DISPLACEMENT OF SOIL SOLUBLES THROUGH PLANT ROOTS BY MEANS OF AIR PRESSURE AS A METHOD OF STUDYING SOIL FERTILITY PROBLEMS

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INTRODUCTION

The intake of dissolved substances by plant roots growing in nutrient media is a subject of much scientific interest, but the many investigations on this subject have failed to satisfactorily explain the processes by which soil solubles are taken in by plant roots and the relation which the nature and concentration of these soil solubles bears to soil conditions and the growth of plants. What is believed to be a new method of procedure for investigating the plant nutrients of the soil and the selective power of the living plant root is described in the following paper. The data presented and obtained by the use of the method seems to justify its consideration as a means of investigating soil-plant nutritional problems. It is hoped that by its use some of the difficulties connected with research in this field may be in some way lessened.

Acknowledgement is due Paul J. Kramer as the idea for devising this method as a means of studying soil-plant problems resulted from the reading of his article "The absorption of water by the root systems of plants" (3).

Briefly the procedure followed consisted of growing plants in soil, some in soil which was not fertilized and some in fertilized soil. Subsequently to the growing of the plants the tops were cut off and solution forced from the soil through the plant roots by means of air pressure and collected as it emerged from the stem stubs. In some cases the plant roots were killed with heat before the soil solution was forced through them. The solution was collected in consecutive portions, 2 to 4 in number usually distributed over a period of 48 hours. Each portion of solution collected was measured and later analyzed for phosphorus, potassium, and calcium. Determinations were also made for these elements in the soil, and the soil moisture content was determined at the time the collection of the solution from the stem stubs was completed.

Greenhouse Procedure

Bean plants were grown in the greenhouse in two-gallon glazed crocks, each containing the equivalent of 8 kilograms of oven-dry soil. A Brookston loam soil from the vicinity of Unionville, Michigan, was chosen for the experiment. It has been subjected to field tests on bean fertilization for a period of two years. Under field conditions beans did not respond to moderate applications of the fertilizers used. This fact does not seem unusual when it is known that the soil is very fertile, producing high yields of corn, wheat, beets, and alfalfa, as well as beans, without the use of fertilizers although some of the crops mentioned do respond to fertilizer applications. This soil was tested for soluble plant nutrients using Spurway's method (7). It gave low tests for both phosphorus and potassium, indication that a plant response could be expected from an application of these elements in commercial fertilizers.

In order to determine, if possible, the amounts of these elements which would be necessary to apply to the soil to make them available in such concentrations as it is expected they should exist in the soil solution of fertile soils, 100-gram samples of the soil were weighed out and increments of phosphorus as $Ca(H_2PO_4)_2 \cdot H_2O$ added in solution with sufficient water to make the soil up to optimum moisture content when the solution was thoroughly mixed with it. The soil thus treated was allowed to stand for one day and then tested for phosphorus according to Spurway's method (7). The procedure was repeated adding increments of potassium as KCl and testing for this element (7). Applications of $Ca(H_2PO_4)_2 \cdot H_2O$ equivalent to 750 pounds of P_2O_5 per 1,000,000 pounds of soil gave a high test for phosphorus, and KCl equivalent to 1200 pounds of K_2O gave just a positive test for potassium as shown in tables 1 and 2.

Fertilizer was added to the soil in one-half the number of crocks in which beans were to be planted, in the form and at the rate given above. The application was made by mixing the air-dry soil on an oilcloth with a sufficient quantity of a solution of $Ca(H_2PO_4)_2 \cdot H_2O$ and KCl to bring the soil to the optimum moisture content. The quantity of potassium added to the soil, as will be seen, based on the tests made on the samples of soil receiving the trial applications, was not great enough to bring the concentration up to what might be considered

Table I

Soil Tests for Phosphorus and Potassium resulting from Phosphorus Applications

Soil Grams	Water ml.	$Ca(H_2PO_4)_2.H_2O$ Solution 26.8819 grams per liter ml.	Pounds per acre equivalent	Phosphorus P. P. M.	Potassium P. P. M.
100	20.0	0.0	-----	½	----
100	19.5	0.5	150	½ - 1	----
100	19.0	1.0	300	1½- 2	----
100	18.5	1.5	450	4 - 5	----
100	18.0	2.0	600	High	----
100	17.5	2.5	750	High	----

Table II

Soil Tests for Phosphorus and Potassium resulting from Potassium Applications

Soil Grams	Water ml.	KCl Solution 9.5939 grams per liter ml.	Pounds per acre equivalent	Phosphorus P. P. M.	Potassium P. P. M.
100	20.0	0.0	---	½	---
100	19.5	0.5	150	½	---
100	19.0	1.0	300	½	---
100	18.5	1.5	450	½	5
100	18.0	2.0	600	½	5
100	17.5	2.5	750	½	5
100	17.0	3.0	900	½	5
100	16.5	3.5	1050	½	5
100	16.0	4.0	1200	½	5

Table III

Outline of Greenhouse Work

Date of Planting	Unfertilized Crock No.	Dry Weight of Plant Tops	Fertilized Crock No.	Dry Weight of Plant Tops
8/12/33	1A	8.90	2A	15.90
8/14/33	1B	13.32	2B	18.04
8/16/33	1C	16.61	2C	23.38
8/18/33	1D	19.65	2D	18.40
8/20/33	1E	15.62	2E	23.74
9/25/33	3A	10.25	4A	14.20
9/29/33	3B	9.25	4B	19.50
10/3/33	3C	15.05	4C	15.40
10/7/33	3D	13.90	4D	16.60
10/11/33	3E	12.30	4E	14.65

Apparatus and Technique for Displacing Soil Solubles through Plant Roots

In order to force the solution from the soil into the plant roots and out through the cut stem, it is necessary to subject the solution to a force sufficiently great to overcome the resistance offered to the passage of the solution through the root system plus the force necessary to overcome the retaining force exerted by the soil itself on the solution contained. To affect this condition a chamber capable of holding air under pressure was used. The pressure chamber, as it will be called, was made from a steam pressure cooker, not especially because it was considered the most suitable, but because it was available. Its construction was altered in such a way as to make it as effective as possible in serving in its new capacity. A safety valve and outlet valve in combination were installed in the lid. The pressure gauge was left as it was originally. Three holes about 1 cm. in diameter were bored through the lid, equally spaced in the line of a semicircle, and threaded so that they could be closed by screwing in metal plugs. The chamber was tested and found capable of holding at least 30 pounds per square inch of internal pressure. The safety valve was set to release the air at pressures slightly higher, to insure against too much pressure being attained accidentally. The steam entrance was fitted and connected through a needle valve to an air line which was held at a pressure of 30 pounds per square inch by means of a reducing valve.

