in this bulletin will be evident from the following discussion. When a soil is in good tilth with an optimum moisture content, each grain is surrounded by a film of water. The plant root comes in contact with this film, and from it draws the water and the mineral salts necessary for growth. Expressed in physical terms, this film is in equilibrium with the soil—that is, if the soil grain contains a silicate of potassium, as feldspar, for example, the water composing the film will bring into the solution about eight parts per million of potash. If some of this potash is removed by the plant more will go into solution, and the concentration of the film will remain fairly constant as long as any feldspar remains in the soil grain.

Although a difference of opinion exists as to how the plant foods are brought into solution, whether by the action of water, by carbon dioxid, or by acids which are exuded by the root tips, all agree that it is absolutely necessary for them to be in solution before they can be taken up by the plant. The soil may, therefore, be considered as a storehouse of reserve material, while the film of soil solution may be considered as a plain nutrient solution in which the plant grows. Whether this soil solution is acid or alkaline is one of the most important factors in plant growth, as has been noted in the foregoing physiological study.

The acidity or alkalinity determines to a great extent not only the particular kind of crop to be grown upon the soil, but also the yield of the crop. No one would think of trying to grow alfalfa in a peat bog or cranberries in a limestone soil. On the other hand, a soil which is naturally alkaline will, under continuous cropping with a rotation containing clover, for example, give smaller and smaller yields as the alkalinity is diminished, until it will be found impossible to grow this legume on account of the acidity of the soil. This

[1] In this connection mention should be made of the experiments of Micheels (Action des liquides anodiques et cathodiques sur la germination. Bull. Acad. Roy. Belg., Classe des Sci., 1910, *5:* 391), who studied the effect on wheat seedlings of an electric current produced by a pile of 24 Daniell cells, when passing through various nutrient solutions; and who found that the plants grown near the anode developed roots whose length varied from 10 to 25 mm, while those plants in the cathode solution possessed roots from 140 to 150 mm in length. Similar results were obtained in nutrient solutions containing sodium chlorid, potassium chlorid, potassium nitrate, sodium nitrate, and mixtures of these. A second crop being grown in each of these solutions, even after the electric current was discontinued, similar results were obtained as with the first crop, due to modifications brought about in the solution. From our investigations, the injurious effects noted at the anode, as seen from the length of the roots, could well be attributed to the formation of acid, while near the cathode, the solution being alkaline, the conditions were reversed and therefore favorable for root development.

phenomenon has been often noted in the limestone regions, particularly in the Shenandoah Valley of Virginia, where soils derived from limestone rocks, and even now having the undecomposed limestone within a few feet of the surface, have become so acid that clover can no longer be advantageously grown. Ground limestone applied to the surface soil will often restore its original fertility.

The heavy clay soils from which bricks are made are always acid, have a high lime requirement, and are usually very unproductive. The oxids of iron exist in such soils in a finely divided colloidal form brought about by an acid condition, and they are usually remedied by an application of lime. The poisonous properties of subsoils also may be due in a large measure to their acid character.

Investigators working with solution cultures and using single salts might do well to take into consideration the reaction of the solutions after the plants have been placed in them. The moment seedlings are placed in a solution of potassium sulphate a rapid absorption of potash begins with a consequent formation of sulphuric acid. This sulphuric acid is a disturbing factor and other substances placed in the solution and kept under observation might owe their apparent beneficial effect to the fact that they simply act as bases, but in themselves have no direct influence upon the plant. In field culture the residual injurious effect of an application of sulphate and chlorid of potash can be overcome by mixing the fertilizer with about twice its weight of lime.

In the experiments here recorded it is shown that the seedlings grown in culture solutions containing potassium chlorid, potassium sulphate, or hydrochloric or sulphuric acid solutions (10 parts per million), exert a selective action whereby the potash ion is absorbed by the roots, while the chlorid or sulphate ion is for the most part left in solution. This causes the solution to become acid, which in turn acts injuriously on the root development.

The addition of lime or iron or aluminum hydrate to culture mediums containing potassium chlorid, potassium sulphate, hydrochloric acid, or sulphuric acid, keeps these solutions alkaline so that they then act favorably on the root development. This would tend to explain why field applications of sulphate or muriate of potash in time render the soil acid,[1] and why the continued use of Chile saltpeter produces an alkaline condition of the soil.

[1] At the Woburn Experiment Station it has been amply shown that a continuous application of ammonium sulphate renders the soil so acid as to cause the crop to be almost an absolute failure. Adjacent plats, likewise treated with ammonium sulphate, but also given an application of lime, have continued to yield crops as large as are produced by still other plats treated with sodium nitrate only.

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