PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

The Soil Solution and the Mineral Constituents of the Soil

Alfred Daniel Hall, Winifred Elsie Brenchley and Lilian Marion Underwood

Phil. Trans. R. Soc. Lond. B 1914 **204**, 179-200
doi: 10.1098/rstb.1914.0005

V. *The Soil Solution and the Mineral Constituents of the Soil.*

By ALFRED DANIEL HALL, *M.A., F.R.S.*, WINIFRED ELSIE BRENCHLEY, *D.Sc., and* LILIAN MARION UNDERWOOD, *B.Sc.*

(Received June 10, 1913.)

(From the Rothamsted Experimental Station.)

CONTENTS.

		PAGE
	Introduction	179
I.	Growth of Plants in Soil Solutions	181
II.	Relation between Growth of Plant and Concentration of Solution	191
III.	Rate of Diffusion of Nutrients in Soil Solution	194
	Summary and Conclusions	198

INTRODUCTION.

It has long been the accepted theory that plants obtain the mineral constituents they require from the soil through the intermediary of a solution that is formed in the water with which the soil particles remain in contact. As, however, the amounts of phosphoric acid and potash revealed by analysis are always far in excess of the requirements of the crop, and as the variation in these quantities in no way determines the need or otherwise for a further supply of the constituents in the shape of fertilisers, DAUBENY* suggested a distinction between dormant and available plant food in the soil, the latter being the more readily soluble compounds of phosphoric acid and potash, which in virtue of their solubility determine the amount of each constituent obtainable during the short season of a plant's growth. This point of view was revived by B. DYER in 1894,† and has been subjected to considerable examination, without, however, revealing any constant correspondence between the quantities of easily soluble plant food and the response of the soil to particular fertilisers.

A new aspect of the problem was set forth in 1903 by M. WHITNEY‡ and F. K. CAMERON,§ who maintained that as all soils contain practically the same compounds of phosphoric acid and potash possessing a very low solubility, the soil solution must become saturated with these constituents to the same low degree of concentration in all soils, irrespective of the actual amounts of phosphoric acid and potash there present.

* 'Phil. Trans.,' 1845, p. 240.

† 'Chem. Soc. Trans.,' 1894, vol. 95, p. 115.

‡ WHITNEY and CAMERON, Bull. 22, 1903, Bureau of Soils, U.S. Dept. of Agric.

§ 'Journ. Phys. Chem.,' 1910, vol. 14, p. 320.

 [Published separately October 21, 1913.

"From the results of other investigations described and the figures given in the preceding tables the conclusion seems inevitable that all our principal soil types—in fact practically all cultivable soils—contain naturally a nutrient solution which varies within comparatively narrow limits with regard either to composition or concentration, and which is usually sufficient for plant growth. Apparently, therefore, all these soils are amply supplied with the necessary plant foods, and these plant foods are not in themselves a matter of such paramount importance to the agriculturist."*

"This water is moving over the soil particles in films and with slowness. It is long in contact with successive fragments of any particular mineral and all the different minerals making up the soil. Consequently it tends towards a saturated solution with respect to the mineral mass, and it follows that if every soil contains all the common rock-forming minerals, every soil should give the same saturated solution, barring the presence of disturbing factors."†

The authors thus postulate a soil solution of approximate constant composition, and further adduce evidence that this solution, though of great dilution, is capable of satisfying the requirements of the plant, the growth of which (as they maintain) is independent of the concentration of the solution within very wide limits.

It would follow as a corollary that the addition of a soluble fertiliser has no permanent effect in raising the concentration of the soil solution, because it immediately reacts with the comparatively large mass of minerals present (phosphoric acid with basic compounds of calcium, magnesium, iron, and aluminium ; potash with the zeolitic silicates) to form compounds of the same kind as those naturally present in the soil, so that the original equilibrium between the soil solution and these latter compounds is quickly restored with but slight disturbance. Thus they reach the general conclusion that the quantity of mineral plant food in the soil is without significance in the nutrition of the plant, that the observed differences in the fertility of soils are in the main to be attributed to the varying capacity of soils to maintain a supply of water to the plant, and that the response of the crop to particular fertilisers may be set down, not to an additional supply of plant food, but to a precipitating or inhibiting action of the fertiliser upon specific toxins excreted by the plant and possessing a depressing effect upon the same kind of plant when grown again in the same soil.

Little as this view would seem to square with our experience of the effects of phosphatic and potassic fertilisers on particular soils, the theory of a soil solution of constant composition must be valid if the conditions existing in the soil are such as postulated by WHITNEY and CAMERON. The supposition that the plant's roots exert a solvent action upon the solid particles of the soil has been generally

* WHITNEY and CAMERON, *loc. cit.*, p. 46.

† CAMERON, *loc. cit.*, p. 351.

abandoned, for the etching effects observed in the classic experiment of SACHS* can be explained by the carbon dioxide excreted by the roots. It is true that the soil solvent is not pure water, but a dilute solution of this carbon dioxide, yet as the carbon dioxide tension of the air in the soil varies within small limits, this solution would equally become saturated with the phosphoric acid and potash, and the authors' argument would not be invalidated.

Before the theory can be accepted two points appear to require examination. In the first place the soil solution may not be of constant concentration, because the soil minerals may not be so similar as is supposed, especially after the application of fertilisers. WHITNEY and CAMERON'S figures on the point are not convincing and require confirmation. But even if the soil solution does vary in concentration, WHITNEY and CAMERON'S point of view would still hold, unless it is further shown that the plant's growth varies in response to the concentration, irrespective of the total supply of plant food.

Secondly, if a soil solution of constant composition is granted, the maintenance of this solution as the nutrients are extracted from it by the plant's growth may become a factor of importance, determined by the amount of the constituent present in the solid state. The soil solution exists in thin films coating the soil particles; the roots are only in contact with these films over a limited area; should they deplete the films there may be such a lag in the solution of more solid and its travel to the roots as will cause an appreciable difference in the rate at which the plant is supplied from a soil containing little plant food as compared with one possessing a more abundant stock.

The following investigation was set on foot in order to test these points of view and to elucidate the nature and function of the soil solution in the nutrition of the plant.

I.—GROWTH OF PLANTS IN SOIL SOLUTIONS.

(A. D. H. and W. E. B.)

For the purposes of the investigation it was necessary to compare the growth of plants in soil solutions alone, so that neither the direct action of the plants on the soil nor the rate of renewal of the solution from the soil could be factors in the result. The method of water cultures adopted is subject to many disturbances and errors, which were as far as possible minimised as follows:—

1. Each plant grew in its own bottle, holding about 600 c.c. of solution.

2. A "pure line" of seed was chosen, and seeds were selected falling within certain limits of weight.

3. Each unit of comparison in the experiment consisted of 10 plants; the figures given represent the mean dry weight of the plants forming the unit.