Connections were made to the stem stubs of the plants left after the tops were cut off by means of fittings made from rubber tubing. Two pieces of tubing, each about 5 centimeters long but of different sizes, were used. The smaller sized tubing was pulled part way through the larger sized tubing. The smaller and more flexible tubing, which protruded from the end of the larger tubing, was started on to the stem stub which had previously been greased with vaseline and forced on until the stub extended well up into the heavier tubing. The sizes of the pieces of tubing were usually close to two-eighths and three-eighths inches, respectively, inside deameter, depending on the size of the plant stems. After the connections were made on the stem stubs the crock was placed in the pressure chamber. This being done, delivery tubes made from glass tubing having a diameter of about one-half centimeter were inserted through the holes in the lid of the chamber. The rubber seals, made by boring a hole in rubber cushions used for centrifuge tubes, were placed on the tubes with their concave sides next to the lid. The ends of the delivery tubes were then inserted in the rubber connections, attached to the plants, and the rubber seals on the tubes adjusted so that when the lid to the pressure chamber was in place they were just flush with the surface of the lid. Compressed air, when admitted to the chamber after the lid was secured in place, exerted a force on the rubber cushions, pressing them against the lid and forming effective seals around the delivery tubes and around the holes in the lid through which the delivery tubes entered the chamber. Stopcock grease was placed on the ground surfaces of the lid and chamber to facilitate a better seal. The ends of the delivery tubes protruding from the holes in the lid of the pressure chamber were fitted into receiving flasks by means of two-hole rubber stoppers. One of the holes in the stopper held the end of the delivery tube and the other served as an opening to prevent any back pressure accumulating. (Diagram 1 and Plate IV.)

Bean plants which had reached the stage of maturity when they were setting pods were used to obtain the solution from the soil by the air pressure method. The crock and soil containing the plants were weighed, the tops cut off about 5 cm. above the surface of the soil and the connections made as described previously. Following the period in which the crock containing the soil and roots remained in the pressure chamber, the crock and soil were weighed in order to determine the loss of weight not accounted for by the material removed. A core of soil was removed through the center of the crock and its moisture content determined. The plant tops which were cut off were weighed and left to dry. The per cent moisture and dry weight were then calculated on an air-dry basis.

This soil solution forced through the plant roots by means of air pressure, designated in the future for the sake of convenience as the solution, was collected over consecutive periods of time, the length of the periods being varied. Usually the total period was 48 hours. The solution collected from each plant during each of these periods was measured and the volume recorded after which it was returned to the flask in which it was collected, two or three drops of toluene added, and the flask stoppered and set aside.

The roots of the plants in some crocks were killed before the solution was forced through them. This was done by placing the crocks containing the growing plants in a water bath, which was at a temperature of between 80° and 90°C., until the soil at the center of the crock near the surface was at 70°C. (4). After this temperature was attained the crocks were removed from the bath and the soil allowed to cool at room temperature. Cooling under room conditions took about 8 hours. As soon as the soil in the crocks attained room temperature, or as soon afterwards as was convenient, the tops were cut off, the connections made, and the solution obtained in the same way as when the soil was not heated.

In an attempt to see if the changes in the concentrations of the solutions obtained as a result of heating the soil could be affected in another way twenty-five ml. of ether were added to the soil in one of the crocks about 12 hours before the crock was placed in the pressure chamber.

Methods of Analysis

Phosphorus, potassium, and calcium, three elements which have been proved to be necessary in nutrient mediums for growth of plants, were determined in the soil and in the solutions. Determinations for these elements in the soil were made according to the method of Spurway (7).

Phosphorus was determined in the solutions by the colorimetric method described by Truog and Meyer (8) except in cases where the soil had been heated and the concentrations in the solutions were very small. From 1 to 2 ml. of solution, depending on the expected concentration, were diluted to 50 ml. the color developed and the concentration of the solution determined. Phosphorus determinations on the solution obtained from heated soil were made according to the method of Spurway for testing soils (7). One ml. of the solution obtained by means of the plant roots was used in the determination, instead of the 1 ml. of soil extract as used in the soil tests.

Potassium was determined according to the method of Kramer and Tisdall (2), with some modification. Two ml. of solution or, in some cases, 1 ml. of solution and 1 ml. of water were added to a 15 ml. centrifuge tube. Two mls. of 95 per cent alcohol were added and the cobaltinitrite reagent added with stirring. Centrifuging followed precipitation immediately. The precipitate was washed once with 4 ml. of 50 per cent alcohol, recentrifuged, drained, and allowed to dry following which it was titrated in the

Table IV

Soil Tests for Phosphorus, Potassium, and Calcium on Soil in Crock when Removed from Pressure Chamber

	Unfertilized	Fertilized
Reaction	Basic	Basic
Phosphorus	$\frac{1}{2}$	High
Potassium	Low	5
Calcium	150	200

usual manner.

Calcium in the solution was determined according to the method of Clark and Collip (1).

Phosphorus, potassium, and calcium were determined in the soil at the time it was removed from the pressure chamber (7). Results of tests for these elements in the soil, after growing the crop, were the same as before the crop was planted. Compare table 4 with tables 1 and 2.

Experimental Results

Phosphorus and potassium applied to the soil produced a marked increase in the growth of the bean plants, (Plates I, II, and III) especially in the early stages. Plants that grew on the unfertilized soil, however, tended to overcome their initial disadvantage as they approached maturity, but never overcame their slower start completely as can be seen by noting the relative differences in the dry weights of the plant tops grown on the unfertilized and the fertilized soil. (Table 3)

The amount of solution collected by means of a plant root over a given period of time, as a result of air pressure being applied to the soil, varied greatly with the period considered and the individual plant root, as with plant roots in the same crock, and to an even greater extent with the plant roots grown in different crocks, ranging from a few ml. to more than 100 ml. over a 12 to 24 hour period. (Tables 5, 6, 7,

Table V

Soil moisture, dry weight of plant tops, ml. of solution collected, and the concentration of phosphorus, potassium, and calcium in the solutions forced through plant roots from unfertilized soil by means of air pressure over consecutive periods of time.

