HYDROGEN-ION CONCENTRATION RELATIONS IN A THREE-SALT SOLUTION

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INTRODUCTION

The interest of a considerable number of workers, using water-cultures, in solving various phases of the salt-requirements of plants or allied problems, has centered itself in part on attempting to find a desirable control solution. Such a solution should be as simple as possible and defined in such a way as to be duplicated readily by other workers. It would be defined physiologically, in terms of the plant's response; chemically, by a statement of the molecular proportions of its component salts; and physically, by the magnitude of its osmotic properties. A still more complete statement would include the degree of true acidity or alkalinity existing in the solution, as determined by the hydrogen-ion concentration.

Knop's (8), Tottingham's (18), and Shive's (14) 3-salt solutions, have all been recognized as standard solutions. Little is known, however, concerning their true reaction. It was considered worth while to repeat Shive's work with the purpose of determining the part played by the hydrogen-ion concentration in the 36 different sets of salt proportions which he employed.

The publication by the Special Committee on Salt Requirements of Representative Agricultural Plants (16) resulted in our modifying our original purpose to the extent of using instead of the 36 sets of salt proportions having an osmotic concentration of 1.75 atmospheres, the 21 sets of salt proportions of type I with an osmotic concentration of 1.00 atmosphere.

The importance of the true reaction of a culture medium as affecting its biological activities is well recognized. However, only relatively few studies have been made of the direct physiological influence of reaction as measured by the hydrogen-ion concentration upon plants grown in solution-culture.

Toole and Tottingham (17) found a correlation between the weight yield of tops and the hydrogen-ion concentration of the solution—"these two values varying in opposite directions." Hoagland (5) carried out solution-culture experiments in which the concentration, composition and reaction were under control. Intensity of reaction was determined by means of the H-electrode. Salter and McIlvaine (12), more recently, have determined the effect of reaction upon the growth and germination of seeds of wheat, soybean,

corn and alfalfa. A reaction of 2.16 pH was fatal to the seedlings of all the plants, while a reaction of 7.71 pH depressed the growth of all except the corn seedlings.

MATERIALS AND METHODS

The methods used in the preparation of the culture solutions, the germination of the seed and the treatment of the plants throughout the growth period, were those recommended by the Committee on Salt Requirements of Repre-

TABLE 1

Partial volume-molecular concentrations and molecular proportions of KH_2PO_4 , $\text{Ca}(\text{NO}_3)_2$, and MgSO_4 in the 21 solutions, differing by increments of one-eighth in the salt proportions, but all having an osmotic value of approximately 1.00 atmosphere at 25°C.

SOLUTION NUMBER	MOLECULAR PROPORTIONS			PARTIAL VOLUME-MOLECULAR CONCENTRATIONS		
	KH_2PO_4	$\text{Ca}(\text{NO}_3)_2$	MgSO_4	KH_2PO_4	$\text{Ca}(\text{NO}_3)_2$	MgSO_4
IR_1S_1	1	1	6	0.0027	0.0027	0.0161
S_2	1	2	5	0.0025	0.0049	0.0123
S_3	1	3	4	0.0024	0.0071	0.0094
S_4	1	4	3	0.0022	0.0089	0.0067
S_5	1	5	2	0.0022	0.0108	0.0043
S_6	1	6	1	0.0020	0.0122	0.0020
R_2S_1	2	1	5	0.0053	0.0027	0.0132
S_2	2	2	4	0.0049	0.0049	0.0099
S_3	2	3	3	0.0047	0.0071	0.0071
S_4	2	4	2	0.0045	0.0090	0.0045
S_5	2	5	1	0.0041	0.0104	0.0021
R_3S_1	3	1	4	0.0076	0.0025	0.0101
S_2	3	2	3	0.0072	0.0048	0.0072
S_3	3	3	2	0.0068	0.0068	0.0045
S_4	3	4	1	0.0065	0.0086	0.0021
R_4S_1	4	1	3	0.0099	0.0025	0.0074
S_2	4	2	2	0.0094	0.0047	0.0047
S_3	4	3	1	0.0090	0.0068	0.0022
R_5S_1	5	1	2	0.0123	0.0024	0.0049
S_2	5	2	1	0.0118	0.0047	0.0023
R_6S_1	6	1	1	0.0145	0.0024	0.0024
Shive's.....	3.77	1.09	3.14	0.0180	0.0052	0.0150
K^*				0.0044	0.0145	0.0050
$\text{T}^\dagger$				0.0108	0.0101	0.0081

(In addition to the three salts listed above, Knop's, K, and Tottingham's, T, solutions also contain potassium nitrate in the concentrations as given.)

* K — KNO_3 = 0.0059.

† T — KNO_3 = 0.0034.

sentative Agricultural Plants (16). Table 1 gives the molecular proportions and the volume-molecular concentration of the solutions used. The relation of the 21 solutions of type I to each other may be shown readily by the use of the triangle diagram (fig. 1) described in various publications.¹ In addition to the 21 sets of salt proportions varying in increments of one-eighth of the total volume-molecular concentration, a single culture in distilled water was conducted during each of the three time-periods as well as triplicate cultures of Shive's "best," R_6C_2 , having an osmotic concentration of 1.75

FIG. 1. DIAGRAM SHOWING SOLUTION NUMBERS AND VOLUME-MOLECULAR PROPORTIONS OF THE THREE SALTS

atmospheres. For purposes of comparison, there were conducted during the latter two time-periods, duplicate cultures of Knop's solution (designated as K in all of the tables) and Tottingham's best solution (designated as T in all of the tables), each having an osmotic concentration of 1.75 atmospheres (14).

The wheat plants used in this series of experiments belonged to the Fulcaster variety. The seed was obtained from the United States Department of Agriculture. The method of germination used was that described by the Plan of the Committee on Salt Requirements, etc. (16). Seedlings of uniform

¹ For the application of the triangle diagram to studies in plant nutrition, see Schreiner and Skinner (13), Tottingham (18), Shive (14) and Johnson (7).

height were selected and threaded through holes in paraffined corks, prepared as suggested by Tottingham (18). Each culture bottle contained 6 seedlings. The jars used to contain the culture solutions were of white flint glass similar in dimensions to those used by Shive, but having a capacity of slightly more than 210 cc. Before being used, the jars and all the glassware used in the experiments was cleansed with chromic acid cleaning fluid, steamed in the autoclave, treated with alkali, followed with cleaning fluid, rinsed several times with tap water and finally four times with distilled water.