* 'Text-Book of Botany,' English ed., 1875, p. 625.

4. The growth took place in a greenhouse, beginning in early spring; in the summer growth is unsatisfactory, and the plants are liable to fungoid disease.

Because of the difficulty of obtaining any considerable volume of the soil solution as it exists in the soil, one was artificially made by slowly and thoroughly working up such a quantity of the soil in the moist condition in which it came from the field as would produce a mixture containing 20 kgrm. of dry soil and 35 kgrm. of water. On the following day, after settlement, the supernatant liquid was syphoned off and filtered through a Berkefeld filter. In the later experiments an asbestos wool filter was substituted instead, as the Berkefeld proved very slow in action. The contents of the bottles were renewed at fortnightly intervals, fresh solutions being made up for the purpose from newly dug soil. Owing to mechanical difficulties it was impossible to renew in each day more than the solutions constituting one unit, but the units were treated in rotation, and each had the same total period of growth. This renewal of the solutions ensured that the growing plants should never be suffering from lack of nutrient through a depletion of the solution.

The soils were selected from certain of the plots of the permanent wheat and barley fields at Rothamsted, of which the treatment with fertilisers and the crop-producing powers for 60 years are now on record. The plots selected in the two fields had not received fertilisers identical in all respects, but the treatment had been very similar as regards mineral fertilisers. The supply of nitrogen admittedly does not enter into the problem, because this element only reaches the plant after conversion by bacterial action of its insoluble compounds into nitrates and ammonia, compounds which pass wholly into solution. In order that the supply of available nitrogen should not be a factor in the results, to each solution sodium nitrate, at the rate of 0·25 grm. per litre, was added.

Table I shows the manuring and the average crop produced on the selected soils during the last 10 years, 1902–11.

TABLE I.—Yield of Wheat and Barley. Rothamsted, 1902–11.

Character of manuring.	Wheat—Broadbalk.				Barley—Hoos.			
	Plot.	Yield per acre.			Plot.	Yield per acre.		
		Grain.	Straw.	Total produce.		Grain.	Straw.	Total produce.
		bushels.	cwt.	lb.		bushels.	cwt.	lb.
Unmanured continuously	3	10·9	9·6	1801	1, O	9·3	6·2	1276
N only, no P_2O_5, no K_2O	10	18·4	15·0	3256	—	—	—	—
$N+P_2O_5$	11	19·2	21·8	3778	2A	29·7	19·3	3972
$N+K_2O$	—	—	—	—	3A	20·3	15·6	2985
Complete artificial fertiliser	7	31·0	35·5	6015	4A	38·4	25·3	5087
Dung every year	2	35·1	40·8	6925	7/2	44·2	31·6	6184

Wheat was grown in both sets of solutions, those from the soil of the wheat and the barley field; similarly, barley was grown in the solutions from both the barley and wheat field. Growth was good from the outset, and was continued from March to June, each unit growing for a period of eight weeks, after which the roots were washed, and root and shoot were dried and weighed separately. Differences in the rate of development were manifest in the first fortnight, and persisted to the end; it was noticed that the plants growing in the solutions from the dunged soil appeared to have a greater superiority in vigour, especially in their broad green leaves, than was indicated by their final weights. The mean results are set out in Table II.

TABLE II.—Growth of Wheat and Barley in Solutions of Rothamsted Soils. Series I, 1911.—Mean dry weight in grammes.

Soil.	Wheat.				Barley.			
	Shoot.	Root.	Total.	Ratio $\frac{\text{Shoot}}{\text{Root}}$.	Shoot.	Root.	Total.	Ratio $\frac{\text{Shoot}}{\text{Root}}$.
Wheat, Plot 3	0·170	0·135	0·305	1·26	0·212	0·105	0·317	2·02
,, ,, 10	0·157	0·127	0·284	1·24	0·171	0·101	0·272	1·69
,, ,, 11	0·598	0·260	0·858	2·30	0·660	0·175	0·835	3·77
,, ,, 7	0·923	0·448	1·371	2·06	1·302	0·442	1·744	2·95
,, ,, 2	1·137	0·425	1·562	2·68	1·249	0·377	1·626	3·31
Barley, Plot 1, O	0·240	0·169	0·409	1·42	0·264	0·138	0·402	1·91
,, ,, 2A	0·476	0·199	0·675	2·39	0·611	0·137	0·747	4·46
,, ,, 3A	0·208	0·201	0·409	1·03	0·275	0·119	0·394	2·31
,, ,, 4A	1·203	0·627	1·830	1·92	1·600	0·477	2·077	3·35
,, ,, 7/2	1·195	0·511	1·706	2·34	1·364	0·486	1·850	2·81

The important point brought out by these results is that the growth in the solutions of the various soils is not identical, but shows differences which are very parallel to the differences in the growth of the crop on the soils themselves in the field. The diagram (fig. 1) shows a comparison between the yields from the soil solutions and the yield of the crops in the field from the corresponding soils (10 years' average, total produce, 1902–11). The same sequence is preserved in the two cases, but the differences are more pronounced in the solutions, except as regards the unmanured plot, which in the solution receives the nitrogen that is lacking in the field. Further, the growth in the solutions is such as would be anticipated from the composition of the solutions, which corresponds, though in a very approximate fashion, to the past manurial history of the soils, and to their composition as revealed by analysis. Large volumes of the solution from each soil were evaporated, and analyses were carried out by the standard methods, with the results set out in

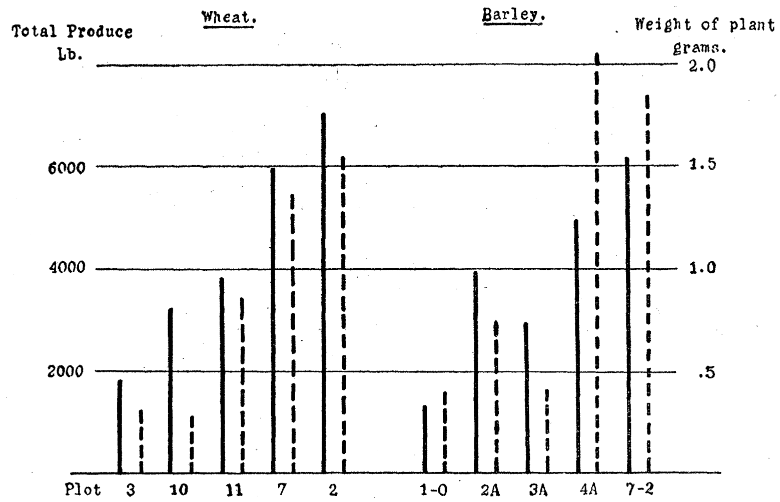


FIG. 1.—Comparison of Crop on Rothamsted Plots with Growth in Solutions of same Soils. Solid line = crop, total produce 1902–11. Broken line = dry weight of plant in soil solution.