Plant No.	Dry Wt. of Plant gm.	Period Hours	Solution Collected ml.	Phosphorus P. P. M.	Potassium P. P. M.	Calcium P. P. M.
		Crock 1A				
		Per Cent Soil Moisture -- 15.67				
1	Total	0 - 24	141	6.21	42.05	30.36
		24- 48	24	9.65	33.11	50.73
	of					
2		0 - 24	147	5.68	41.37	27.32
	Three	24- 48	28	7.86	38.41	42.45
3	8.90	0 - 24	90	5.00	35.80	17.60
		24- 48	16	3.50	156.33*	25.88
		Crock 1B				
		Per Cent Soil Moisture -- 13.70				
1	4.95	0 - 24	29	14.16	214.50	145.44
		24- 48	7	11.49	480.78*	136.09*
2	3.12	0 - 24	24	14.10	180.13	82.73
		24- 48	5	11.92	448.59*	-----
3	5.25	0 - 24	36	15.25	176.38	91.08
		24- 48	7	10.83	337.06*	54.44*
		Crock 1C				
		Per Cent Soil Moisture -- 17.06				
1	3.67	0 - 12	38	6.38	94.71	59.21
		12- 24	29	6.37	60.28	17.76
		24- 48	48	5.68	69.40	17.76
2	6.65	0 - 12	13	9.09	193.60	120.38
		12- 24	17	17.50	145.58	30.59
		24- 48	19	16.06	290.26	25.66
3	6.29	0 - 12	74	6.64	107.08	56.25
		12- 24	45	3.94	29.15	24.67
		24- 48	56	7.56	76.41	33.55
		Crock 1D				
		Per Cent Soil Moisture -- 13.39				
1	8.05	0 - 12	36	17.86	96.59	65.13
		12- 24	6	11.42	232.03*	55.26*
		24- 48	5	8.96	431.47*	67.10*
2	5.40	0 - 12	20	9.56	113.25	97.69
		12- 24	3	4.25	172.53*	-----
		24- 48	3	4.19	799.14*	-----
3	6.20	0 - 12	28	14.37	87.34	65.15
		12- 24	6	7.32	104.67	45.39*
		24- 48	5	3.25	401.82*	49.34*

Table V
(Continued)

Plant No.	Dry Wt. of Plant gm.	Period Hours	Solution Collected ml.	Phosphorus P. P. M.	Potassium P. P. M.	Calcium P. P. M.
		Crock 3B Per Cent Soil Moisture -- 17.84				
1	3.55	0 - 12	92	5.68	67.56	14.85
		12- 24	54	4.89	21.34	11.84
		24- 48	35	9.49	64.76	30.59
2	2.10	0 - 12	31	10.55	118.34	25.66
		12- 24	17	11.03	111.13	17.76
		24- 48	9	10.75	321.23	33.55
3	3.60	0 - 12	46	7.14	63.48	16.78
		12- 24	23	8.23	53.88	19.76
		24- 48	9	6.70	197.22	35.55
		Crock 3D Per Cent Soil Moisture -- 17.30				
1	3.95	0 - 8	37	10.12	93.39	30.51
		8 - 24	38	11.52	36.78	26.30
		24- 48	19	10.72	133.01	49.44
2	5.90	0 - 8	47	9.93	56.18	21.04
		8 - 24	53	12.36	19.70	14.73
		24- 48	26	7.97	106.01	41.02
3	4.05	0 - 8	46	9.17	59.48	17.88
		8 - 24	54	12.36	16.71	15.78
		24- 48	35	7.39	70.72	25.24
		Crock 3E Per Cent Soil Moisture -- 21.55				
1	3.70	0 - 8	35	9.56	116.57	38.92
		8 - 23	45	6.37	66.56	29.45
		23- 48	41	8.01	137.57	41.02
		48- 72	21	6.89	134.37	54.70
2	3.75	0 - 8	42	9.58	132.88	43.13
		8 - 23	71	5.33	78.88	28.40
		23- 48	104	4.37	60.49	17.88
		48- 72	71	3.44	59.94	31.56
3	4.85	0 - 8	58	6.33	95.35	30.51
		8 - 23	75	5.08	49.73	26.30
		23- 48	122	3.52	33.55	13.68
		48- 72	90	2.87	36.11	16.83

* Single determination

Table VI

Soil moisture, dry weight of plant tops, ml. of solution collected, and the concentration of phosphorus, potassium, and calcium in the solutions forced through plant roots from unfertilized soil by means of air pressure over consecutive periods of time. Roots killed by heating soil in crock containing plants to 70°C.

Plant No.	Dry Wt. of Plant gm.	Period Hours	Solution Collected ml.	Phosphorus P. P. M.	Potassium P. P. M.	Calcium P. P. M.
		Crock 3A Per Cent Soil Moisture -- 17.37				
1	4.30	0 - 4	54	0.50	4.28	152.37
		4 - 16	60	0.50	4.71	152,37
		16- 40	10	0.50	9.43	134.79
2	3.10	0 - 4	36	0.50	3.95	157.25
		4 - 16	45	0.50	6.22	183.62
		16- 40	5	0.50	----	189.48
3	2.85	0 - 4	38	0.50	5.04	141.63
		4 - 16	60	0.50	5.51	145.53
		16- 40	18	0.50	9.23	171.90
		Crock 3C Per Cent Soil Moisture -- 17.42				
				O		
1	5.30	0 - 3	35	0.50	4.16	159.88
		3 - 12	42	0.50	3.46	161.98
		12- 36	15	0.50	8.15	168.30
2	5.10	0 - 3	53	0.50	4.23	135.69
		3 - 12	67	0.50	2.95	161.99
		12- 36	38	0.50	3.66	146.21
3	4.65	0 - 3	41	0.50	2.91	161.99
		3 - 12	49	0.50	3.27	161.98
		12 -36	26	0.50	8.45	164.09

Table VII

Soil moisture, dry weight of plant tops, ml. of solution collected, and the concentration of phosphorus, potassium, and calcium in the solutions forced through plant roots from soil fertilized with 750 pounds P_2O_5 and 1200 pounds of K_2O per 1,000,000 pounds of oven-dry soil by means of air pressure over consecutive periods of time.