To protect the roots in the culture jars from the light and excessive absorption of heat, the jars were wrapped in paper jackets which were black inside and white outside. These jackets or wrappers were prepared as described by Shive (14).

The solutions in the culture jars were replaced at the end of each $3\frac{1}{2}$ days by fresh solutions of similar volume. Hence the solutions were renewed nine times during the growth period of 35 days. As the rate of absorption is approximately the same as the rate of transpiration in wheat (10), we have in the amount of solution absorbed a measure of the transpiration; these data are recorded elsewhere as transpiration.

Since it was impossible to control the external conditions under which the cultures were to be conducted, the alternative was to submit all the plants to these conditions in an approximately similar way. This was accomplished practically by placing the cultures on a slowly rotating table; the cultures in a given circle on the table were subjected to the same variations in the surroundings. As the solutions were always used in duplicate there were two rows of circles on the table. The outside row is designated throughout this paper as series A, and the inner row, as series B. Thus the two circles or series of cultures for a given growth period had slightly different aerial surroundings, although the different cultures of the same circle were comparable. The rotating table used in this work was 4 feet in diameter and was attached to a ball-bearing base. The table was rotated by a small $\frac{1}{4}$ -horsepower motor, belted to a reducing gear, which, in turn, was belted to the table. The table made a complete revolution every 4 minutes.

As it was appreciated that seasonal variations influence the physiological condition of the plant and hence the growth rate—the culture series were conducted in duplicate through three different time-periods of the year. It was hoped by this means to eliminate seasonal variation and to arrive, at least approximately, at the physiological properties of the solutions as determined by the chemicals alone. The first duplicate series was conducted from July 1 to August 5, 1919. The second duplicate series was conducted from November 23 to December 28, 1919; and the third from January 21 to February 25, 1920. The length of each time-period was 35 days. The period from July 1 to August 5 is characterized throughout this paper as the "first time-period," the period from November 23 to December 28, as the "second time-period," and the period from January 21 to February 25 as the "third time-period."

Determination of hydrogen-ion concentration

The initial reaction of the culture solutions was determined and also the reaction at the end of each 3½-day interval, when the solutions were renewed. The hydrogen-ion concentrations of the solutions employed in the experiments recorded here were determined colorimetrically according to the method of Clark and Lubs (1). The recommendations of these authors in the purification of the salts for the buffer mixtures, were followed carefully. Although it is desirable to check the values of the buffer mixtures against the hydrogen electrode, it is not altogether necessary when relative rather than absolute values are desired. Clark and Lubs have pointed out that the absolute accuracy of the buffer mixtures is far within the experimental error that occurs in determining differences of color value between an unknown and the standards. Gillespie and Hurst (3, 4), using buffer mixtures prepared similarly in their determinations on soils, checked the mixtures electrometrically. They confirm the values assigned by Clark and Lubs and the accuracy of the composition of the buffer mixtures, adding that "if the substances used are pure this is unnecessary."

RESULTS*Aerial conditions*

Records were obtained for: (a) air temperature; (b) relative humidity; (c) evaporating power of the air; (d) intensity of the absorbed radiant energy; and (e) duration of sunshine.

(a) Temperature changes and changes in the relative humidity were recorded on a hygro-thermograph placed near the rotating table. The maximum and minimum changes of temperature were recorded daily from the thermograph sheet and the mean temperature calculated. The data of these changes are expressed in terms of the Centigrade scale.

(b) The changes in the relative moisture-holding capacity of the air were recorded daily, and show maximum, minimum, and the mean expressed as relative humidity. The hygrograph was standardized at the beginning of each time-period by means of a sling psychrometer and the relative humidity determined by reference to Marvin's (11) psychrometric tables.

(c) The evaporating power of the air was measured by means of white and black standardized spherical porous cup atmometers [Livingston (9)]. The atmometers were weighed and cleaned weekly. Readings were corrected by multiplying by the coefficient of correction of the cup used.

(d) The intensity of the absorbed radiant energy [Livingston (9)] is expressed as the difference in the losses between the black cup and the white cup. Both white and black cups were placed on the innermost circle on the rotating table along with one of the control solutions and the culture in distilled water.

(e) The duration of sunshine expressed in hours, was obtained from the records of the Marvin Sunshine Recorder of the United States Weather Bureau Station located about 300 yards from the greenhouse in which these experiments were performed.

A summary of the aerial conditions for each time-period is given in table 2.

TABLE 2
Weekly averages of aerial conditions for the three time-periods

DATE, WEEK ENDING	ATMOMETRIC DATA (CORRECTED)			SUNSHINE*	RELATIVE HUMIDITY			TEMPERATURE		
	Loss white cup	Loss black cup	Difference		Average maximum	Average minimum	Mean	Average maximum	Average minimum	Mean
Time-period: July 1 to August 5, 1919										
	gm.	gm.	gm.	hours	per cent	per cent	per cent	°C.	°C.	°C.
July 8.....	82.6	153.6	70.9	100.6	79.5	38.1	58.8	33.2	14.0	23.6
July 15.....	113.5	130.9	17.5	49.4	80.7	37.5	59.1	29.2	11.3	20.3
July 22.....	76.0	98.2	22.2	69.5	80.8	41.1	60.9	32.0	15.1	23.5
July 29.....	109.1	130.7	21.6	68.4	79.8	43.4	61.6	32.7	14.1	23.4
August 5.....	83.4	112.7	29.3	58.1	80.1	39.2	59.6	27.0	11.5	19.3
Total.....	464.6	626.1	161.5	346.0						
Daily average.....	13.3	17.9	4.6	9.8	80.1	39.8	59.9	30.8	13.2	22.0
Time-period: November 23 to December 28, 1919										
November 30.....	96.5	106.9	10.4	8.5	75.5	56.7	66.1	22.0	14.6	18.3
December 7.....	114.5	137.7	23.3	17.7	76.5	45.1	60.8	25.3	11.6	18.5
December 14.....	112.5	123.2	10.7	14.6	76.2	50.2	63.2	23.6	13.1	18.4
December 21.....	109.1	125.0	15.8	31.3	75.2	44.0	59.6	24.8	11.8	18.3
December 28.....	109.6	120.6	11.0	16.7	70.2	37.4	53.8	28.0	12.7	20.4
Total.....	542.2	613.4	71.2	88.8						
Daily average.....	15.5	17.5	2.0	2.4	74.7	46.7	60.7	24.7	12.8	18.8
Time-period: January 21 to February 25 1920										
January 28.....	117.4	139.0	21.7	24.9	67.7	41.7	54.7	27.7	14.6	21.2
February 4.....	126.1	143.4	17.3	26.3	64.7	37.5	51.1	27.8	14.1	21.0
February 15.....	168.9	193.3	24.4	21.5	68.0	41.6	54.8	28.2	14.9	21.6
February 18.....	50.9	58.3	7.3	11.0	68.3	42.3	55.3	28.1	15.2	21.7
February 25.....	114.9	143.5	28.6	36.4	66.8	34.5	50.7	29.7	14.9	22.3
Total.....	574.1	677.5	99.4	120.1						
Daily average.....	16.5	19.4	2.8	3.3	67.1	39.5	53.3	28.3	14.7	21.5

* We are indebted to Mr. Morgan R. Sanford, of the U. S. Weather Bureau Station, for the figures from which the data of this column were computed.

Fresh weight of tops

All of the plant cut off just above the grain was considered as the top of the plant. All of the tops of a single culture were cut into approximately 2-cm. lengths and placed in a weighed test-tube. When all the tops of both series had been harvested in this manner, they were weighed immediately and the weight recorded as fresh weight of tops for each culture as a whole. Thus all of the values reported in this paper respecting any particular culture refer in every case to the entire six plants in that culture, and not to a single plant.

After the fresh weight of tops had been determined the tops were dried for 24 hours at a temperature of 78°C., after which they were dried to constant weight at 102°C. The test-tubes containing the tops were transferred from the oven to the desiccator and were allowed to cool before weighing. Each tube was stoppered with a rubber stopper of known weight while being weighed, the same rubber stopper being used for all the tubes.

The root systems of each single culture were placed together and excess liquid removed by blotting paper. They were then placed in a weighed test-tube and dried to constant weight in the same manner as described for the tops.

Dry weights of entire plants

These data are obtained as the direct summation of the actual dry weights of tops and roots. The calculated relative values are shown in table 3.

The first two columns of each time-period present the data for series A (the outer row on the rotating table) and series B (the inner row on the rotating table). The data as given in the tables are not the actual weights but the relative values of the weights expressed in terms of the weight of culture R_1S_1 . The weight of culture R_1S_1 is considered as unity and its actual weight is given in parentheses, in grams. If it is desired to know the actual weight of any other culture of the series, it may be obtained by multiplying the relative weight of that culture by the actual weight of culture R_1S_1 as given in parentheses in the same column. The average seven highest cultures of each time-period are designated by H and the five cultures giving the lowest yields are designated by L.

Essentially the cultures showing the best yields of tops are the cultures which give the maximum weights of the entire plants.

To present graphically the data of table 3 use is made of triangle diagrams (fig. 2) similar to that shown in figure 1. The culture numbers are the same as those in figure 1 except that the numbers at the intersections within the triangle have been omitted as a matter of convenience. The areas with crosses on the triangle indicate the seven cultures having the highest dry weights. The areas with small circles indicate the five cultures having the lowest dry weights. The cultures having maximum and minimum weights are indicated

by large circles in their respective areas. It should be noted here that there is within the large triangle a smaller inner triangle composed of six solutions all of which offer favorable growth conditions. This triangle may be defined by giving the culture numbers at the apices, namely: R_2S_2 , R_2S_4 , R_4S_2 . The areas of low yields are confined mainly to the lower apices of the large triangle.

TABLE 3

Dry weight of entire plants

Relative dry weights of series A and B and averages, grown at the three time-periods

SOLUTION NUMBER	TIME-PERIODS								
	July 1 to August 5, 1919			November 23 to December 28, 1919			January 21 to February 25, 1920		
	A	B	Average	A	B	Average	A	B	Average
IR ₁ S ₁	1.00L (2.10)	1.00L (1.96)	1.00L (2.03)	1.00L (0.676)	1.00L (0.658)	1.00L (0.667)	1.00L (1.53)	1.00L (1.59)	1.00L (1.56)
S ₁	1.14	1.09	1.11	1.24	1.19	1.22	1.19	1.15L	1.17L
S ₂	1.08	1.08L	1.08L	1.10	1.25	1.18	1.31	1.36H	1.34
S ₃	1.06	1.28H	1.17	1.06	1.12L	1.09L	1.04L	1.33	1.19
S ₄	1.11	1.34H	1.22	1.03	1.01L	1.02L	1.36H	1.46H	1.41H
S ₅	1.03	1.10	1.06L	0.97L	0.82L	0.90L	1.29	1.29	1.29
R ₄ S ₁	0.98L	0.97L	0.94L	0.92L	1.32	1.12	1.18L	1.10L	1.14L
S ₁	1.32H	1.16	1.24H	1.30H	1.32	1.31H	1.47H	1.35	1.41H
S ₂	1.55H	1.39H	1.47H	1.25H	1.32H	1.29H	1.18L	1.45H	1.32
S ₃	1.42H	1.03L	1.23	1.19	1.35H	1.27H	1.34	1.46H	1.40H
S ₄	1.00L	0.92L	0.96L	1.00L	1.07L	1.04L	1.45H	1.27	1.36H
R ₄ S ₁	0.98L	1.23	1.10	1.17	1.34H	1.26	1.27	1.09L	1.18
S ₂	1.24H	1.33H	1.28H	1.40H	1.26	1.33H	1.46H	1.25	1.36H
S ₃	1.36H	1.29H	1.33H	1.33H	1.19	1.26	1.53H	1.54H	1.54H
S ₄	1.15	1.24	1.19	1.12	1.16	1.14	1.30	1.35	1.33
R ₄ S ₁	1.31H	1.18	1.24H	1.21	1.28	1.25	1.28	1.06L	1.17L
S ₁	1.40H	1.39H	1.40H	1.19	1.32H	1.26	1.52H	1.38H	1.45H
S ₂	0.98L	1.29	1.13	1.02L	1.40H	1.21	1.32	1.15	1.24
R ₄ S ₁	1.20	1.29H	1.25H	1.47H	1.30	1.39H	1.02L	1.25	1.14L
S ₂	1.16	1.26	1.20	1.25H	1.34H	1.30H	1.67H	1.44H	1.56H
R ₄ S ₁	1.14	1.11	1.13	1.47H	1.38H	1.43H	1.28	1.29	1.29
Shive's.....			1.08*	1.40	1.33	1.42*	1.32	1.26	1.21*
K.....				1.06	1.28	1.17	1.48	1.55	1.52
T.....				1.11	1.26	1.19	1.82	1.59	1.71
Distilled H ₂ O.			0.16			0.05			0.23

* Average of three cultures.

FIG. 2. DRY WEIGHT OF ENTIRE PLANTS

Diagrams showing the position of the cultures having the highest seven and lowest five relative yields, dry weight of entire wheat plants, averages of series A and B; high-yield areas are designated by crosses, areas of low yield by small circles; the cultures giving maximum and minimum yields are marked by large circles in their respective areas.

Transpiration

The total relative amounts of water (grams) absorbed by cultures are shown in table 4. These data are plotted on the triangle diagrams shown in figure 3.

TABLE 4

Transpiration

Relative amounts of transpiration of plants of series A and B, grown at three different time-periods

SOLUTION NUMBER	TIME-PERIODS								
	July 1 to August 5, 1919			November 23 to December 28, 1919			January 21 to February 25, 1920		
	A	B	Average	A	B	Average	A	B	Average
IR ₁ S ₁	1.00L (878)	1.00L (908)	1.00L (893)	1.00 (422)	1.00 (411)	1.00 (416)	1.00L (728)	1.00L (680)	1.00L (704)
S ₂	1.09L	1.06	1.07L	1.09H	0.98L	1.04	1.10	1.10	1.10
S ₃	1.07L	1.03L	1.05L	0.97L	1.04	1.00	1.14H	1.18H	1.16H
S ₄	1.24H	1.16	1.20H	0.93L	0.97L	0.95L	1.08	1.11	1.10
S ₅	1.20	1.25H	1.22H	0.98	1.00	0.99	1.15H	1.27H	1.21H
S ₆	1.09	1.03	1.06L	0.89L	0.91	0.90L	1.16H	1.18H	1.17H
R ₁ S ₁	1.01L	0.96L	0.99L	0.94L	1.04	0.99	1.03L	1.06	1.05
S ₂	1.22	1.06	1.14	1.05H	1.09H	1.07H	1.11H	1.07	1.09
S ₃	1.35H	1.15H	1.25H	1.10H	1.06H	1.08H	1.05	1.12	1.09
S ₄	1.29H	1.01L	1.15	1.05H	1.12H	1.09H	1.01L	1.07	1.04L
S ₅	1.14	1.05L	1.09	0.94L	0.92	0.93L	1.11	1.05L	1.08
R ₂ S ₁	1.14	1.18H	1.16	0.99	1.12H	1.06H	1.10	0.94L	1.02L
S ₂	1.17	1.12H	1.14	1.05	1.03	1.04	1.12H	1.13H	1.13H
S ₃	1.19	1.07	1.13	1.14H	1.02	1.08H	1.09	1.15H	1.12H
S ₄	1.17	1.13	1.15	0.96	0.92L	0.94L	1.03L	1.09	1.06
R ₃ S ₁	1.23H	1.05	1.14	1.01	1.00	1.01	1.11	1.04L	1.08
S ₂	1.28H	1.14	1.21H	0.98	0.97L	0.98L	1.12H	1.22H	1.17H
S ₃	1.04L	1.15H	1.09	1.01	1.03	1.02	1.04	1.01L	1.03L
R ₄ S ₁	1.21	1.15H	1.18H	1.18H	1.07H	1.13H	0.95L		0.95L
S ₂	1.25H	1.12H	1.18H	0.99	1.05H	1.02	1.17H	1.07	1.12H
R ₅ S ₁	1.24H	1.11	1.17H	1.14H	1.09H	1.11H	1.06	1.16H	1.11
Shive's.....			0.98*			0.97*	1.03	1.05	0.98*
K.....				0.93	0.95	0.94	1.05	1.10	1.08
T.....				0.92	0.88	0.90	1.11	1.13	1.12
Distilled H ₂ O.						0.03			0.01

* Average of three cultures.

FIG. 3. TRANSPIRATION

Diagrams showing relative amounts of water lost by transpiration; areas of high transpiration indicated by crosses, areas of low transpiration indicated by small circles; the cultures showing the highest loss or lowest loss of water are designated by larger circles in their respective areas.

Water requirement

The water requirement of plants is commonly defined as the number of grams of water required to produce 1 gm. of dry weight of plant material. As calculated, it is the total number of grams of solution absorbed, divided by the dry weight of the entire plants. The data of the water-requirements are given in table 5 and figure 4.

TABLE 5
Water requirement

Showing relative amounts of water absorbed to produce 1 gm. of dry weight of plant material of series A and B and averages, conducted through three different time-periods

SOLUTION NUMBER	TIME-PERIODS								
	July 1 to August 5, 1919			November 23 to December 28, 1919			January 21 to February 25, 1920		
	A	B	Average	A	B	Average	A	B	Average
IR ₁ S ₁	1.00 (414)	1.00H (463)	1.00 (438)	1.00H (625)	1.00H (626)	1.00H (625)	1.00H (476)	1.00H (427)	1.00H (451)
S ₂	0.97	0.97	0.97	0.87	0.82	0.85	0.93H	0.96H	0.95H
S ₃	0.99	0.96	0.98	0.89	0.83	0.86	0.87	0.86	0.87
S ₄	1.18H	0.90	1.04H	0.88	0.86	0.87	1.03H	0.84	0.94
S ₅	1.10	0.93	1.02H	0.96H	0.98H	0.97H	0.84	0.87	0.86
S ₆	1.07	0.93	1.00	0.92	1.11H	1.02H	0.90H	0.92H	0.91H
R ₄ S ₁	1.13H	0.99H	1.06H	0.99H	0.79L	0.89	0.87	0.96H	0.92H
S ₂	0.94L	0.92	0.93L	0.81L	0.82	0.82L	0.75L	0.79L	0.77L
S ₃	0.88L	0.83L	0.86L	0.88	0.80L	0.84	0.89	0.77L	0.83
S ₄	0.90L	0.98H	0.94L	0.88	0.83	0.86	0.76L	0.73L	0.75L
S ₅	1.15H	1.14H	1.15H	0.94H	0.87H	0.91H	0.76L	0.83L	0.80L
R ₄ S ₁	1.17H	0.96	1.07H	0.85	0.82	0.84	0.86	0.92	0.89
S ₂	0.95L	0.84L	0.90L	0.75L	0.81	0.78L	0.77L	0.91	0.84
S ₃	0.88L	0.82L	0.85L	0.86	0.85	0.86	0.71L	0.75L	0.73L
S ₄	1.03	0.91	0.97	0.86	0.80L	0.83L	0.79	0.81L	0.80L
R ₄ S ₁	0.95L	0.89L	0.92L	0.84L	1.10H	0.97H	0.86H	0.96H	0.91H
S ₂	0.92L	0.82L	0.87L	0.82L	0.73L	0.78L	0.74L	0.88	0.81L
S ₃	1.07	0.90	0.99	0.99H	0.74L	0.87	0.79	0.88	0.84
R ₄ S ₁	1.02	0.89L	0.96	0.81L	0.83	0.82L	0.93H	†	†
S ₂	1.09	0.89L	0.99	0.79L	0.79L	0.79L	0.70L	0.74L	0.72L
R ₄ S ₁	1.10H	0.99H	1.05H	0.78L	0.78L	0.78L	0.83	0.90	0.87
Shive's.....	0.97	0.91	0.94*	0.75	0.71	0.69*	0.78	0.83	0.82*
K.....				0.88	0.75	0.82	0.71	0.72	0.72
T.....				0.83	0.70	0.77	0.61	0.71	0.66
Distilled H ₂ O.			0.63			0.67			0.74

* Average of three cultures.

† Container overturned.

FIG. 4. WATER REQUIREMENTS

Diagrams showing the position of the cultures having the highest five and lowest seven relative water-requirements, averages of series A and B, grown at three different time-periods; areas of high water-requirements are marked by crosses, areas of low water-requirements by small circles; the cultures having the maximum and minimum water-requirements are designated by large circles in their respective areas.

Hydrogen-ion concentration

Measurements of the hydrogen-ion concentration were made of the nutrient solutions at the beginning of each time-period and again at the end of each $3\frac{1}{2}$ -day interval. The data thus obtained are presented in tables 6, 7 and 8.

TABLE 6

Showing changes of pH at the end of each $3\frac{1}{2}$ -day interval, averages of series A and B, conducted from July 1 to August 5, 1919, inclusive

SOLUTION NUMBER	JULY									AUGUST	
	1	4	8	11	15	18	22	25	29	1	5
	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH
IR ₁ S ₁	5.3	5.6	6.4	6.4	7.0	6.8	7.0	6.8	6.9	6.9	6.8
S ₂	5.3	5.8	6.5	6.4	7.2	6.9	7.0	6.9	7.1	6.9	6.6
S ₃	5.2	5.8	6.4	6.4	6.9	6.8	7.1	6.8	6.9	6.9	7.1
S ₄	5.2	5.9	6.5	6.4	6.8	7.1	7.1	6.6	6.2	6.2	5.7
S ₅	5.2	5.9	6.3	6.3	6.7	6.4	6.2	6.1	5.7	6.2	5.6
S ₆	5.2	5.9	6.1	6.1	6.5	6.2	6.1	5.8	5.8	6.0	5.6
R ₃ S ₁	5.0	5.4	6.1	6.1	6.5	6.5	6.3	6.3	6.2	6.3	6.1
S ₂	4.9	5.5	6.2	6.2	6.4	6.3	6.2	6.1	6.1	6.6	5.8
S ₃	4.9	5.5	6.1	6.1	6.2	6.1	5.8	5.7	5.5	6.2	5.1
S ₄	4.9	5.4	6.1	6.0	6.0	5.9	5.6	5.6	5.4	5.8	4.9
S ₅	4.9	5.6	5.9	5.9	5.8	5.8	5.4	5.5	5.3	5.5	5.2
R ₃ S ₁	4.9	5.3	6.1	6.1	6.2	6.3	6.1	6.1	5.6	6.4	5.7
S ₂	4.9	5.5	6.1	6.1	6.1	6.0	5.7	5.7	5.5	5.8	5.3
S ₃	4.9	5.3	5.9	5.9	5.8	5.5	5.4	5.5	5.3	5.6	5.0
S ₄	4.9	5.4	5.7	5.7	5.6	5.4	5.3	5.2	5.0	5.3	4.9
R ₄ S ₁	4.9	5.3	5.9	6.0	6.1	6.1	5.8	5.9	5.9	6.2	5.7
S ₂	4.9	5.2	5.9	5.9	5.9	5.8	5.4	5.4	5.3	5.5	5.0
S ₃	4.9	5.3	5.7	5.5	5.5	5.3	5.2	5.1	5.0	5.3	4.9
R ₅ S ₁	4.7	5.3	5.9	5.9	5.9	6.0	5.7	5.7	5.5	5.9	5.4
S ₂	4.7	5.2	5.7	5.6	5.5	5.5	5.2	5.2	5.0	5.4	4.7
R ₆ S ₁	4.9	5.2	5.9	5.9	5.8	5.9	5.6	5.5	5.4	5.6	5.2
Shive's*.....	4.6†	4.9	5.4	5.5	5.5	5.7	5.5	5.5	5.4	5.5	5.3
K.....											
T.....											
Distilled H ₂ O.....	5.8	6.4	7.0	6.3	6.3	6.7	6.3	6.3	7.8	7.1	6.2

* Averages of 3 cultures.

† Shive (15) reports the value, pH = 4.7; the difference between our values has little significance, since it is within the limit of experimental error for the colorimetric method

It will be observed that the difference between the initial and final pH (fig. 5) for a given $3\frac{1}{2}$ -day interval is greater when the nutrient solution contains only small amounts of the phosphate radical. Thus, the solutions along the basal

line of the triangle show the greatest changes in pH due, apparently, to the fact that they are insufficiently buffered by the lesser quantities of KH_2PO_4 . While the solutions near or at the upper apex of the triangle are more highly

TABLE 7

Showing changes of pH at the end of each 3½-day interval, averages of series A and B, conducted from November 23 to December 28, 1919, inclusive

SOLUTION NUMBER	NOVEMBER			DECEMBER							
	23	26	30	3	7	10	14	17	21	24	28
	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH
IR ₁ S ₁	5.3	5.5	5.6	6.1	6.5	6.0	6.3	6.1	5.8	5.4	5.4
S ₂	5.3	5.4	5.6	6.1	6.7	6.1	6.4	6.1	6.1	6.0	5.5
S ₃	5.2	5.4	5.5	6.1	6.6	6.2	6.5	6.2	6.1	5.4	5.2
S ₄	5.2	5.5	5.6	6.1	6.7	6.1	6.5	6.1	6.0	5.8	5.4
S ₅	5.2	5.5	5.6	6.2	6.6	6.2	6.4	6.1	6.0	5.6	5.6
S ₆	5.2	5.5	5.7	6.3	6.3	6.1	6.1	6.0	6.0	5.9	5.7
R ₂ S ₁	5.0	5.2	5.4	5.7	6.1	5.7	6.0	5.7	5.6	5.4	5.0
S ₂	4.9	5.3	5.3	5.8	6.3	5.9	6.1	6.0	6.0	5.8	5.3
S ₃	4.9	5.3	5.4	5.9	6.3	5.9	6.1	6.0	6.0	5.7	5.3
S ₄	4.9	5.3	5.4	5.9	6.3	5.9	6.1	6.0	5.9	5.7	5.4
S ₅	4.9	5.3	5.4	5.9	6.2	6.0	5.9	5.9	5.8	5.6	5.5
R ₃ S ₁	4.9	5.1	5.3	5.8	6.1	5.6	5.9	5.8	5.7	5.5	5.1
S ₂	4.9	5.1	5.3	5.5	6.1	5.6	6.0	5.9	5.8	5.7	5.1
S ₃	4.9	5.2	5.3	5.7	6.1	5.8	6.0	5.9	5.7	5.5	5.0
S ₄	4.9	5.2	5.3	5.6	6.1	5.7	5.7	5.7	5.6	5.5	5.4
R ₄ S ₁	4.9	5.0	5.2	5.5	5.9	5.5	5.9	5.9	5.6	5.5	4.9
S ₂	4.9	5.0	5.2	5.5	5.9	5.6	5.9	5.6	5.6	5.5	4.9
S ₃	4.9	5.0	5.2	5.5	5.9	5.6	5.7	5.7	5.5	5.5	5.3
R ₅ S ₁	4.7	4.9	5.1	5.5	5.9	5.5	5.8	5.7	5.6	5.5	4.8
S ₂	4.7	4.9	5.1	5.5	6.0	5.6	5.9	5.6	5.5	5.4	4.9
R ₆ S ₁	4.9	4.8	5.1	5.5	5.9	5.5	5.8	5.6	5.6	5.5	4.9
Shive's*.....	4.6†	4.6	4.7	5.2	5.5	5.2	5.5	5.4	5.3	5.4	4.7
K.....	5.1	5.1	5.3	5.9	6.1	5.8	5.9	6.3	6.2	5.5	5.4
T.....	4.9	4.6	5.1	5.4	5.8	5.4	5.7	6.1	5.9	5.1	4.8
Distilled H ₂ O.....	5.8	6.3	5.6	6.3	5.9	6.5	6.3	6.3	5.7	7.4	6.2

* Averages of 3 cultures.

† Shive (15) reports the value, pH = 4.7; the difference between our values has little significance, since it is within the limit of the experimental error for the colorimetric method.

buffered because of the increased quantity of the phosphate salt present, they are also more highly acid (the pH is less), because of the dissociation of the hydrogen-ion in this salt. These observations are in harmony with Salter

and McIlvaine. The reaction of all the solutions in which plants had been grown was toward the neutral point ($\text{pH} = 7$).²

TABLE 8

Showing changes of pH at the end of each 3½-day interval, averages of series A and B, conducted from January 21 to February 25, 1920, inclusive

SOLUTION NUMBER	JANUARY			FEBRUARY							
	21	25	28	1	4	8	11	15	18	22	25
	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH
IR ₁ S ₁	5.3	5.6	6.2	6.6	6.7	6.5	6.7	7.0	6.7	6.9	6.4
S ₂	5.3	5.7	6.2	6.6	6.8	6.6	6.7	7.1	6.9	7.1	6.8
S ₃	5.2	5.4	5.9	6.2	6.4	6.2	6.3	7.3	6.9	7.5	7.2
S ₄	5.2	5.6	6.1	6.4	6.7	6.6	6.7	7.1	6.7	7.4	6.8
S ₅	5.2	5.8	6.3	6.6	6.5	6.2	6.3	6.6	6.3	7.2	6.8
S ₆	5.2	5.7	6.3	6.5	6.3	6.1	6.4	6.6	6.4	7.4	6.5
R ₃ S ₁	5.0	5.3	5.9	6.2	6.4	6.3	6.5	6.6	6.4	6.7	6.7
S ₂	4.9	5.3	5.9	6.3	6.5	6.3	6.4	6.7	6.5	7.0	6.3
S ₃	4.9	5.4	5.9	6.2	6.4	6.2	6.3	6.5	6.3	6.4	6.3
S ₄	4.9	5.4	5.9	6.1	6.2	6.0	6.1	6.3	6.1	6.3	6.2
S ₅	4.9	5.4	5.9	6.1	6.0	5.6	5.9	6.0	5.9	5.8	6.0
R ₃ S ₁	4.9	5.1	5.7	6.0	6.1	6.0	6.3	6.5	6.4	6.2	6.2
S ₂	4.9	5.3	5.8	6.0	6.2	6.1	6.3	6.4	6.2	6.1	6.2
S ₃	4.9	5.3	5.7	6.0	6.1	5.8	6.0	6.1	5.9	5.8	5.7
S ₄	4.9	5.2	5.6	5.9	5.9	5.4	5.6	5.6	5.4	5.3	5.3
R ₄ S ₁	4.9	5.1	5.6	5.9	6.1	5.9	6.2	6.4	6.3	6.0	6.0
S ₂	4.9	5.1	5.6	6.0	6.1	5.9	6.0	6.1	5.9	5.5	5.6
S ₃	4.9	5.2	5.6	5.8	5.8	5.3	5.4	5.4	5.5	5.0	5.3
R ₅ S ₁	4.7	5.0	5.4	5.8	6.0	5.8	6.1	6.2	6.1	5.8	5.7
S ₂	4.7	5.1	5.6	5.8	5.8	5.5	5.6	5.5	5.5	5.3	5.5
R ₆ S ₁	4.9	4.9	5.4	5.9	6.0	5.7	6.1	6.0	5.9	5.6	6.0
Shive's*.....	4.6†	4.8	5.1	5.4	5.6	5.4	5.6	5.6	5.5	5.5	5.5
K.....	5.1	5.4	5.9	6.1	6.0	5.8	6.1	6.3	6.1	6.0	5.9
T.....	4.9	5.0	5.4	5.8	5.7	5.5	5.5	5.6	5.4	5.1	5.3
Distilled H ₂ O.....	5.8	6.6	6.3	6.1	5.9	4.7	5.0	5.1	5.0	5.6	5.5

* Averages of 3 cultures.

† Shive (15) reports the value $\text{pH} = 4.7$; the difference between our values has little significance, since it is within the limit of the experimental error for the colorimetric method.

² This in general substantiates the observations of Itano (6), Hoagland (5), Salter and McIlvaine (12), and Duggar (2).

FIG. 5. DIAGRAMS SHOWING THE RELATION BETWEEN THE INITIAL pH VALUES, AND FINAL pH VALUES, AVERAGES OF SERIES A AND B, FOR THE THREE TIME-PERIODS

Condition of plants

The roots of the cultures throughout the three time-periods were fairly uniform. Roots of R_1S_1 , R_1S_2 , R_1S_3 were shorter, often of a brownish color, and had fewer secondary rootlets.

No very significant differences in size or condition of tops were noticeable until near the end of the growth period. At that time there were noticeable differences in height as well as apparent differences in vigor of plants; these differences were closely connected with the dry weights of cultures. The growth of the cultures during the second time-period was poor, due first of all to poor seasonal light conditions and second, to mildew infection.

Cultures of all three time-periods were infected to a greater or less extent with mildew but this infection never became a limiting factor except possibly in the cultures of the second time-period.

So-called magnesium or tip injury appeared in cultures R_1S_1 , R_2S_1 , R_3S_1 , R_4S_1 , R_5S_1 , and R_6S_1 . The greatest amount of this injury occurred in culture R_1S_1 and the injury declined progressively toward the upper apex.

It may be that the yellowing of the leaves of potato plants grown in sand-cultures as reported by Johnston (7) is due in part at least to an excess of magnesium, for his data show that the plants having the greatest approximate percentage of yellow leaf-area are the plants grown in solutions R_1S_1 , R_2S_1 , R_3S_1 , etc. However, he makes no mention of the correlation.

DISCUSSION

Comparison of various weight data

The cultures of the first time-period having maximum and minimum yields, R_2S_3 and R_3S_1 , respectively, show the same relative transpiring powers. During the second time-period there is agreement between the cultures showing minimum transpiration; though the culture having the highest transpiring power, R_6S_1 , does not have the maximum weight. There is good general agreement between transpiration quantities and yield of plants during the third time-period. As an indicator of relative physiological activity, including growth, transpiration quantities are valuable; but their value rests chiefly in the corroborative evidence which they offer in support of other data. Our data as to the general relation between growth and transpiration support Shive's (14) conclusion that "water transpired appears to be as good a criterion as is the final dry weight, for judging the comparative growth obtained in the different solutions." The authors, however, have not found any direct correlation between high root-yields and low transpiration as he suggests.

Water-requirement and dry weight

It was noticed at the time the water-requirement data were calculated, that the cultures having the lowest water-requirements were the cultures that gave the total maximum yields of plants. A comparison of the triangles of the

three time-periods will show how consistently this relation held true. The areas showing high yields of plants correspond with the areas showing low water-requirements. The relation between transpiration and water-requirements is in general the same as for yield of plants and water-requirements; cultures having a high water-requirement have low transpiring powers and the minimum dry-weight yields.

Relation of ion ratios to yields

The high-yield areas (fig. 2) tend to concentrate themselves in the central portion of the triangle diagrams, whereas the maximum and minimum ion ratio values are grouped along the marginal lines of the triangles, leaving an unoccupied space in the center. Reference to table 9 giving the actual values

TABLE 9
Cation ratios—Values of the three cation ratios and the pH values of the nutrient solutions used in the experiments reported herein

SOLUTION NUMBER	Mg/Ca	Mg/K	Ca/K	pH*
IR ₁ S ₁	5.96H	5.96H	1.00	5.3
S ₂	2.51H	4.92H	1.96H	5.3
S ₃	1.32	3.91H	2.95H	5.2
S ₄	0.75	3.04H	4.04H	5.2
S ₅	0.39L	1.95H	4.90H	5.2
S ₆	0.16L	1.00H	6.10H	5.2
R ₁ S ₁	4.88H	2.49H	0.51	5.0
S ₂	2.02H	2.02H	1.00	4.9
S ₃	1.00	1.51	1.51	4.9
S ₄	0.50	1.00	2.00H	4.9
S ₅	0.20L	0.51	2.53H	4.9
R ₂ S ₁	4.04H	1.32	0.32L	4.9
S ₂	1.50	1.00	0.66	4.9
S ₃	0.66	0.66	1.00	4.9
S ₄	0.24L	0.32L	1.32	4.9
R ₃ S ₁	2.96H	0.74	0.25L	4.9
S ₂	1.00	0.50	0.50	4.9
S ₃	0.32L	0.24L	0.75	4.9
R ₄ S ₁	2.04H	0.39L	0.19L	4.7
S ₂	0.48	0.19L	0.39L	4.7
R ₅ S ₁	1.00	0.16L	0.16L	4.9
Shive's.....	2.88	0.83	0.29	4.6

* Note: After this article had gone to press, McCall and Hagg reported (Soil Science, v, 10, p. 481-485) the pH values of all 6 types of solutions. It should be noted that their values for type I vary from ours by an approximate difference of 0.5 pH.

FIG. 6. DIAGRAMS TO SHOW THE RELATION OF THE DRY WEIGHT OF THE ENTIRE PLANTS OF SERIES A AND B, TO THEIR POSITION ON THE TRIANGLE DIAGRAM, AND THE CLOSE AGREEMENT BETWEEN THE TWO SERIES, A AND B, DURING EACH TIME-PERIOD

of these ratios will show that the solutions in this unoccupied central portion of the triangles have ratios of intermediate value with a tendency toward unity. Attention has been called to the fact that there seems to be an inner triangle, all the cultures of which, by reason of their salt balance, seem to offer optimum growth conditions. This inner triangle has as its apices cultures R_2S_2 , R_4S_2 , and R_4S_4 . These solutions are all characterized by ion ratios which tend to become unity in respect to each other. The molecular proportions of the three salts of this inner triangle show this same relation thus:

Hydrogen-ion concentration and plant yields

A comparison of the hydrogen-ion concentrations of the solutions (fig. 5 and 6) giving high and low yields shows that the pH does not at least become a limiting factor, in spite of the rather high initial acidity of the solutions in the upper portion of the triangle. Solutions which are poorly buffered because of the small quantity of phosphate present and hence show maximum changes of pH during the $3\frac{1}{2}$ -day interval, are the solutions which support minimum-weight yields. It is doubtful in this instance that it is the absence of sufficient buffer material that results in poor-weight yields; rather it may be the absence of sufficient proper nutrient salts.

Hydrogen-ion concentration—transpiration

Figures 7, 8 and 9 show the amounts of solution absorbed during each $3\frac{1}{2}$ -day interval for each time-period. The number of grams of solution absorbed are plotted as ordinates, and the days on which the solutions were renewed, as abscissae. The pH of the solutions at the end of each $3\frac{1}{2}$ -day interval is plotted on the same diagrams, with the pH values as ordinates. Cultures R_1S_1 , R_3S_3 and R_4S_1 are thus plotted.

The alteration in the reaction of the culture solutions in which the wheat plants had been grown increases with the age of the plants, for the first few weeks of growth. The alteration is due probably to either one of two things, the excessive withdrawal of certain ions from the solution, or the excretion of ions by the plants. The fact that for a time the increase in alkalinity of

* These figures refer to the molecular proportions of the three component salts (table 1), but for the sake of emphasis, the order of the arrangement of the components has been varied in some instances.

FIG. 7. DIAGRAMS SHOWING THE RELATION BETWEEN THE CHANGE OF pH AND THE GRAMS OF SOLUTION ABSORBED BY R_1S_1 , AVERAGES OF SERIES A AND B, AS MEASURED AT THE END OF EACH $3\frac{1}{2}$ -DAY INTERVAL

FIG. 8. DIAGRAM SHOWING THE RELATION BETWEEN THE CHANGE OF pH AND THE NUMBER OF GRAMS OF SOLUTION ABSORBED BY R_4S_4 , AVERAGES OF SERIES A AND B, AS MEASURED AT THE END OF EACH $3\frac{1}{2}$ -DAY INTERVAL

FIG. 9. DIAGRAM SHOWING THE RELATION BETWEEN THE CHANGE OF pH AND THE NUMBER OF GRAMS OF SOLUTION ABSORBED BY R_6Si_1 , AVERAGES OF SERIES A AND B, AS MEASURED AT THE END OF EACH $3\frac{1}{2}$ -DAY INTERVAL

the solutions tends to parallel the course of absorption would suggest that the change of pH may be due in part to the absorption of certain ions from the solutions.

The figures indicate that the ionic absorption, if such it is, apparently takes place in relatively the same manner in all of the solutions. A quantitative analysis of the solutions would in a large measure indicate whether or not the change in reaction was due in any way to the absorption of certain of the ions.

SUMMARY

1. Wheat plants were grown 5 weeks in duplicate series, during three different time-periods, in water-culture solutions composed of the three main salts varied in increments of $\frac{1}{8}$, all having an osmotic value of 1 atmosphere. The salts used were: KH_2PO_4 , MgSO_4 and $\text{Ca}(\text{NO}_3)_2$, together with a "trace" of FePO_4 .

2. Record was taken of the aerial conditions such as temperature, relative humidity, evaporating power of the air, effective radio-intensity, and daily hours of sunshine. The cultures grown during the first time-period, July 1 to August 5, were conducted under the most favorable environmental conditions, as stated in terms of total hours of sunshine and effective radio-intensity. The environmental conditions of the cultures grown during the third time-period, January 21 to February 25, were less favorable, when judged by the same criteria. The conditions under which the cultures of the second time-period, November 23 to December 28, were grown, were least favorable toward promoting maximum growth. All the plant-measurement data were shown to correspond to these seasonal variations.

3. No culture gave consistently maximum yields of tops, roots, or total dry weight throughout the three time-periods. Cultures R_3S_2 , R_2S_3 , R_2S_4 , R_3S_3 , R_3S_4 , and R_4S_2 were usually included among the seven maximum cultures of each period. There was good agreement, however, between duplicate series of a given time-period.

4. Comparison of the water-requirements and the dry-weight yields show that the cultures having the maximum dry weights have the minimum water-requirements.

5. Data are presented which show that the hydrogen-ion concentration of solutions in which wheat has been grown tends to become less than the initial reaction of the solution. Thus all cultures were acid at the beginning and tended to become neutral. No data were obtained which explain the changes of pH in the solution. It was suggested that these differences may have been due to the selective absorption by the plant of certain ions from the solution.

6. There was no apparent direct correlation between the yield of the plants and the pH or the change of pH. Growth was generally less in those cultures (R_1S_1 and R_1S_6) which were poorly buffered, because of the insufficient quantity

of monopotassium phosphate present. They do show that degrees of acidity which have proven inhibitive to such microorganisms as *Actinomyces* and *Azotobacter* have no observable effect upon the growth of the wheat plant.

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A. Cultures of series A and B on rotating table at the end of the first time-period, July 1 to August 5, 1919.

B. Cultures of series A and B on rotating table at the end of the second time-period, November 23 to December 28, 1919.

C. Cultures of series A and B on rotating table at the end of the third time-period, January 21 to February 25, 1920.

D. Cultures of series A and B on rotating table at the beginning of the second time-period, November 24, 1919. The black and white porous cup atmometers may be seen just above the tops of the cultures.

E. Showing the relative position of the thermohygrograph, on top of the two white supports, to the cultures on the rotating table, at the right.