Table III. For comparison, the amounts of phosphoric acid and potash in the soil, both soluble in strong hydrochloric acid and in a 1-per-cent. solution of citric acid, are appended, as well as the amount annually supplied to the soil in the manure. It will be seen that, where there had been no phosphoric acid supplied, the amount in the soil solution varies from 0·525 to 0·881 parts per million, but rises to about four parts per million in the solution of the soil from plots receiving phosphoric acid

TABLE III.—Composition of Soil Solutions and Soils—Rothamsted.

Field and plot.	Phosphoric acid.				Potash.			
	Soil solution, parts per million.	Soil. Total.	Soil. Citric acid soluble.	Manure annual supply, lb. per acre.	Soil solution.	Soil. Total.	Soil. Citric acid soluble.	Manure annual supply, lb. per acre.
		per cent.	per cent.			per cent.	per cent.	
Wheat, Plot 3 . .	0·656	0·114	0·0078	0	3·64	0·220	0·0032	0
,, ,, 10 . .	0·881	0·123	0·0074	0	3·55	0·240	0·0032	0
,, ,, 11 . .	3·839	0·197	0·0405	60	3·88	0·197	0·0032	0
,, ,, 7 . .	3·938	0·195	0·0547	60	26·22	0·262	0·0232	100
,, ,, 2 . .	4·838	0·215	0·0560	46	29·85	0·285	0·0384	60
Barley, Plot 1, o .	0·525	0·099	0·0055	0	3·40	0·183	0·0036	0
,, ,, 2A . .	3·900	0·173	0·0425	60	3·88	0·248	0·0023	0
,, ,, 3A . .	0·808	0·102	0·0081	0	30·33	0·257	0·0407	100
,, ,, 4A . .	4·025	0·182	0·0500	60	24·03	0·326	0·0298	100
,, ,, 7/2 .	4·463	0·176	0·0447	46	26·45	0·167	0·0321	60

annually. Similarly, the potash in the solutions of soils from plots not receiving potash approximates to 3·5 parts per million, but rises to between 24 and 30 parts per million in the solutions from plots receiving potash annually.

The relative composition of the soil solutions is also similar to that of the soils, as judged either by the "total" or the "available" plant food they contain.

Thus the growth made by plants in the soil solutions is such as would be expected from the composition of the solutions, and the past history and the present composition of the soils from which the solutions were made.

The experiments were resumed in the following year, and, as the results given by the wheat and barley soils had been so similar, they were on this occasion confined to solutions made from the barley soils only. In order to examine further the conclusion that no other factor entered into the effects produced by the soil solutions than the amount of plant food they contained, comparisons were made between (1) a culture solution made up in the laboratory to the same concentration in essential nutrients as the solutions from the completely manured soils, (2) the soil solutions, (3) the soil solutions from the partially manured plots, with their essential deficiencies repaired by the addition of phosphoric acid or potash, or both. A further artificial solution (4) was made up to a much higher concentration, to one in common use in the laboratory; lastly (5), the salts in this artificial solution were added to the soil solutions. Thus, for each plot, the following comparisons were obtained :—

Nature of solution.	Nutrients, parts per million.				
	From soil.		From added salts.		
	P_2O_5.	K_2O.	P_2O_5.	K_2O.	
1. Artificial culture solution .	Nil	Nil	4·7	26·7	Low concentration.
2. Soil solution	0·6 to 4·7	3·4 to 26·7	Nil	Nil	Varies with plot.
3. Soil solution with added salts	(as 2)	(as 2)	4·5	26·5	Varies with plot; additions as required.
4. Artificial culture solution . .	Nil	Nil	303·5	312·4	High concentration.
5. Soil solution with added salts	As (2)	As (2)	303·5	312·4	" "

As before, in all cases sodium nitrate was added at the rate of 0·25 grm. per litre, or 41 parts nitrogen per million. Barley plants were grown for seven weeks, from March to April, with the results set out in Table IV.

From these results the following conclusions may be drawn. The artificial culture solution, which was calculated to be approximately equivalent to the soil solutions yielded by the completely manured plots 4A and 7/2, yielded plants whose weight (0·763) was distinctly lower, but of the same order, as those grown in the soil solutions from the completely manured plots (0·963 and 1·465). The artificial

TABLE IV.—Growth of Barley in Solutions from Hoos Barley Plots. Series II, 1912.

Set.	Nature of solution.	Shoot.	Root.	Total.	Ratio $\frac{\text{Shoot}}{\text{Root}}$.
1	Artificial culture solution, low concentration. . . .	0·514	0·249	0·763	2·06
4	,, ,, high ,, . . .	0·652	0·291	0·943	2·24
2	Soil solution, Plot 1, O, unmanured	0·116	0·100	0·216	1·16
3	,, ,, + added salts, low concentration	0·865	0·349	1·214	2·48
5	,, ,, ,, high ,,	0·677	0·297	0·974	2·28
2	Soil solution, Plot 2A, lacking potash	0·353	0·133	0·486	2·65
3	,, ,, + added salts, low concentration	0·795	0·359	1·154	2·22
5	,, ,, ,, high ,,	0·619	0·306	0·925	2·02
2	Soil solution, Plot 4A, complete fertiliser	0·685	0·278	0·963	2·47
5	,, ,, + added salts, H. C.	0·926	0·423	1·349	2·19
2	Soil solution, Plot 7/2, dunged	1·069	0·396	1·465	2·70
5	,, ,, + added salts, H. C. .	0·814	0·472	1·286	1·73

culture solution of high concentration yielded heavier plants (0·943), approaching those obtained in the solutions from the completely manured soils, though still below the maximum. The soil solutions from the unmanured (1, O) and imperfectly manured plots (2A) yielded plants of a much lower order of magnitude (0·216 and 0·486). The addition of the missing nutrients to the solutions from the imperfectly manured soils produced growth approaching the maximum (1·214 and 1·154); when the nutrients were added to set up the higher concentration, the growth produced was equal to that obtained from the artificial culture solution of the same concentration (0·974 and 0·925 against 0·943), though still below the maximum.