Plant No.	Dry Wt. of Plant gm.	Period Hours	Solution Collected ml.	Phosphorus P. P. M.	Potassium P. P. M.	Calcium P. P. M.
		Crock 2A				
		Per Cent Soil Moisture -- 16.58				
1	Total	0 - 24	127	18.22	72.56	62.81
		24- 48	17	16.20	172.71	83,85
2	of	0 - 24	104	16.50	63.71	51.65
		24- 48	15	19.50	150.74	97.36
	Three					
3		0 - 24	102	18.15	88.94	45.55
	15.97	24- 48	13	14.41	239.87	86.96
		Crock 2C				
		Per Cent Soil Moisture -- 16.79				
1	9.39	0 - 12	91	16.86	157.05	47.11
		12- 24	44	21.41	148.31	35.59
		24- 48	24	22.10	330.21	66.11
2	7.00	0 - 12	36	32.15	276.58	82.73
		12- 24	17	34.72	308.44	57.26
		24- 48	14	30.40	436.47	77.95
3	6.99	0 - 12	84	16.56	125.88	49.20
		12- 24	44	17.76	93.92	22.70
		24-,48	25	20.16	231.13	55.26
		Crock 2D				
		Per Cent Soil Moisture -- 17.50				
1	6.15	0 - 12	59	13.89	59.18	29.66
		12- 24	23	18.15	151.65	58.61
		24- 48	15	11.17	446.20	85.95*
2	6.55	0 - 12	57	13.93	127.44	41.03
		12- 24	23	13.05	114.92	48.83
		24- 48	6	20.49	467.89	115.25*
3	5.70	0 - 12	18	30.70	442.17	67.40
		12- 24	8	26.88	524.96	56.65*
		24- 48	6	15.67	642.09	97.67*

Table VII
(Continued)

Plant No.	Dry Wt. of Plant gm.	Period Hours	Solution Collected ml.	Phosphorus P. P. M.	Potassium P. P. M.	Calcium P. P. M.
		Crock 4C				
		Per Cent Soil Moisture -- 17.03				
1	6.60	0 - 12	68	18.52	90.49	37.87
		12- 24	46	14.81	42.25	27.35
		24- 48	42	23.68	105.19	28.40
2	3.55	0 - 12	32	23.76	91.45	44.18
		12- 24	27	15.24	48.35	30.51
		24- 48	32	19.35	96.17	17.88
3	5.25	0 - 12	38	22.36	113.64	43.13
		12- 24	22	21.26	95.25	27.35
		24- 48	25	32.30	200.77	56.80
		Crock 4D[1]				
		Per Cent Soil Moisture -- 18.26				
1	5.95	0 - 12	39	15.90	84.10	116.76
		12- 24	17	14.95	72.67	117.81
		24- 48	7	14.47	307.22	112.55
2	7.70	0 - 12	91	12.68	72.00	114.65
		12- 24	58	12.60	55.66	98.87
		24- 48	42	24.46	87.40	66.27
3	2.95	0 - 12	28	13.51	105.97	225.09
		12- 24	15	16.82	193.62	82.05
		24- 48	16	23.02	211.14	19.99

1- 25 cc. of ether added to soil

Table VIII

Soil moisture, dry weight of plant tops, ml. of solution collected, and the concentration of phosphorus, potassium, and calcium in the solutions forced through plant roots from soil fertilized with 750 pounds P_2O_5 and 1200 pounds of K_2O per 1,000,000 pounds of oven-dry soil by means of air pressure over consecutive periods of time. Roots killed by heating soil in crock containing plants to 70°C.

Plant No.	Dry Wt. of Plant gm.	Period Hours	Solution Collected ml.	Phosphorus P. P. M.	Potassium P. P. M.	Calcium P. P. M.
		Crock 2E				
		Per Cent Soil Moisture -- 15.70				
1	8.80	0 - 3	96	1.00	8.47	359.06
		3 - 7	52	1.00	9.78	334.99
		7 -24	33	1.00	18.92	353.83
2	7.47	0 - 3	85	1.00	9.84	324.52
		3 - 7	46	1.00	8.64	315.10
		7 -25	29	1.00	12.20	341.27
3	7.47	0 - 3	87	1.00	11.27	362.20
		3 - 7	51	1.00	13.24	330.80
		7 -25	33	1.00	25.35	359.73
		Crock 4B				
		Per Cent Soil Moisture -- 16.80				
1	7.05	0 - 4	46	0.50	11.24	250.34
		4 -12	37	1.00	10.34	239.82
		12-36	34	1.00	10.06	234.56
2	6.85	0 - 4	39	0.50	11.50	247.18
		4 -12	35	1.00	11.14	249.29
		12-36	33	1.00	11.91	269.27
3	5.60	0 - 4	35	0.50	12.01	250.34
		4 -12	28	1.00	11.59	247.18
		12-36	20	1.00	12.07	249.29
		Crock 4E				
		Per Cent Soil Moisture -- 16.87				
1	5.65	0 - 3	34	1.00	18.52	295.57
		3 -12	51	1.00	17.49	310.30
		12-36	40	1.00	23.91	334.94
2	4.40	0 - 3	29	1.00	17.44	315.55
		3 -12	40	1.00	17.34	344.05
		12-36	35	1.00	27.07	390.23
3	4.60	0 - 3	22	1.00	17.40	312.40
		3 -12	34	1.00	16.24	330.28
		12-36	28	1.00	17.03	397.10

and 8.) Heating the soil resulted in a much increased rate of flow and also shortened the time in which the flow was decreased to zero. This fact is evident when the amounts of solutions collected over a given period of time, as is recorded in tables 6 and 8, are compared with the amounts recorded in tables 5 and 7. The solutions obtained by means of roots in soil which was not subjected to heating were perfectly clear and colorless at the time of collection, but some of the solutions collected, after standing for from 12 to 24 hours, became somewhat turbid. Solutions obtained by means of roots in soil subjected to heating were clear but slightly yellow.