These results amply confirm the conclusion drawn from the previous set of experiments—that the growth made by plants in the soil solutions is in the main determined by the amount of plant food they contain. One other point was suggested by the results, that the soil solutions, particularly those from the soil of the dunged plot, were better media for growth than the artificial culture solutions of equivalent concentration, possibly owing to the presence of soluble nitrogen compounds specially valuable to the plant in the earlier stages of growth. On the other hand, it is unsafe to lay much stress on such differences in weight as are exhibited in the growth of the plants in the solutions regarded as complete (0·943, 1·214, 0·974, 1·154, 0·925, 0·963, 1·349, 1·465, 1·286).

In order to check the conclusions still further, a third series of experiments were made. A solution containing per million 4·5 of phosphoric acid and 26·5 of potash was taken as a standard, this being the approximate composition of the solutions of soils from the completely manured plots of the barley fields 4A and 7/2. To the solutions from the imperfectly manured plots (1, O, 2A, 3A), phosphoric acid and potash were added, (1) in amounts required to bring the proportion of these constituents up to the standard, allowance being made for the small amount already present that had been derived from the soil, (2) in amounts equal to the standard, over and above those which the soil had supplied. A set was also included to which no addition of sodium nitrate was made; to the rest, nitrates equivalent to 40 parts N per million were added. In Series II there was a slight imperfection in the comparison, because the added nutrients were equal to those contained in the solutions from the completely manured plots, thus, in the solutions from the imperfectly manured plots to which nutrients were added, there was a small surplus of nutrient derived from the soil.

Barley was again grown, and the growth was prolonged for four weeks only, from June to July. The cool, sunless season of 1912 enabled trustworthy experiments to be made at so late a period. The results obtained are set out in Table V, the dry weight of the whole plant only being given.

TABLE V.—Barley and Peas in Solutions from Hoos Field Barley Soils.
Series III, 1912.

	Artificial culture solution.	Plot 1, O, unmanured.	Plot 2A, lacking potash.	Plot 3A, lacking phosphoric acid.	Plot 4A, complete manure.	Plot 7/2, dunged.
	Parts per million.					
Phosphoric acid in original solution	4·5	0·525	3·90	0·808	4·025	4·463
Potash in original solution . .	26·5	3·40	3·88	30·33	24·03	26·45
Nature of solution.	Dry weight of plant.					
Barley—						
Solution only	0·319	0·149	0·213	0·167	0·303	0·403
„ +N	0·292	0·149	0·226	0·184	0·346	0·404
„ +N, P_2O_5 and K_2O to standard	—	0·420	0·395	0·323		
„ +N + standard P_2O_5 and K_2O	0·366	0·435	0·400	0·364	0·358	0·438
Peas—						
Solution only	1·731	1·082	1·184	1·192	1·449	1·630
„ +N	1·524	1·157	1·404	1·335	1·720	1·743
„ +N, P_2O_5 and K_2O to standard	—	2·299	1·800	1·961		
„ +N + standard P_2O_5 and K_2O	1·769	2·553	2·493	2·136	2·157	2·182

The results of this series are in strict conformity with those of the preceding series. It is noteworthy that the addition of nitrogen to the soil solutions produced no increase in the plant, indicating that the soils themselves had yielded more than enough nitrate for the needs of the plant, the growth of which had been limited by the amount of phosphoric acid and potash present in the solution. The evidence was slight for the presence in the soil solutions, even in those from the dunged plot, of other substances favourable to growth.

In order to check the conclusions still further the set of experiments in this series was duplicated with peas instead of barley (lower part of Table V).

Peas do not form so sensitive a culture plant as barley because the growth is maintained for a long time on the food store in the seed itself, but when allowance is made for this fact and the somewhat greater margin of error, the results obtained with peas were in complete accord with those yielded by barley.

The growth in the soil solutions being such as would be expected from the composition of the solutions, and comparable with the growth of crops on the soils themselves, it is interesting to compare the composition of these artificially made solutions with that of the natural soil solution as far as it can be ascertained. The drainage from the Rothamsted wheat plots is collected separately by a tile drain running below each plot, and on various occasions when the drains ran during the progress of these experiments samples were taken and analysed as below.

TABLE VI.—Phosphoric Acid and Potash found in Soil Solutions and Drainage Waters at various Dates. Parts per million.

	Soil solution.	Drainage water.		
		10/1/11.*	2/4/11.†	14/5/11.†
	Phosphoric acid.			
Plot 3. Unmanured	0·656	0·236	0·520	0·622
„ 10. Ammonium salts only	0·881	0·395	0·541	0·502
„ 11. „ + phosphoric acid	3·839	0·642	0·608	0·961
„ ‡13. „ „ + potash	3·938	0·620	0·780	0·918
	Potash.			
Plot 3	3·64	2·04	5·29	7·15
„ 10	3·55	1·07	3·88	4·87
„ 11	3·88	1·89	10·49	3·55
„ 13	26·22	2·94	11·77	13·55

* The drains had been running two days earlier. † The drains had not run during the preceding month.

‡ Plot 13, the drainage water from which was analysed, receives the same manurial treatment as Plot 7, the soil of which was used for the soil solution analysed.

It is not to be expected that the drainage water will represent the soil solution. When rain falls on the surface one of its effects will be to push downward the soil water already present until a saturated layer forms (*i.e.* a layer containing more water than the soil particles can hold by surface tension) and this layer travels downward until it reaches the drain, which then begins to run. In the drainage water there will always, however, be a certain dilution due to rainwater which has travelled more rapidly down cracks, worm tracks, and other large cavities, and this dilution will increase with the time that elapses after the drain begins to run. The analyses in Table VI show that the drainage waters were always more dilute than the solutions made from the corresponding soils, but their content in phosphoric acid and potash is of the same order of magnitude and follows the same sequence as the soil solutions. Thus our conclusion is strengthened that the soil solutions experimented upon do represent the natural solution existing in the soil *in situ*.

We may now consider how far these results bear on the theory that crops leave behind in the soil specific toxins which depress the growth of succeeding crops of the same kind. In Series I wheat and barley yielded almost exactly the same weight of plant, whether they grow in solutions from the wheat or the barley soils (Table I). As a rule the wheat plants were a little heavier when grown in the solutions from the barley soils than when grown in solutions from the corresponding wheat soils (3 compares with 1, O, 11 with 2A, 7 with 4A, 2 with 7/2), but the barley plants were similarly heavier in the solutions from the barley soils. The ratio of root to shoot is very close in the two sets. Again, wheat and barley grown in the same solution yield weights agreeing within the range of error of such experiments. These facts alone would dismiss the hypothesis that the wheat soils contain any soluble toxin injurious to wheat but not to barley, and *vice versâ*, notwithstanding the 60 years' repeated growth of these crops on the same soils. In Series II the demonstration was pushed a stage further by including in the comparison an artificial culture solution made from pure salts and containing phosphoric acid and potash in the same proportions as the solutions from the completely manured plots. Another set of the soil solutions was boiled before use, since boiling had been reputed to destroy the toxin and would at any rate kill off any bacteria that might be factors in the result. Lastly in another set the solutions were evaporated, the residue ignited and dissolved afresh in a minimum quantity of hydrochloric acid, then diluted to the original volume. The results obtained are set out in Table VII.