Much variation in the concentrations of phosphorus, potassium, and calcium in the solutions are evident from the data in tables 5 and 7. Nevertheless, it will easily be seen that the phosphorus concentrations in the solutions obtained from unfertilized soil are, on the average, not quite half as high as they are in the solution obtained from soil which received fertilizer applications. Potassium and calcium in the solutions varied more than did phosphorus and were less consistent in any respect. On the average, the concentrations of both potassium and calcium were greater in the solutions obtained by means of the plant roots in fertilized soil than they were in the solutions obtained by means of the plant roots in unfertilized soil. However, the inconsistency was so marked that it does not seem plausible to attach any significance to the average condition.

An inspection of the data in the same tables, however, reveals a certain consistency in some respects. The concentrations of phosphorus, potassium, and calcium in the solutions obtained by means of plant roots in the same crock were in closer agreement than the concentrations of these elements in the solutions obtained by means of plant roots in different crocks. When the concentration of these elements in the solutions procured by means of a given plant root are followed through the consecutive periods in which these solutions were collected, it is evident that considerable variation exists. However, a change in the concentration of an element in the solution obtained by means of one plant root in a given period was usually accompanied by changes in concentration in the same direction although not necessarily of the same magnitude in the solutions obtained by means of the other plant roots in the same crock in that period. The more or less parallel fluctuations in the concentrations of phosphorus, potassium, and calcium in the solutions obtained by means of plant roots in the same crock during the time the solutions were being collected were not consistent with regard to the direction the changes in concentration would take.

Collecting the solutions in portions over consecutive periods rather than as a composite lot was done with the idea of distinguishing between solutions in the roots at the time the tops were removed and that forced in by air pressure later. The data obtained did not indicate any consistent differences in the concentration of phosphorus, potassium, and calcium in the first and subsequent portions collected. (Tables 5 and 7.) The potassium content increased in the latter periods, but this was not equally true of phosphorus and calcium.

Phosphorus, potassium, and calcium in the solution obtained by means of roots subjected to heating differed greatly from the concentration of these same elements in the solution obtained by means of roots not subjected to heating. Compare the concentrations of these elements recorded in tables 5 and 7 with those in tables 6 and 8. As a result of the roots and soil having been heated, the concentration of phosphorus and potassium in the solution is greatly reduced and the concentration of the calcium is much increased.

General Discussion

Since the method makes use of plant roots in the displacement of soil solubles, plants must be grown; and the nature of the method apparently assigns their growth to the more or less artificial conditions coincident with plants which are grown in a limited amount of nutrient medium in a container.

Being employed on a Purnell assistantship in which bean fertilization had been designated as the problem of investigation, it was logical for the writer to choose the bean plant as the plant to be used in this research. Furthermore, it seemed logical to use soil as the nutrient medium, since its use approximates, as nearly as possible, natural conditions concurrent with the growing of the crop.

Regardless of what may be the opinion concerning the method for determining the choice of composition and rate of fertilizer applications, the results obtained were gratifying. Increasing the concentration of the phosphorus in the soil solution or, more exactly, in a dilute acid extract of the soil, to that considered sufficient, and increasing the potassium slightly, resulted in a markedly increased growth of the bean plants. Whether or not it is due to the greatly increased concentration of phosphorus in the soil solution or to large additions of potassium, or both, cannot be discerned without further experiment.

Plants from seed sown in August produced a somewhat higher dry weight per plant than did those from seed sown later. This is probably due to the more favorable growing weather in the early fall. The smaller differences between the plants grown on the fertilized and unfertilized soils at maturity than in the early stages of growth may possibly be accounted for, partially at least, by the fact that as the plants increased in size crowding resulted, slowing up the growth of the larger plants.

The exact nature of the solution forced from the cut stem stubs of the plants by the application of air pressure is not known. There can be no doubt that it is not soil solution, unaltered; nor can it be root sap entirely, squeezed out by the pressure applied, inasmuch as the amount obtained in many cases is equivalent in weight to several times the weight of the green plant top cut from the root. While a table is not included which gives the green weight of the plant tops, the green weights were determined. Moisture content of the green plant tops ranged with small variation around 85 per cent, thus the green weight of a plant top can easily be determined from the dry weights of the plant tops given in tables 5, 6, 7, and 8. To say that the solution obtained is soil solution which is altered as a result of being forced through the plant roots is probably as complete and accurate a statement as can be made. The solution is altered more by living roots than by dead roots.

Planting was spread over a period of time in order to have the plants as near the same age as possible when the roots were used to displace solution from the soil. Two crocks were planted at a time, one containing fertilized soil and the other unfertilized soil in order to determine, also, the effect of fertilizer on plant growth. The apparatus allowed the use of only one crock at a time and since each crock usually remained in the pressure chamber 48 hours, there would have been considerable difference in the age of the plants when they were used to displace soil solution if the planting had been done all at one time. Possibly this would not have permitted comparison of the soil solution displaced through the plant root on the same basis.

Any difference in the rate of flow of solution through different plant roots in the same crock would appear at first thought to be entirely a function of the absorbing surface of the root in contact with the solution in the soil. One would, with this in mind, expect more solution to be obtained through the roots of large plants than through small ones, however, this is not always true. Evidently some structural property peculiar to the individual plant interferes with the passage of the solution into or through the roots. However, a greater dry weight of top may not necessarily be associated with a correspondingly larger root system, especially the surface area of the root system.

Differences in the rate of flow through plant roots in different crocks may be accounted for in several ways, besides differences due to the individual plant root. The moisture content of the soil seems to be a very important factor governing the rate of flow. Soil moisture contents below a certain minimum value did not allow any solution to be forced from the soil into the plant roots. This was the case with crock 2B (Table 3.) The soil had a moisture content of 13.47 per cent when the crock was removed from the pressure chamber, no solution having been obtained. Also when crock 2D (table 7) was placed in the pressure chamber no solution was obtained, due to the dryness of the soil. But when crock 2D was removed from the pressure chamber, water added to the soil, and the crock replaced in the pressure chamber after a short time was allowed for the soil to absorb the water, solutions were forced from the soil through the plant roots and collected in the receiving flasks. Other soil having a moisture content which approached the minimum made possible the collection of only small amounts of solution by means of plant roots. (See table

5, crocks 1B and 1D.) The moisture content in the soil in crock 1D is seen to have been lower than it was in crock 2B from which no solution was obtained. However, the moisture content of the soil in crock 1D was determined after the soil was removed from the chamber. Eighty ml. of solution is equivalent to the removal of 1 per cent moisture from the soil and since 112 ml. were removed through the plant roots and as there is always a small loss of weight which was not accounted for, it is evident the moisture content was well above the minimum at the time the crock was placed in the chamber. Moisture contents of around 2 per cent above the minimum seemed to be sufficient to allow a maximum rate of flow. A higher water content than this, as near as can be judged from the variable results, does not increase the rate of flow materially in the first period but does seem to reduce the rate at which the flow falls from its maximum to zero. This becomes apparent when the amounts of solution collected in the successive periods in tables 5 and 7 are compared with the amounts of solution collected in the successive periods under crock 3E, table 5.

It is evident that the rate of flow decreases rather rapidly from the beginning of the flow. This decrease, as has been seen, takes place regardless of a high soil moisture content. There seem to be only two ways to account for this-- clogging or collapsing of the root systems of the plants or the removal of solution by the roots in the immediate vicinities of the roots faster than it is replaced by the soil. Clogging, it would seem, would necessarily account for the less rapid decrease in the rate of flow coincident with a high moisture content and, apparently, both clogging and a deficient replacement of solution in the vicinities of the root surfaces may be responsible for the decrease in the rate of flow through plant roots in soil having lower moisture contents. The increased rate of flow which resulted from subjecting the soil containing the root systems of plants to heating is in accordance with the results obtained by Kramer (3) when he applied suction to the cut stem stubs of plants, some of which were in soil which had been heated from 56° to 60°C. and others in soil which was not heated previously to applying suction. Considering the protoplasm in the roots to be killed as a result of heating, the greater porosity noted in the dead roots is in keeping with the known facts regarding the effects of killing the protoplasm on the porosity of living membranes. No explanation is apparent as to why the rate of flow decreases so much faster in the case of dead roots than in the case of living roots unless it can be attributed to greater clogging of the system or the collapse of the root hairs.

Differences in the relative concentrations of phosphorus, potassium, and calcium in solutions obtained by means of living and dead roots are attributed to a property associated with the living protoplasm of the root cells often referred to as selectivity. The concentration of these elements in the solution obtained by means of dead roots, approaches the concentration in which these elements exist in the soil extract. This can be seen by comparing the concentration of these elements in the soil, table 4, with the concentration of these elements in the solutions in tables 6 and 8. Higher concentrations of phosphorus and potassium in the solutions obtained by means of living roots than in solutions obtained by means of dead roots apparently must be attributed to some power peculiar to the living protoplasm enabling it to concentrate these elements as they are taken in through the living root membranes from the less concentrated soil solution which surrounds the roots. The soil solution as a term used to designate the solution in the soil at optimum moisture conditions is not comparable to the solutions obtained by the air pressure method used here as it has never been obtained unaltered. No doubt concentrations in the soil solution as it exists in soil are different from those in a dilute acid extract of the soil, with which the comparison is made, or in solutions forced out of the soil at moisture conditions sufficiently high to make expulsion possible. This appears more probable when we consider the several forms of soil water and the surface energy connected with these forms. To what extent plant roots are able to remove these various forms of water is little known. Regardless of this, the premise that soil solubles are concentrated as the solution from the soil passes into the plant roots by some force as yet not understood does not seem illogical. Higher concentration of potassium, especially, tends to correlate with a small rate of flow. In cases where very little solution was obtained, it will be seen that the concentration of potassium is usually extremely high, a condition which accounts for the extreme variability of the concentration of this element in the solutions. This is the case, whether or not the small rate of flow is due to a low moisture content of the soil or some peculiarity of the individual plant. There seems to be no way to account for this fact at present. It would be interesting to study the effect of producing a lower rate of flow by decreasing the amount of pressure applied to the soil, on the concentration of potassium in the solution obtained. Associated with this ability to concentrate appears one of differentiation. Phosphorus and potassium were much more concentrated in the solution obtained by means of living roots. Calcium, on the contrary, was much more concentrated in the solution obtained by the dead roots.

The low concentration of phosphorus and potassium and the high concentration of calcium in the solution obtained from the soil by means of dead roots indicates that when the plant root is killed it acts merely as a filtering device for the removal of solution from the soil, the concentration of these elements in the solution removed being of about the same order as in the soil solution. The living root, on the contrary, serves as more than a filtering device being able to concentrate in the solutions to a marked degree some elements which apparently are desirable and to repress the intake of others.

Pierre and Pohlman (5) in their work with exuded plant sap from corn, sorghum, and Sudan grass plants report a similar, although a more marked concentrating of phosphorus, in the exuded plant sap over the concentration of phosphorus in the displaced soil solution as well as in the soil extract. Silica was similarly concentrated while calcium and chlorides were found in the exuded plant sap in less concentration than in the soil solution.

Better correlation of the concentration of phosphorus in the solution with applications of this element to the soil than existed between the concentration of potassium and calcium and the application of these elements is as would be expected since the addition of phosphorus to the soil increased its concentration in the soil extract to a much greater extent than did the addition of potassium and calcium increase the concentration of these elements in the soil extract.

Pohlman and Pierre (6) found in their work with exuded plant sap that applications of phosphorus to the soil resulted in an increased concentration of phosphorus in the exuded sap and that the concentration of phosphorus in the exuded sap correlated well with the water soluble phosphorus and with the available phosphorus in the soil as determined by the Truog method. The concentrations of phosphorus in exuded sap reported in their article as well as those reported in the previous article (5) are much higher than any found in the solution obtained by means of bean plant roots using the air pressure method.

Calcium, though only added to the soil in association with phosphorus, increased materially in amount in the soil extract and in the solution obtained by means of dead roots as a result of the applications of phosphorus and potassium salts to the soil. Whether this is due to the actual amount of calcium added or to the fact that the treatment may have resulted in making the calcium already present more soluble is a matter of conjecture. However, the soil treatment resulted in a slight decrease in the pH of the soil which no doubt has some effect on the solubility of calcium.

The addition of 25 ml. of ether to the soil in crock 4D, table 7, was made to see if it might result in increasing the porosity of the root membranes as did killing the roots by heating. The odor of ether was evident in the solutions forced through the roots, but the analysis of these solutions did not show any marked differences in the concentrations of phosphorus, potassium, and calcium from those in the solutions forced through roots in soil to which ether was not added, although the calcium content of the solution was higher, especially in the first period.