TABLE VII.—Growth of Barley in Solutions from Hoos Field Barley Plots. Weight of Plant in grammes. Series II, 1912.

Set.	Treatment of solution.	Artificial culture solution.	Plot 1, O, un-manured.	Plot 2A, lacking potash.	Plot 4A, complete manure.	Plot 7/2, dunged.
2	Soil solution, unboiled	0·763	0·216	0·486	0·963	1·465
6	" boiled	—	0·212	0·601	0·956	1·253
3	" with added nutrients, unboiled	—	1·214	1·154		
7	" " " boiled .	—	1·385	1·022		
8	" residue ignited and redissolved	—	0·203	0·396	0·660	0·604

In this series boiling was without effect, whether the solutions contained added nutrients or not; the residue left on evaporation, after ignition and re-solution, gave generally lower results, in some cases to a marked degree. The soil solutions from completely manured plots gave higher yields than the artificial solutions of corresponding strength.

In order to ascertain whether the results were limited in any way by the nature of the plant (it might be objected as regards Series I that barley and wheat are so closely akin as to excrete the same toxin) the experiments in Series II were repeated with sunflowers, white lupins, and buckwheat, with the results set out in Table VIII.

TABLE VIII.—Growth of Various Plants in Solutions from Hoos Field Barley Soils. Weight of Plant in grammes, 1912.

Plant.	Treatment of solution.	Artificial culture solution.	Plot 1, o, unmanured.	Plot 2A, lacking potash.	Plot 4A, complete manure.	Plot 7/2, dunged.
Buckwheat . .	Soil solution, unboiled . . .	—	0·178	0·300	0·708	0·921
,, . .	,, boiled	—	0·265	0·505	1·145	0·938
,, . .	,, unboiled, added nutrients	—	0·668	0·986		
,, . .	,, boiled, added nutrients	—	0·634	0·729		
White lupins .	Soil solution, unboiled . . .	—	1·691	0·845	1·248	1·439
,, .	,, boiled	—	1·685	0·825	1·724	1·085
,, .	,, unboiled, added nutrients	—	1·086	1·170		
,, .	,, boiled, added nutrients	—	1·898	1·282		
Sunflowers . .	Soil solution, unboiled . . .	—	0·335	0·314	1·075	1·863
,, . .	,, boiled	—	0·338	0·651	—	0·733
,, . .	,, unboiled, added nutrients	—	1·366	1·205		
,, . .	,, boiled, added nutrients	—	Failed	1·176		

These plants are far from being so suitable for experiment as barley, and the results are somewhat erratic (*e.g.* white lupins gave almost their maximum yield in the solution from the unmanured plot, indicating that growth had been mainly sustained on the original food store in the seed), but they in no way indicate the presence of a toxin in the soil solutions which depresses the growth of barley but *ex hypothesi* is without effect on plants of another order. Finally in Series III (Table V) both barley and peas grew as freely in the soil solutions from the completely manured plots and in the solutions from the incompletely manured plots after repair of the deficiency by adding salts, as in the artificial solutions made up with pure salts. Indeed, the superiority, though hardly large enough to be significant, lay with the plants grown in the soil solutions. Thus the experiment yielded no evidence of the existence in soils on which a particular plant had been growing for 60 years and upwards, of a soluble "toxin" having a depressing effect upon the growth of that plant.

II.—The Relation between the Growth of the Plant and the Concentration of the Nutritive Solution.

(A. D. H. and L. M. U.)

As the second stage in the investigation it was necessary to ascertain if the concentration of the soil solution is a factor in the rate of growth of the plant. It has been generally assumed* that, within very wide limits, the plant will be indifferent to the concentration of the soil solution, provided that the total amount of nutrients available, in this case of phosphoric acid and potash, is adequate.

A standard solution was made up containing per litre 0·5 grm. each of potassium di-hydrogen phosphate, magnesium and calcium sulphates, and sodium chloride, 1·0 grm. potassium nitrate, and 0·04 grm. ferric chloride, equivalent to N 138, P_2O_5 261, and K_2O 743 parts per million. Barley was grown in bottles containing 600 c.c. of the above solution, at full strength, and diluted to 1/5, 1/10, and 1/20 respectively, the trials being made in duplicate only. Growth proceeded for eight weeks from March 10 to May 8, with the result set out in Table IX.

Table IX.—Growth of Barley in Nutritive Solutions of varying Concentration. March 10–May 8, 1911.

Concentration of solution.	Dry weight of plant in grammes.			
	Shoot.	Root.	Total.	Ratio $\frac{\text{Shoot}}{\text{Root}}$.
1	1·323 1·605	0·332 0·470	1·655 2·075	4·0 3·4
1/5	0·977 1·087	0·268 0·405	1·245 1·492	3·7 2·5
1/10	0·742 0·690	0·288 0·253	1·030 0·943	2·6 2·7
1/20	0·462 0·369	0·219 0·168	0·681 0·537	2·1 2·2

From the very outset the growth in the various solutions proceeded in the order of their concentration, so that the final weights may be taken to represent the rates of

* Binner and Lucanus, 'Landw. Versuchs.-Stat.,' 1866, vol. 8, p. 128; Cameron, *loc. cit.*, p. 403.

growth throughout and not an ultimate condition brought about by the exhaustion of the food supply, though the more dilute solutions were at the finish depleted of the nitrogen they originally contained. In order to obviate the effects of this depletion of the solution, in the next set of experiments the solutions were renewed weekly, the other conditions remaining as before, with the results set out in Table X.

TABLE X.—Growth of Barley in Nutritive Solutions of varying Concentration renewed weekly. May 18–June 20, 1911.

Concentration of solution.	Dry weight of plant in grammes.			
	Shoot.	Root.	Total.	Mean.
1	0·187 0·450	0·078 0·124	0·265 0·574	0·420
1/5	0·235 0·095	0·084 0·074	0·319 0·169	0·244
1/10	0·048 0·047	0·038 0·084	0·086 0·131	0·108
1/20	0·034 0·047	0·028 0·027	0·062 0·074	0·068

This series, grown late in the season, was less satisfactory, but the results are confirmatory of those obtained before, and some unused nitrate remained in all the solutions, except after the last two weeks' growth in the solutions of greatest dilution.

A new series was now arranged in which the plants were grown in coarse sand contained in vertical glass cylinders through which the nutritive solution slowly percolated. The cylinders contained 800 grm. of coarse sand mixed with 4·25 grm. calcium hydrogen phosphate (the potassium phosphate was withdrawn from the nutritive solution) and 100 c.c. of the nutritive solution daily was allowed to drip very slowly on the sand, percolate through it and escape. Growth was continued for two months, March 26 to May 21, with results set out in Table XI.

The solutions escaping from the sand were regularly tested and found to contain nitrate, except in the last weeks of growth with the more dilute solutions.

Though late in the season for satisfactory work with water cultures two more experiments were made in 1912, in which barley and lupins were employed as test plants and 500 c.c. of solution were dropped through daily, with results set out in Table XII.

TABLE XI.—Growth of Barley in Nutritive Solutions of varying Concentrations percolating through Sand.

Concentration of solution.	Shoot.	Root.	Total.	Ratio $\frac{\text{Shoot}}{\text{Root}}$.
1	2·969 2·393	0·769 0·787	3·738 3·180	3·5
1/5	1·218 1·698	0·304 0·555	1·522 2·253	3·4
1/10	1·148 0·837	0·690 0·221	1·838 1·058	2·2
1/20	0·488 0·603	0·280 0·308	0·768 1·011	1·8

TABLE XII.—Growth of Barley and White Lupins in Nutritive Solutions of varying Concentration percolating through Sand.

Concentration of solution.	Dry weight of plant in grammes.					
	Barley, 11/6/12 to 17/7/12.			White lupins, 25/7/12 to 26/8/12.		
	Shoot.	Root.	Total.	Shoot.	Root.	Total.
1	0·614 1·128	0·136 0·227	0·750 1·355	0·92 1·01	0·403 0·541	1·323 1·551
1/5	1·317 1·802	0·263 0·383	1·580 2·185	1·26 1·24	0·854 0·777	2·114 2·017
1/10	0·766 1·056	0·216 0·275	0·982 1·331	1·12 1·16	0·426 0·750	1·546 1·910
1/20	0·771 0·947	0·213 0·308	0·984 1·255	0·99 0·81	0·755 0·740	1·745 1·550

In this series the strongest solution was too concentrated for the health of the plant, due doubtless to the higher temperatures and the considerable transpiration from the plant, which would still further concentrate the solution retained by the sand. The barley plants were also much affected by rust attacks.

Erratic as are the results shown by individual plants, there can be no doubt about the general superiority of the plants growing in solutions of higher concentration, as will be best seen by a comparison of the weights from the 1/5 and the 1/20 concentrations.

The whole series of experiments confirm the conclusion previously reached from the experiments described in Part I, that the concentration of the nutritive solution, within certain wide limits, irrespective of the total amount of plant food available, is a factor in the rate of plant growth, which varies directly, though not proportionally, with the strength of the solution in the particular nutrient, or nutrients, limiting the growth.*

III.—The Rate of Diffusion of the Nutrients in the Soil Solution.

(A. D. H. and L. M. U.)

As was indicated in the introduction, it is conceivable that the nutrient in a soil solution may take so long to diffuse along the films coating the soil particles from the points where solution is effected to the root hairs that have exhausted the solution with which they are immediately in contact, that the plant may be continually running short of the food it could utilise. In order to test this hypothesis barley was grown in the same nutrient solutions (1) in a bottle as usual, (2) when diffused through a mass of pure sand in such a manner that the sand was nowhere saturated, but each particle was coated with a film of the solution. In the first case there will be no lag due to slowness of diffusion, because the liquid is being constantly mixed by convection currents, the daily aëration, etc., but in the second case the dissolved substances will have to travel to the roots in the surface film, sometimes for considerable distances, and the lag may become evident in a retardation of growth.

Cameron† has shown that for each soil there is a critical content of water that will induce a "crumb structure," in which state the soil contains no free water and is not sensibly wet, but can readily be crumbled without pasting. This condition can be found with fair accuracy by trial and corresponds to the optimum water content for growth. The sand used in the experiments was a uniform fine silver sand, the grains of which were above 0·2 mm. in diameter, and the critical water content corresponded to about one of water to five of sand. When wetted with this proportion of water the sand could be squeezed into a coherent mass but no water would exude, it also could be rubbed down into a fine crumb.

As the bottles held 600 c.c. of the culture solution, jars containing 3000 grm. of sand, through which 600 c.c. of the same solutions were diffused, were used in the comparisons; the same solutions varying in concentration from 1 to 1/20 were employed as in the preceding experiments, and barley was the trial plant. Every two or three days the jars were weighed and the original water content restored by the addition of pure water. Table XIII shows the results obtained.

It will be seen that so far from there being any retardation of growth in the sand

* See also Pouget and Chouchak, 'Compt. Rend.,' 1912, vol. 154, p. 1709.

† Bureau of Soils, U.S. Department of Agriculture, Bull. 50, 1908.

TABLE XIII.—Comparative Growth of Barley in Sand and Water Cultures of Equal Concentration.

Concentration of solution.	Dry weight of plant in grammes.	
	Water.	Sand.
1	1·655 2·075	7·050 4·200
1/5	1·245 1·492	3·539 3·031
1/10	1·030 0·943	3·171 2·882
1/20	0·681 0·537	1·556 1·437

due to slowness of diffusion of the nutrients in the water films, the sand cultures were markedly superior to the water cultures, though as before the rate of growth varies with the concentration of the nutrients in the solution. The experiment was repeated, and this time the nutrients in a concentrated solution were placed inside narrow cylinders of porous earthenware themselves filled with sand and packed in the sand in which the plant was growing. Thus the roots never came into contact with the nutrient solution until it had diffused through the porous cell and into the mass of sand beyond. The results are set out in Table XIV, from which it will be seen that the porous pot had introduced no new factor.

TABLE XIV.—Comparative Growth of Barley in Sand and Water Cultures of Equal Concentration. May 18–June 20, 1912.

Concentration of solution.	Dry weight of plant in grammes.	
	Water.	Sand.
1	0·265 0·574	2·923 1·974
1/5	0·319 0·169	0·601 0·867
1/10	0·086 0·131	0·512 0·682
1/20	0·062 0·074	0·405 0·516

Again the growth varied with the concentration of the solution, and again the sand cultures were greatly superior to the corresponding water cultures.