The use of air pressure as a means of forcing solution from the soil through plant roots appears to offer a profitable means of investigating soil-plant nutritional problems, and although the investigation using this method has not been sufficient to prove its value conclusively or to define its scope and limitations it may not be out of place to point out some of the general ways in which it appears to be applicable to investigations of this nature.

Thus far the air pressure method has only been applied to plants grown in potted soil but there appears to be no reason why it cannot be applied to plants grown in the field if the soil containing the roots is removed intact and placed in a pressure chamber. The method could be applied equally well using plants growing in sand or water cultures, and it appears that this procedure offers an unlimited opportunity for studying the effects of the various solubles common to nutrient media in regard to their individual and relative concentrations on the intake of the separate elements from solution. Toxic and other unhealthy conditions could be studied from a standpoint of solubles removed from the nutrient media by the roots.

It is possible that this method offers a means of studying the habits of plant feeding relative to the age of the plant and the kind of plant considered. Therefore, it may be possible through this method to account for the adaptability of certain plants to certain soil conditions in the different periods of growth, and of the adaptability of certain plants to certain soils and their characteristic conditions.

There is little doubt but that there is an explanation for the processes of plant feeding if only we can learn the basic principles on which these are dependent. Possibly this method through its proper application may lead to a better knowledge of the physical and chemical processes involved in the intake of solubles from nutrient media by plant roots and the effect of various environmental factors on these processes.

Summary

Air pressure applied to soil containing plant roots displaced solutions from the soil through the cut stems of the plants. Solutions were obtained by this means from soil over a range of moisture conditions, both above and below the apparent optimum value. The amount of solution collected varied greatly with soil moisture conditions and individual plant roots, but under optimum conditions a weight of solution equal to several times that of the green plant top was often obtained in from 12 to 24 hours. Solutions so obtained were clear and colorless.

Killing the plant roots by subjecting them to heat resulted in an increased rate of flow of solution from the cut stems as a result of the applied air pressure. The solution obtained in contrast to that obtained by means of living roots, although clear, was slightly yellow.

The rate of flow of the solution from cut stems decreased with time. This decrease was fastest in the case of dead roots and evident in the case of both living and dead roots regardless of the soil moisture content.

Analysis of the solutions obtained showed a wide variation in the concentration of phosphorus, potassium, and calcium among individual plant roots in the same crock, also a wide variation of the concentrations of the solutions obtained by means of plant roots in different crocks.

On the average the concentrations of phosphorus, potassium, and calcium in the solutions obtained by means of

plant roots grown in fertilized soil were higher than the concentrations of these elements in solutions obtained by means of plant roots grown in unfertilized soil, however, the only element to be consistent in this respect was phosphorus. The concentration of phosphorus in the solution obtained by means of plant roots in unfertilized soil was about one-half that obtained by means of plant roots in fertilized soil. A good deal of variability is evident, but in general the highest concentration of phosphorus in the solutions obtained by means of the roots in the unfertilized soil is below or nearly equal to the lowest concentration obtained by means of the roots in the fertilized soil.

The better correlation of phosphorus in the solution with fertilizer application that was obtained with potassium and calcium was to be expected inasmuch as the fertilizer application increased the concentration of the phosphorus in the soil extract to a much more marked degree than it did the concentration of potassium and calcium.

Solutions obtained from soil by means of living roots contained phosphorus and potassium in much greater concentrations than in the soil extract. Calcium, on the contrary, existed in the solution in less concentration than in the soil extract. (7) The concentration of these elements in the solution obtained from soil by means of dead roots approached closely the concentration of these elements in the soil extract, the concentration of phosphorus and potassium being low and the concentration of calcium high.

In consideration of the relative concentrations of phosphorus, potassium, and calcium in the solutions obtained from the soil by means of living and dead root systems and the concentrations of these elements in the soil extract, it appears that the living protoplasm in the root membrane has the power to concentrate certain desirable solubles as they are taken into the roots from the less concentrated solution surrounding the roots and to repress the intake of other elements. Solutions obtained from the soil by means of dead roots have a phosphorus, potassium, and calcium content similar to that in a dilute acid extract of the soil, indicating that the roots when dead act similarly to a mechanism for filtering off the solution contained in the soil.

The method used in this investigation for displacing solution from the soil by means of the root systems of plants grown in the soil is suggested as one which may be of value in the study of soil-plant nutritional problems.

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Plate I

1. Received 750 pounds of P_2O_5 and 1200 pounds of K_2O per 1,000,000 pounds of oven-dry soil.
2. Untreated.

Plate II

3. Received 750 pounds of P_2O_5 and 1200 pounds of K_2O per 1,000,000 pounds of oven-dry soil.
4. Untreated.

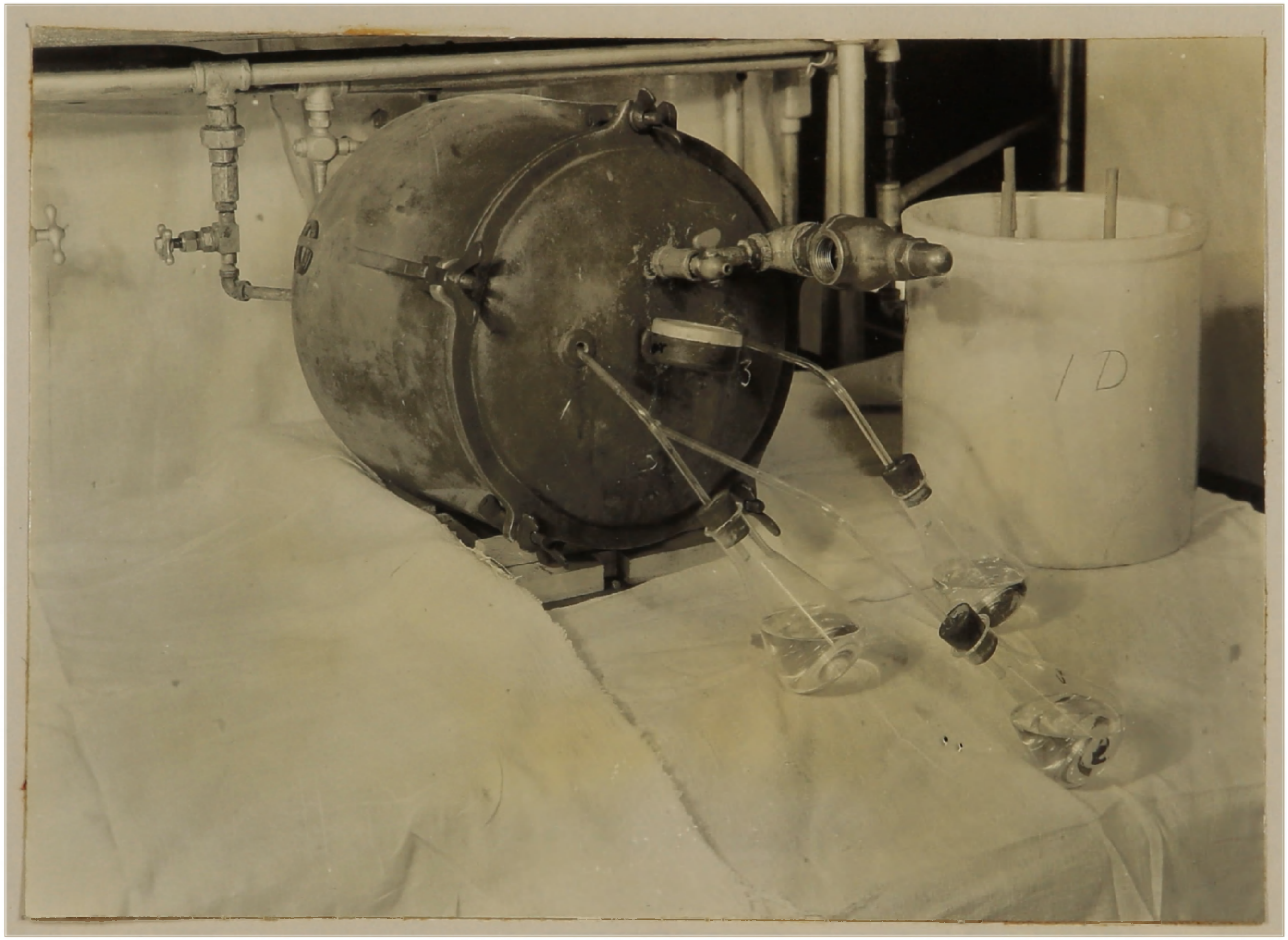
Seeded four days later than 1 and 2.

Plate III

5. Received 750 pounds of P_2O_5 and 1200 pounds of K_2O per 1,000,000 pounds of oven-dry soil.
6. Untreated.

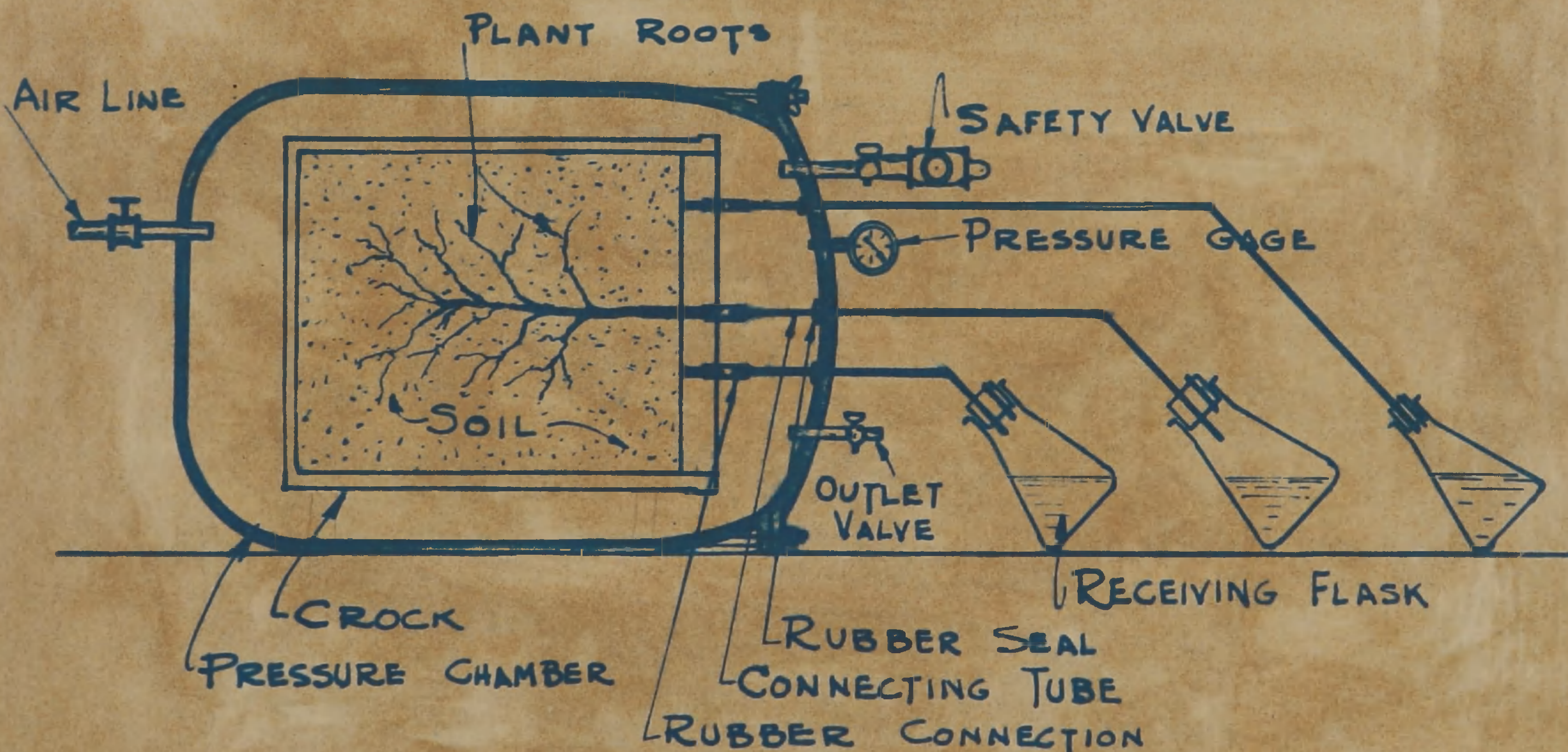
Seeded four days later than 3 and 4.

Plate IV



Apparatus

DIAGRAM 1



Cross section showing only one root system

C.W.L. 1-15-33