There is thus no depression of growth due to slowness of diffusion of the nutrients in the water films on sand particles; it might be supposed, however, that the lag would become operative in the extended film that must exist on the far finer particles found in an ordinary soil. Accordingly a large quantity of sandy soil was graded into "coarse sand" as before, fine sand between 0·2 and 0·04 mm., and silt between 0·04 and 0·01 mm. Pure kaolin was taken to represent a clay material largely constituted of still finer particles. The critical water content was determined by trial as before, and the same solution was diffused through all the materials. Barley was grown five weeks with the following results:—

TABLE XV.—Growth of Barley in Nutrient Solution diffused over Solid Particles of various Grades.

Nature of medium.	Dry weight of plant in grammes.		
	1.	2.	Mean.
Water	1·350	1·190	1·270
Coarse sand	1·456	1·369	1·412
Fine sand	0·581	0·624	0·602
Silt	0·800	0·472	0·636
Kaolin	1·026	0·719	0·872

Through an accident the barley in the water cultures received twice the volume of nutrient solution that was diffused through the solid media; hence the comparison in this case was not exact. However, the sand culture preserved its superiority. In the media of finer grain there was evidently some factor at work depressing the growth, though it would not appear to be the time required for diffusion, because it was least active in the kaolin, the finest medium of all.

The experiment was repeated with lupins with results set out in Table XVI.

TABLE XVI.—Growth of Lupins in Nutrient Solution diffused over Solid Particles of various Grades.

Nature of medium.	Dry weight of plant in grammes.		
	1.	2.	Mean.
Water	0·822	1·162	0·942
Coarse sand	2·486	2·462	2·474
Fine sand	0·896	1·367	1·131
Silt	1·416	1·371	1·393
Kaolin	1·742	1·925	1·833

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

On this occasion the growth in each of the solid media was superior to that in the same volume of solution in the free liquid state, so that the possibility of a retardation of growth due to slowness of diffusion may be dismissed. Some explanation is, however, required of the superiority of the cultures in sand over the water cultures, and, again, of the superiority of the cultures in coarse sand and kaolin over those in fine sand and silt. We were led to suspect that differences in the aëration of the roots might be the disturbing factor. The sand when properly wetted remains in a very open state, with large air spaces between the aggregates, and the roots could be observed traversing the whole medium freely; the kaolin preserved a very similar structure, whereas the fine sand and silt quickly settled down to a close mass. The appearance of the roots after they had been washed out of the sand, etc. (see photograph, fig. 2), showed that they had been able to develop

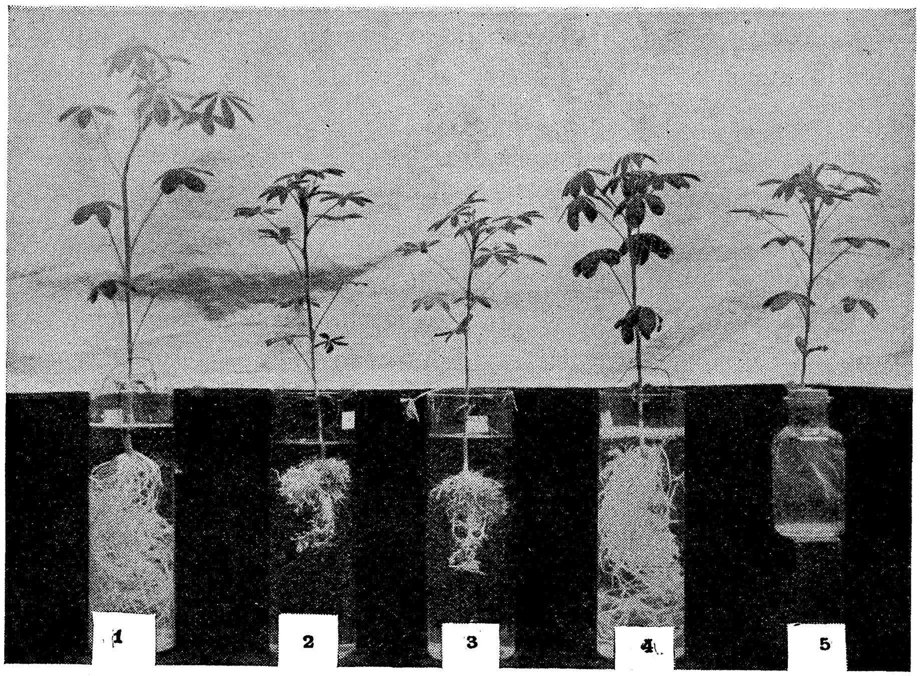


FIG. 2.—Appearance of Roots washed out of—1. Silver sand. 2. Fine sand. 3. Silt. 4. Kaolin. 5. Water culture.

freely in the coarse sand and kaolin, but had been greatly restricted in the fine sand and silt.

Comparative water cultures were then arranged in which one series were not aërated at all, whereas in the other bottles a continuous current of air was bubbled through the solutions. The experiment was repeated with barley and lupins, and the results obtained are set out in Table XVII.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

TABLE XVII.—Growth of Barley and Lupins in Water Cultures variously Aërated.

Plant.	Treatment of solution.	Dry weight of plants in grammes.				
		1.	2.	3.	4.	Mean.
Barley . . .	Not aërated	1·591	1·552	1·024	1·090	1·314
,, . . .	Aërated continuously . . .	2·528	1·646	2·159	2·156	2·122
Lupins . . .	Not aërated	0·99	0·94	0·62	0·78	0·83
,, . . .	Aërated once a day	0·73	0·67	0·68	0·79	0·72
,, . . .	Aërated continuously . . .	1·60	1·65	1·43	1·45	1·53

These results are convincing as to the enormous gain to the plant from continuous aëration of the root, and to this factor alone may be set down the superiority of the cultures in solid media over the ordinary water cultures in which the aëration is not continuous.

Finally, another set of experiments was tried with the coarse sand, silt, and kaolin, in which the water was added to the solid medium from below, so as to obviate as much as possible the settlement of the silt that had been so pronounced in the previous experiments. Settlement still occurred, but the growth made was more nearly equal (see Table XVIII), though the results are not conclusive as to whether aëration is the only factor concerned and whether the fine particles in the kaolin and silt are not holding back some of the nutrients from the plant by "adsorption."

TABLE XVIII.—Growth of Lupins in Solid Media, watered from below.

Medium.	Dry weight of plant.
Sand	2·713
Sand	3·866
Silt	1·929
Kaolin	1·853
Kaolin	1·719

The difficulty of obtaining good crops on soils containing a large proportion of silt particles has repeatedly been observed; it may, in part, be set down to the ease with which the particles slip into a condition causing deficient aëration in the soil.

SUMMARY AND CONCLUSIONS.

Solutions were made by extracting the soils from certain of the Rothamsted plots on which wheat and barley had been grown for 60 years and upwards. Wheat and barley were grown in these solutions, which were renewed fortnightly. The comparative growth in the solutions was closely parallel to the growth of the crop on the plots in the field and corresponded to the composition of the solutions. The composition of the solutions as regards phosphoric acid and potash corresponded to the past manurial treatment of the soils and to the amount of phosphoric acid and potash they now show on analysis. Growth in the soil solutions agreed with the growth in artificial culture solutions containing equivalent amounts of phosphoric acid and potash. Growth in the soil solutions from imperfectly manured plots was brought up to the level of that in the solutions from completely manured plots on making up their deficiencies in phosphoric acid and potash by the addition of suitable salts. The phosphoric acid and potash content of the soil solutions was of the same order as the phosphoric acid and potash content of the natural drainage water from the same plots.

Wheat grew as well as barley in the solutions of the wheat soils, and *vice versâ*. In a similar set of solutions from the same soils the growth of buckwheat, white lupins and sunflowers corresponded with that of wheat and barley. Boiling effected no alteration in the nutritive value of the soil solutions.

In nutritive solutions of various degrees of dilution the growth of plants varied directly, but not proportionally, with the concentration of the solution, though the total plant food present in the solution was in excess of the requirements of the plant. When the nutrient solution was diffused as a film over sand or soil particles, as in nature, there was no retardation of growth due to the slowness of the diffusion of the nutrients to the points in the liquid film which had been exhausted by contact with the roots. Growth in such nutrient solutions forming a film over sand particles was much superior to the growth in a water culture of equal concentration, but the growth in the water culture was similarly increased if a continuous current of air was kept passing through it.

From these data it is concluded:—

(1) The composition of the natural soil solution as regards phosphoric acid and potash is not constant, but varies significantly in accord with the composition of the soil and its past manurial history.

(2) Within wide limits the rate of growth of a plant varies with the concentration of the nutritive solution, irrespective of the total amount of plant food available.

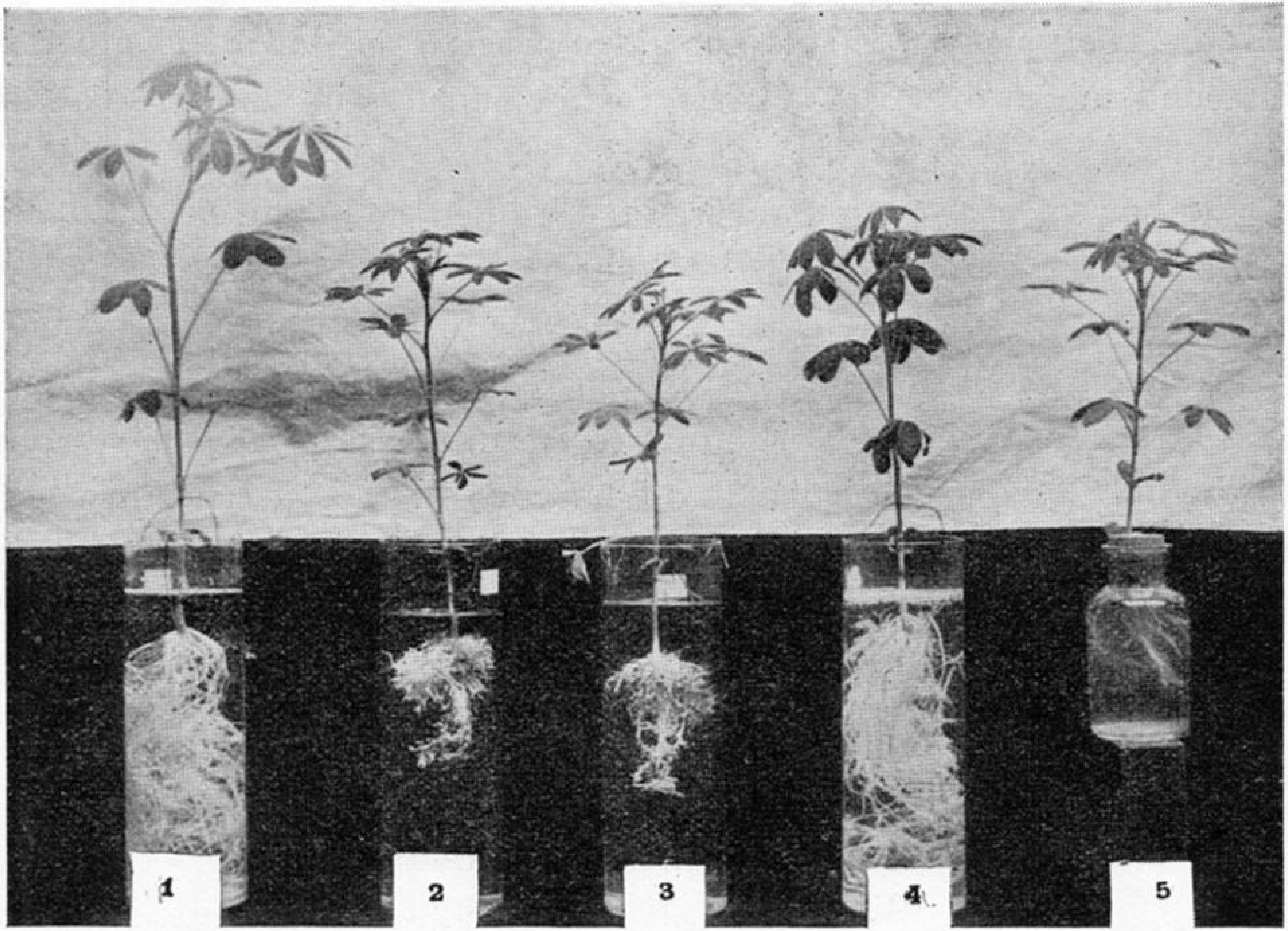
(3) When other conditions, such as the supply of nitrogen, water, and air, are equal, the growth of the crop will be determined by the concentration of the soil solution in phosphoric acid and potash which, in its turn, is determined by the amount of these substances in the soil, their state of combination, and the fertiliser supplied.

(4) On normal cultivated soils the growth of crops like wheat and barley, even when repeated for 60 years in succession, does not leave behind in the soil specific

toxic substances which have an injurious effect upon the growth of the same or other plants in that soil.

The net result of these investigations is to restore the earlier theory of the direct nutrition of the plant by fertilisers. The composition of the soil solution which determines the growth of the plant is dependent upon the amount and the mode of combination of the phosphoric acid and potash in the soil, both of which are affected by the fertiliser supply, though to what extent is not yet determinable.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES



'IG. 2.—Appearance of Roots washed out of—1. Silver sand. 2. Fine sand. 3. Silt. 4. Kaolin. 5. Water culture.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES