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ROOT DEVELOPMENT AND SOIL MOISTURE

JOHN P. CONRAD* and F. J. VEIHMEYER†

INTRODUCTION

The root development of plants and its relation to the amount and availability of soil moisture have been the subject of much study and speculation. Observations in California have yielded results which differ from conclusions drawn from some studies of similar nature elsewhere. Climatic conditions prevalent in California afford excellent opportunity for such study because the effective rainfall occurs almost entirely during the winter months and because soil-moisture conditions during a summer growing season are, in consequence, largely under control.

Where the water table is far from the surface, experiments in California[14] have shown that the capillary movement of moisture is too slow to meet the needs of growing plants. Naturally then, roots must extend into a body of soil to utilize its moisture. Under these conditions, furthermore, direct evaporation causes material loss of moisture from only shallow depths of the soil, and moisture below 8 inches is lost by evaporation at an extremely slow rate, while plant transpiration accounts for the greater part of the water loss below this depth. It was, therefore, suggested[14] that the results of soil-moisture determinations, if made on adequate samples properly timed, would indicate the presence or absence of roots of plants growing on the soil. With soil previously wet, relatively dry soil below the surface layer would indicate the presence of roots. This paper presents some data in support of this suggestion. While it has to do with the development of the roots of grain-sorghum plants in relation to soil moisture, it is thought that the results obtained justify wider application.

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SOIL MOISTURE DETERMINATIONS

Because of variations in soil texture between the different samples, Briggs and McLane[5] and Alway, McDole, and Trumbull[2] have pointed out the need of expressing soil moisture as a ratio. The former investigators used the moisture equivalent, while the latter took the hygroscopic coefficient as the basis of comparison. Puri[12] has shown, however, that the hygroscopic coefficient cannot be determined satisfactorily, and Linford[10] has further demonstrated that there cannot be equilibrium between relatively dry soil and saturated vapor, as many investigators have assumed. The hygroscopic coefficient, which has been considered an equilibrium point by some workers, is, therefore, of doubtful value for use in evaluating the moisture content of soils. On the other hand, moisture-equivalent determinations, when made in accordance with an exact procedure, have proved[16] to give reproducible results and may be used with confidence. For these reasons, the exclusive use of the moisture equivalent as a measure of the relative moisture retentiveness of soils strongly suggests itself.

Sedimentary soils are generally stratified, with the different layers often varying widely in texture from one another. Sand, gravel, and other variations in soil texture may occur as isolated pockets in any one layer, making the soil still more variable. The surfaces between strata are, furthermore, often irregular. In samples taken under such conditions, the soil from one hole at a given depth may vary in texture from that secured from an adjacent hole. For these reasons, a moisture-equivalent determination has been made on each sample taken in this study. This is a very desirable procedure to follow in all field studies directly bearing on the relation of soil moisture to plant growth, and may be necessary for the proper interpretation of results when relatively few samples are taken.

A typical case is illustrated in the results obtained in an intensive soil-moisture study at Davis, California. The soil of the particular area which was being investigated is Yolo silt loam. An intensive soil survey made according to standard practice had not indicated that this soil was exceptionally non-uniform to a depth of 6 feet. On January 17, 1927, samples by one-foot increments to a depth of 9 feet were taken with a specially designed soil tube[15] from 6 holes, five of which were located within a circle 12 inches in diameter, the sixth being at the center of the circle. The holes were, therefore, only about 4 inches apart, and were as close as possible to each other without interfering. Moisture determinations were made in the usual way, and moisture equivalents were run on each sample by the procedure described in a citation previously mentioned.[16] The ratio of the moisture content to the moisture equivalent of each sample was calculated and expressed in percentage. For the sake of convenience, this ratio will be referred to as 'relative wetness'; in the same way Alway, McDole, and Trumbull[2] have suggested the term 'relative moistness' for the ratio of moisture content to the hygroscopic coefficient. The moisture percentage, moisture equivalent, and relative wetness of the samples are given in table 1.

TABLE 1

MOISTURE CONTENTS,* MOISTURE EQUIVALENTS, AND RELATIVE WETNESS OF SAMPLES OF SILT LOAM SOIL TAKEN WITHIN A CIRCLE ONE FOOT IN DIAMETER. DISTANCE BETWEEN HOLES ABOUT 4 INCHES. JANUARY 17, 1927, DAVIS, CALIFORNIA

Hole	Depth of soil sampled, in feet									
	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	Mean
					MOISTURE CONTENT					
1	25.3	23.6	15.6	11.0	11.0	9.3	11.6	13.7	16.9	15.3
2	25.9	23.9	16.8	11.2	9.9	9.4	11.7	14.4	16.4	15.9
3	24.6	23.2	17.2	12.0	10.0	9.0	11.2	15.2	15.3	15.3
4	25.8	23.8	17.4	11.3	9.8	9.1	12.2	15.1	14.7	15.6
5	25.4	23.3	13.5	10.9	9.4	9.0	13.8	13.1	14.1	14.4
6	25.6	23.1	19.5	11.8	10.4	9.2	11.8	13.9	15.9	15.7
Mean	25.4	23.5	16.7	11.4	10.1	9.2	12.0	14.2	15.6	15.3
Standard deviation	0.47	0.33	2.00	0.44	0.55	0.02	0.29	0.83	1.05	....
Coefficient of variability	1.9	1.4	12.0	3.9	5.4	0.2	2.4	5.8	6.9	....
					MOISTURE EQUIVALENT					
1	24.0	22.6	19.7	18.5	18.4	14.0	16.7	21.0	24.3	19.9
2	24.5	21.4	18.6	17.8	15.4	13.0	15.8	20.3	22.4	18.8
3	23.6	21.8	18.2	18.6	14.7	12.1	17.2	22.2	20.2	18.7
4	24.1	23.0	18.1	16.9	13.7	11.6	15.6	22.6	20.2	18.4
5	23.6	22.6	14.9	16.3	12.5	11.7	17.8	22.3	18.7	17.8
6	24.1	21.0	21.0	17.9	16 2	13.0	16.5	19.8	20.6	18.9
Mean	24.0	22.1	18.4	17.7	15.1	12.6	16.6	21.4	21.1	18.8
Standard deviation	0.34	0.79	2.06	0.91	2.04	0.93	0.83	1.15	1.98	....
Coefficient of variability	1.4	3.6	11.2	5.1	12.7	7.4	5.0	5.4	9.4	....
					RELATIVE WETNESS					
1	106	104	79	60	60	66	70	65	70	76
2	106	112	90	63	64	72	74	71	73	81
3	104	106	95	64	68	74	65	68	76	80
4	107	104	96	67	71	78	78	67	73	82
5	108	103	91	67	75	77	77	59	75	81
6	106	110	93	66	64	71	71	70	77	81
Mean	106	106	91	64	67	73	72	66	74	80
Standard deviation	1.3	3.6	5.8	2.8	5.4	4.4	4.9	4.3	2.5	....
Coefficient of variability	1.3	3.4	9.4	4.4	8.1	6.0	6.8	6.4	3.4	....

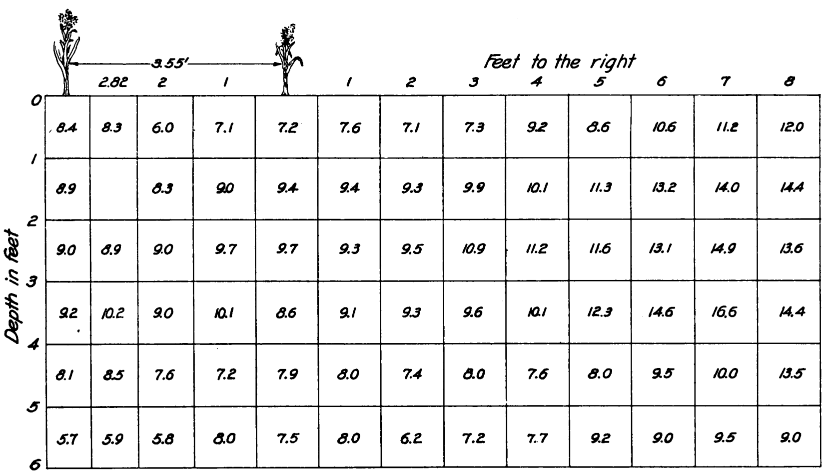
* Moisture contents and moisture equivalents are percentages on a dry-weight basis. Relative wetness is the ratio of moisture content to moisture equivalent expressed as percentage.

The variations in moisture equivalents are especially important, for they reflect the variations in soil texture at the same depth. These samples were only a few inches apart. In fact, they were as close as it would be convenient to take them to the depth indicated. With a greater distance between holes, a greater difference in soil texture might be expected. While the moisture content of the soil in the depts 0 to 1, 1 to 2, and 5 to 6 feet in the 6 holes did not vary any more than might be expected, the variations in the other depths are surprisingly great when the closeness of sampling is considered. It has been shown elsewhere(14)(18) that the moisture equivalent of the soils of the Yolo series at Davis is a fair measure of the maximum field capacity of these soils. Although the difficulties in determining the moisture contents and moisture equivalents make it seem probable that such work may sometimes involve a percentage of error of as much as 10, in the ratios of moisture content to moisture equivalent the soil within the 1-foot circle tested was obviously wet to not quite 3 feet in depth. The soil was sampled the day after heavy rains had ceased. The figure 79 for the relative wetness in the third foot of hole 1 (table 1) would indicate that the rain had not penetrated so deeply there as in the rest of the area.

A procedure sometimes used in soil-moisture field studies bearing on plant growth involves the determination of moisture equivalents on but a very small proportion of the samples taken. From experience gained in this and other studies, the writers feel that in soil that is not unusually uniform, such a procedure may lead to erroneous conclusions unless the differences due to variation in texture can be minimized by taking a considerable number of samples for each condition investigated.

SOIL-MOISTURE CONDITIONS AFTER MATURITY OF GRAIN SORGHUM

The methods of sampling and expressing the results as outlined above were used in a field study of the relation of soil moisture to root development. Several strips of White Yolo, a grain sorghum, were planted during the first week in May, 1923, across a field which had been clean-cultivated the previous season, leaving strips of unplanted land. Because of the absence of competition on one side, the outside row next to the unplanted, clean-cultivated land grew much better than the inside rows. Soil samples were taken with the soil tube previously mentioned, on September 18 and 19, 1923, in one-foot increments to a total depth of 6 feet. Thirteen holes were made, each approximately one foot apart, beginning at the second row of sorghum from the edge of the unplanted land, and continuing across the first row and 8 feet into the unplanted land on a line at right angles to the row. Moisture determinations were made on these samples in the usual way, and moisture equivalents were run in duplicate on each of the oven-dried samples. The mean of the two moisture-equivalent determinations was used to calculate the relative wetness of each sample.



Depth in feet	(plant)	2.82	2	1	(plant)	1	2	3	4	5	6	7	8
0–1	8.4	8.3	6.0	7.1	7.2	7.6	7.1	7.3	9.2	8.6	10.6	11.2	12.0
1–2	8.9		8.3	9.0	9.4	9.4	9.3	9.9	10.1	11.3	13.2	14.0	14.4
2–3	9.0	8.9	9.0	9.7	9.7	9.3	9.5	10.9	11.2	11.6	13.1	14.9	13.6
3–4	9.2	10.2	9.0	10.1	8.6	9.1	9.3	9.6	10.1	12.3	14.6	16.6	14.4
4–5	8.1	8.5	7.6	7.2	7.9	8.0	7.4	8.0	7.6	8.0	9.5	10.0	13.5
5–6	5.7	5.9	5.8	8.0	7.5	8.0	6.2	7.2	7.7	9.2	9.0	9.5	9.0

Fig. 1. Moisture contents of soil after sorghum plants have matured. The soil to the right of plant rows was kept free of all vegetation.

Figure 1 shows the percentages of moisture found. These, and all other moisture data presented in this paper, are calculated on the basis of weight of oven-dried soil. The moisture percentages, alone, convey no accurate idea as to which portions of the soil mass were wet and which were dry. With their respective moisture equivalents, however, these figures gain interest. There is close agreement between the moisture content corresponding to the moisture equivalent and the maximum field capacity of the Yolo soils at Davis; and indeed the work of Alway and McDole,[1] and Burr and Russell[7] indicates that this agreement is also fairly close in other localities. The moisture equivalents of the samples obtained in this test may therefore be taken to represent the amount of moisture in the soil after the last rain in the spring and after downward movement had practically ceased.

Figure 2 gives the relative wetness of the respective samples of figure 1, which may be taken to represent the percentage of the initial moisture remaining after the sorghum plants had matured. The plants at this time were not permanently wilted. It is interesting to note that 54 per cent represents the theoretical wilting coefficient as suggested by Briggs and Shantz[6] when the moisture equivalent is used as the indirect measure of the wilting coefficient. Although it has been found[19] recently that a common factor to calculate the

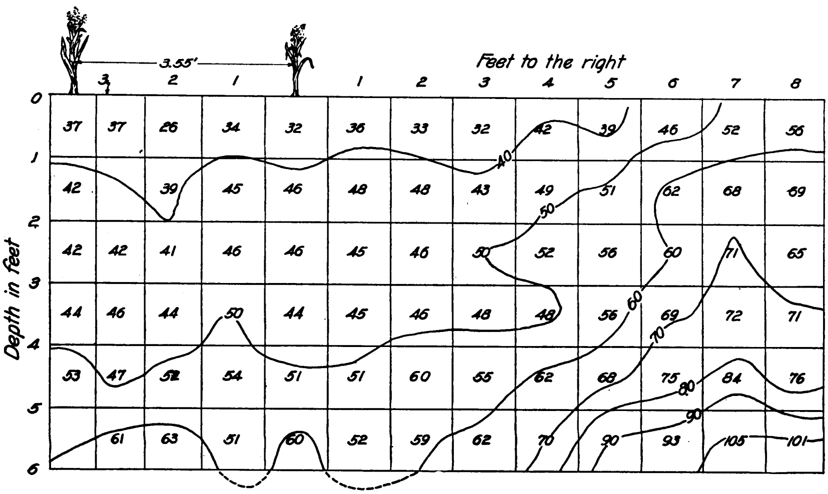


Fig. 2. Moisture conditions of soil after sorghum plants have matured. The irregular curved lines join points of equal relative wetness (moisture content ÷ moisture equivalent × 100).

amount of residual moisture in the soil at the beginning of permanent wilting cannot be used for all soils, the soils of the Yolo series at Davis were found to agree fairly closely with the accepted Briggs and Shantz ratio. While the different Davis soils tested did not agree exactly with each other, the ratio of the residual moisture at permanent wilting to the moisture equivalent averaged about 50 per cent.

The irregular curved lines across the chart in figure 2 were drawn just as contour lines are made on topographical maps, by connecting points of equal relative wetness, starting with the 40 per cent and continuing with 10 per cent intervals, as indicated in the figure. These lines have not been smoothed out, but show all of the errors inherent in the methods and assumptions used. As has been stated before, a percentage error of 10 in the relative wetness may sometimes occur. If these curves were smoothed out into an ideal case, they might be represented by a series of concentric arcs extending out from the last row into the unplanted area. The center of these arcs would be the crown of the plant. Of course, this ideal situation is modified by the drying out of the surface soil by direct evaporation, which tends to flatten the curves as they approach the surface. The curves of 60, 70, 80, 90, and 100 per cent undoubtedly would have swung under the crown of the plant if samples had been taken to a sufficient depth.

SOIL-MOISTURE CONDITIONS AND ROOT DISTRIBUTION

A second test, similar to that described above, was made at Davis on a piece of unirrigated land which had been cleanly cultivated during 1924. The soil was heavier in texture than that first used and is classed as Yolo clay loam. During the winter of 1924 and 1925, the land was plowed, and in the spring it was worked into a seed bed by shallow surface cultivations. On April 24, 1925, a single row 100 feet long of Double Dwarf milo, a grain sorghum, was seeded on a plot of ground that was kept free from weeds. Throughout the growing season of 1925, the adjacent land also was kept free from weed growth by cultivation and hoeing. The row of sorghum plants under observation paralleled on one side a single row or another variety, which was 29 feet distant. On the other side there was a pasture 36 feet away.

During the second week of October, 1925, a trench was dug to a depth of about 10 feet across the row of sorghum plants at right angles, and was extended 8 feet on one side of the row and 15 feet on the other side. A system of coordinates was marked off on the face of the trench, and samples were taken at the places indicated in table 2. The samples were obtained by driving a steel tube 1-13/16 inches in diameter, into the face of the trench. The soil sampling started on October 20, 1925, a few days after the trench was dug. The soil in the face of this trench had, therefore, dried out to some extent before the samples could be obtained. In order to avoid errors that might have resulted from this surface drying, the first 4 inches of soil from each hole was discarded, and the soil from the next 4 or 5 inches in each hole was taken for the samples for moisture determinations.

These samples were placed in weighing cans and moisture determinations made in the usual manner. After the soil had been oven-dried and weighed a 30-gram sample for a moisture-equivalent determination was taken from each can. All roots were removed from the moisture-equivalent sample by sieving and returned to the original

TABLE 2

MOISTURE CONTENTS, MOISTURE EQUIVALENTS, AND AMOUNT OF ROOTS FROM SAMPLES TAKEN FROM A TRENCH UNDER AND ACROSS A SINGLE ROW OF SORGHUM PLANTS

	Center						1 foot to right					
Depth of soil sampled	Moisture	Moisture equivalent	Relative wetness	Dry soil in sample	Milligrams of roots	Milligrams of roots in 100 grams soil	Moisture	Moisture equivalent	Relative wetness	Dry soil in sample	Milligrams of roots	Milligrams of roots in 100 grams soil
0.5	11.3	27.5	41	210.70	4.5	2.14	10.8	27.8	39	193.80	......	−0.50*
1.5	12.8	26.0	49	160.00	6.0	3.75	12.9	26.2	49	199.55	4.7	2.36
2.5	12.2	25.1	48	184.10	5.7	3.10	13.5	26.7	51	184.15	1.5	0.81
3.5	12.3	26.4	47	180.95	9.5	5.25	15.1	29.7	51	173.20	11.0	6.36
4.5	14.3	28.2	50	206.20	5.3	2.57	14.0	29.0	48	212.80	5.4	2.54
5.5	11.8	24.8	48	218.60	1.4	0.64	12.2	26.4	46	210.20	2.4	1.14
6.5	14.2	25.6	56	231.25	3.8	1.64	15.0	25.6	59	244.70	2.0	0.82
7.5	16.5	27.3	60	269.75	3.9	1.45	17.0	27.3	62	259.15	......	−0.50
	2 feet to right						3 feet to right					
0.5	11.8	27.2	43	233.60	1.1	0.47	11.8	26.6	44	223.60	......	−0.50
1.5	13.1	27.0	49	196.60	2.1	1.07	14.2	27.0	52	169.15	3.5	2.07
2.5	13.7	26.4	52	198.85	4.8	2.41	13.4	25.6	53	169.85	5.9	3.47
3.5	14.8	26.9	53	176.90	3.6	2.03	16.6	32.8	51	184.10	5.0	2.72
4.5	13.3	27.1	49	181.30	4.0	2.20	13.6	25.4	54	209.75	......	......
5.5	13.7	26.3	52	221.65	2.2	0.99	14.9	26.6	56	226.10	7.0	3.09
6.5	14.4	25.5	56	249.40	......	−0.50	14.6	26.3	55	255.90	1.8	0.72
	4 feet to right						5 feet to right					
0.5	11.5	26.0	44	188.65	......	−0.50	15.0	27.0	56	229.55	0.6	0.26
1.5	15.6	26.2	60	212.25	3.2	1.50	18.3	27.0	68	186.80	0.6	0.32
2.5	14.1	25.4	56	166.40	3.9	2.35	14.8	24.2	61	173.30	4.9	2.83
3.5	15.5	27.6	56	197.55	3.7	1.87	17.9	26.9	67	184.90	4.1	2.22
4.5	14.8	25.2	59	200.50	3.4	1.70	19.4	27.7	70	186.10	4.0	2.15
5.5	16.9	28.2	60	224.45	12.8	5.67	17.8	27.8	64	201.00	4.5	2.24
6.5	13.6	25.1	54	217.25	2.4	1.10	13.9	26.0	54	217.45	4.2	1.93

* −0.50 is used to indicate that the sample contained less than 0.50 milligrams of roots to 100 grams of soil.

TABLE 2 (continued)

Depth of soil sampled	Moisture	Moisture equivalent	Relative wetness	Dry soil in sample	Milligrams of roots	Milligrams of roots in 100 grams soil	Moisture	Moisture equivalent	Relative wetness	Dry soil in sample	Milligrams of roots	Milligrams of roots in 100 grams soil
	6 feet to right						7 feet to right					
0.5	14.7	25.2	58	200.70	0.6	0.29	15.5	27.4	57	207.70	1.2	0.58
1.5	18.6	25.9	72	194.50	....	−0.50	19.0	26.2	72	204.45	....	−0.50
2.5	17.4	28.8	60	188.05	....	−0.50	18.5	24.5	75	185.75	2.3	1.24
3.5	19.8	26.8	74	179.15	5.4	3.02	....	26.7	....	176.40	0.9	0.51
4.5	19.4	27.3	71	199.05	3.0	1.51	22.9	29.7	77	191.70	0.2	0.10
5.5	20.2	30.1	68	230.50	0.9	0.39	21.0	29.6	71	216.50	1.6	0.74
6.5	13.5	25.6	53	236.75	....	....	....	....	....	....	....	....
	1 foot to left						2 feet to left					
0.5	11.4	28.8	40	199.40	0.5	0.25	10.8	27.5	39	166.50	4.5	2.70
1.5	13.2	27.0	49	177.25	3.0	1.69	13.6	26.2	52	191.80	5.8	3.02
2.5	12.1	26.0	46	182.40	13.2	7.24	13.5	26.0	52	206.75	6.0	2.90
3.5	12.3	26.8	46	206.30	6.2	3.02	11.9	25.9	46	187.95	15.5	8.26
4.5	13.4	29.7	45	190.15	7.3	3.81	14.4	30.0	48	206.45	9.0	4.36
5.5	13.5	27.4	49	175.80	2.5	1.42	14.0	27.4	52	219.35	12.5	5.70
6.5	15.0	25.4	59	226.80	7.5	3.31	15.4	25.6	60	211.85	5.0	2.36
	3 feet to left						4 feet to left					
0.5	11.3	26.9	42	177.05	2.5	1.41	12.9	26.2	49	135.75	....	−0.50
1.5	14.6	27.8	52	178.10	2.0	1.12	15.1	27.0	56	193.85	....	−0.50
2.5	14.1	27.0	52	170.45	2.5	1.47	14.7	25.9	57	179.30	12.3	6.86
3.5	12.6	25.5	49	194 95	10.5	5.39	13.2	27.2	48	195.85	5.3	2.71
4.5	15.1	28.1	54	197.95	3.9	1.97	16.8	29.2	57	185.90	6.7	3.61
5.5	15.5	31.2	50	181.15	1.4	0.77	15.5	26.3	59	185.80	4.4	2.37
6.5	16.0	25.7	63	255.50	1.8	0.70	16.4	24.4	67	200.85	2.0	1.00
	5 feet to left						6 feet to left					
0.5	13.0	26.2	50	174.75	....	....	14.1	27.4	52	210.25	....	−0.50
1.5	15.9	27.1	59	173.50	1.7	0.98	18.3	26.9	68	186.20	0.9	0.48
2.5	13.9	23.1	60	197.45	1.6	0.81	16.2	26.4	62	183.10	5.7	3.11
3.5	17.3	23.2	74	198.80	3.1	1.57	21.4	29.4	73	192.75	3.9	2.02
4.5	18.5	29.0	64	200.25	6.0	2.98	20.9	29.8	70	190.55	1.5	0.79
5.5	21.0	26.8	78	202.90	....	−0.50	....	....	....	....	....	....

TABLE 2 (concluded)

Depth of soil sampled	7 feet to left: Moisture	Moisture equivalent	Relative wetness	Dry soil in sample	Milligrams of roots	Milligrams of roots in 100 grams soil	8 feet to left: Moisture	Moisture equivalent	Relative wetness	Dry soil in sample	Milligrams of roots	Milligrams of roots in 100 grams soil
0.5	16.4	26.4	62	194.40	....	−0.50	13.2	25.6	51	238.40	....	−0.50
1.5	18.7	26.3	71	171.15	1.1	0.64	19.1	27.0	71	184.15	1.5	0.81
2.5	19.5	31.4	62	168.10	2.9	1.72	16.7	23.0	73	198.70	4.5	2.26
3.5	19.7	26.0	76	196.05	1.8	0.92	23.9	29.7	81	212.35	1.7	0.80
4.5	20.2	27.4	74	....	....	....	22.4	29.3	77	214.40	0.8	0.37
5.5	19.2	28.0	68	....	....	....	19.3	27.4	70	227.85	0.8	0.35
6.5	18.1	25.6	71	....	....	....	14.5	25.6	57	227.10	2.3	1.01
	9 feet to left						10 feet to left					
0.5	14.4	27.2	53	219.15	....	−0.50	15.3	26.2	58	200.50	....	−0.50
1.5	18.5	25.2	73	183.25	....	−0.50	21.1	26.9	78	184.60	....	−0.50
2.5	19.3	25.6	75	171.90	1.2	0.70	20.8	25.6	81	184.00	0.6	0.33
3.5	24.9	31.2	80	180.45	2.2	1.22	25.2	31.5	80	185.25	2.0	1.08
4.5	23.6	29.3	81	215.40	1.2	0.56	24.7	30.3	82	180.55	1.0	0.56
5.5	22.1	28.1	79	193.40	....	−0.50	21.4	27.4	80	221.80	0.7	0.32
6.5	16.6	26.9	62	238.85	1.5	0.63	18.0	27.4	66	225.25	....	−0.50
	11 feet to left						12 feet to left					
0.5	15.6	27.1	57	207.85	1.0	0.48	16.8	27.5	61	217.60	....	−0.50
1.5	20.9	26.3	79	154.50	1.0	0.65	20.1	26.1	77	197.05	....	−0.50
2.5	21.0	25.5	82	168.00	0.3	0.18	20.8	26.2	79	188.90	....	−0.50
3.5	22.0	26.2	84	156.90	0.7	0.44	28.4	31.9	89	162.15	1.5	0.92
4.5	23.6	28.9	82	212.30	....	−0.50	24.0	29.3	82	209.05	1.0	0.48
5.5	21.8	26.7	82	208.35	0.5	0.24	22.8	26.9	84	205.60	2.0	0.97
6.6	16.2	25.2	64	223.15	....	−0 50	19.6	27.4	72	229.20	....	−0.50
	13 feet to left						14 feet to left					
0.5	17.0	26.6	64	224.80	0.2	0.09	16.7	27.3	61	223.55	....	−0.50
1.5	20.9	27.2	77	187.50	....	−0.50	21.0	26.8	78	195.15	....	−0.50
2.5	22.0	26.9	82	177.65	1.0	0.56	20.0	24.9	80	171.50	....	−0.50
3.5	24.2	28.4	85	166.70	0.7	0.42	26.4	31.0	85	159.45	....	−0.50
4.5	23.9	29.0	83	209.20	1.6	0.77	21.8	26.1	83	197.35	0.9	0.46
5.5	20.4	25.7	80	128.65	....	−0.50	....	....	....	....	....	....

samples. Then roots which were visible to the unaided eye were removed as completely as possible from all of the samples. The larger roots were picked out with forceps, and the soil was washed through sieves of decreasing sizes, the roots which remained on the sieves being removed with a small brush, and adhering soil particles being separated. As all of the work of removal of the roots was done by one operator, the same care was given to each sample.

The results of the samplings are given in table 2 and in figure 3, which also shows the lines of equal relative wetness, as well as those indicating the distribution of the roots. The lines of relative wetness and the lines connecting points having the same amount of roots to 100 grams of soil were drawn in the same manner as the relative wetness lines in figure 2.

TABLE 3

RAINFALL, IN INCHES, AT DAVIS, CALIFORNIA

Year	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1922	2.29	5.85	1.47	0.40	0.40	0	0	0	0	1.56	3.29	7.37	22.63
1923	2.62	0.70	0	2.22	0.10	0	0	0	0.35	0.40	0.53	0.88	7.80
1924	2.46	2.76	1.18	0.38	0.05	0	0	0	0	2.05	1.42	3.55	13.85
1925	1.05	4.28	3.10	2.15	1.63	0.02	0	0.03	0.10	0.10	1.71	1.29	15.46

The rainfall at Davis during 1922, 1923, 1924, and 1925, is given in table 3. From September 1, 1923, to September 1, 1924, 8.99 inches of rain fell, while the rainfall from September 1, 1924, to April 24, 1925 (the date the sorghum was planted) was 17.60 inches. There was only 1.67 inches of rain during the time the plants were growing. As the plot of ground used in this test was kept clean of all vegetation during 1924, a large portion of this rainfall was probaly retained in the soil. The soil was thus doubtless wet to a depth of at least 7 feet at the time the row of sorghum was seeded. Although no record is available of the moisture condition of the soil at this time, experience with the soils at this station shows that in years of normal rainfall the soil is wet to a depth of at least 7 feet at the end of the rainy season; it is therefore safe to assume that below the surface mulch, the relative wetness of the soil to a depth of 7 feet was about 100. The results given in table 2 and figure 3 may be taken to indicate the percentage of the amount of the initial water (present in the soil when the plants were seeded) which remained after they had matured. The moisture equivalents given in table 2 indicate that the soil in the plot used in this test was much more uniform in texture than that in the area first tested.

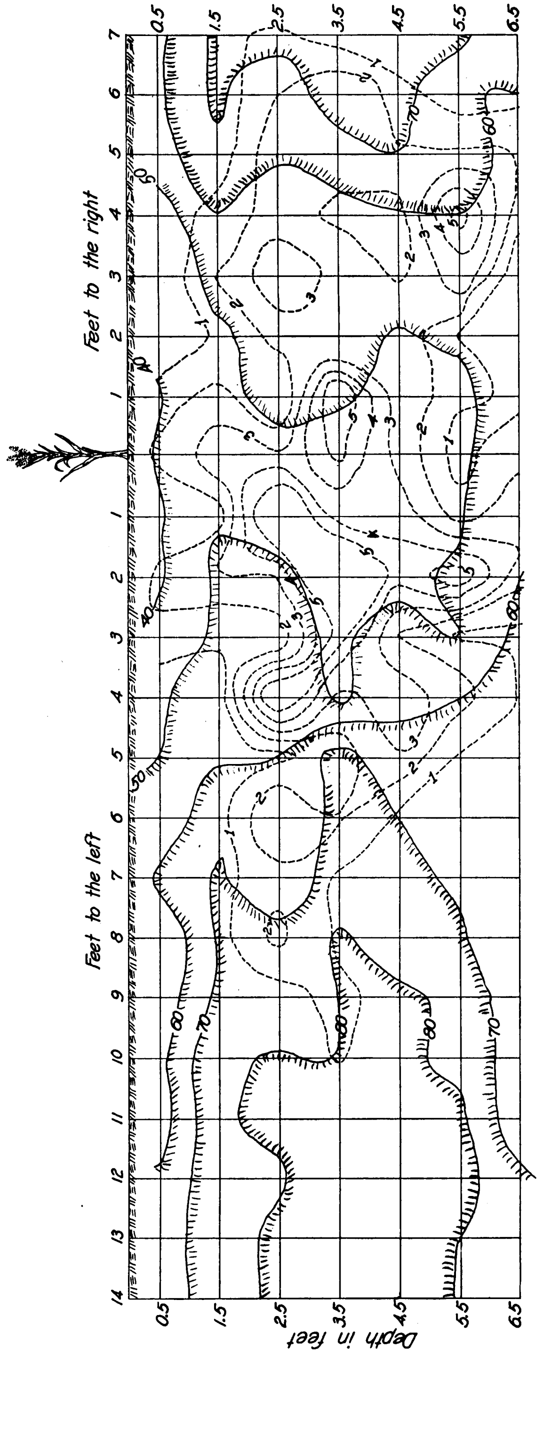


Fig. 3. Soil moisture conditions and distribution of roots after sorghum plants have matured. The solid irregular curved lines join points of equal relative wetness (moisture content ÷ moisture equivalent × 100). The dotted curved lines join points having the same weights of roots; the figures 1, 2, 3, 4, and 5 are actual weights of roots in milligrams to 100 grams of soil.

Some of the samples contained such a small amount of roots that no attempt was made to segregate them, and the amount of roots to 100 grams of soil was assumed to be less than 0.50 milligrams. Figure 3 shows that the soil to a depth of 6 inches was relatively dry even at considerable distance from the row of sorghum plants. This drying out was probably due to evaporation of moisture directly from the surface of the soil. Therefore, in working out the correlation between the percentages for relative wetness and milligrams of roots to 100 grams of soil, the samples from the 0.5 foot depth of soil were not used; and those from which the roots were not removed, because of the small amount contained in them, were listed as having less than 0.50 milligrams to 100 grams of soil. With these assumptions, the correlation between the figures for relative wetness and weight of roots to unit weight of soil was found to be $r = -0.582 \pm 0.040$. This coefficient of correlation, with its relatively small probable error, may be considered to be decidedly significant.

Figure 3 illustrates further the relation of distribution of roots to the relative wetness of the soil. It will be seen that a large majority of the roots are enclosed within the line representing the location of relative wetness of 60 per cent. The line which joins points having one milligram of roots to 100 grams of soil is, in fact, the only one which has its greater portion without the line of 60 per cent relative wetness. As has been mentioned before, tests on these Yolo soils at Davis show that the residual moisture at permanent wilting is about 50 per cent of the moisture equivalent. The bulk of the roots is therefore in soil which has been reduced to about the wilting coefficient.

It must be remembered that only weights of roots were obtained in this experiment. Of course, root hairs, a portion of the roots constituting a part of the actual absorbing surface, could not be seen or measured by the methods employed. It is assumed, however, that there is close relation between weight and absorbing surface.

DISCUSSION

Previous investigations[14][18] at this station have shown that the loss of moisture by direct evaporation from the surface of the soil is practically confined to shallow depths of soil, and that losses from deeper layers (aside from percolation when excessive amounts of water are applied) are due to transpiration from plants growing on the soil. There is, furthermore, abundant evidence[11][14][18][22] that capillary movement of moisture from moist soil to drier soil, especially when the soil is not in contact with a free water surface, is too limited in extent and in rate to be effective for use by the roots of plants; and it appears very probable that capillarity cannot be counted on to move moisture appreciable distances from moist soil into soil that has been dried by root extraction.

It is, therefore, evident that an additional moisture supply can be obtained only by the elongation of the absorbing portion of the roots into new moist soil, unless the moisture be returned to the dry soil by rain or irrigation. The shape of the relative wetness lines in figures 2 and 3 indicates that this elongation process took place under the sorghum plants studied. Apparently, the moisture was removed in successive zones. The drying out of the soil below the surface layer which was affected by direct evaporation could be accounted for only by the presence of roots; and, indeed, the data presented in this paper clearly indicate this explanation to be correct. The negative correlation between the relative wetness of the soil and the density of roots shows that the soil was dried because of the presence of roots. It is apparent, then, that the results of soil sampling, made in the manner described in this paper, may be used to indicate the distribution of roots of plants.

Moisture studies[19] made in small containers show that plants will permanently wilt as soon as the moisture reaches a certain percentage, which is roughly 50 per cent of the moisture equivalent in soils at Davis. If a portion of the root system is partly in dry soil‡ and partly in wet soil, the needs of the plants might be adequately met by absorption from the moist soil. A situation of this kind is illustrated in figure 3. Here part of the root system is in dry soil and part in moist soil. In October the transpiration requirements of the plants were being adequately met by these conditions, although the greater amount of the root system was in dry soil. At this station it has been observed sometimes that plants were not showing evidence of lack of water when the upper few feet of soil (which presumably contained the greater portion of the roots) was dry, if the lower layers of soil (in which the ends of the roots were located) were moist. There is no reason to assume that because the greater amount of roots or of absorbing surface may be in the top layers of soil, absorption by the

‡ A remarkable constancy of the residual moisture content for a given soil when permanent wilting is attained has been observed.[19] There appears to be a rather narrow range of soil-moisture percentage, below which plants cannot obtain moisture rapidly enough to permit them to function properly, but above which transpiration needs of the plant seem to be satisfied adequately. In this discussion, soil containing a percentage of moisture below this range is called dry soil, and soil with a moisture content above this range is called moist or wet soil.

smaller amount of roots in the deeper moist layers cannot be sufficient, especially under low evaporation conditions, to satisfy the needs of plants when the top layers become dry.

The question arises as to whether roots may elongate into dry soil when they are supplied with moisture from roots of the same plant in moist soil. Shantz,[13] says of the trees of the African grasslands: "These drought-resistant plants also have the ability to push their roots into a dry soil, and in this way be prepared rapidly to absorb soil moisture when it comes . . . but ordinary field crops have no such ability." In this connection may be mentioned Livingston's[9] studies at Tucson, Arizona, with desert plants, which showed that the roots of seedlings elongated directly downward so rapidly as to make it appear possible for them to reach a permanent and adequate water supply before the soil, wet thoroughly by the frequent showers of the rainy season, can produce injury through conditions of drought. The deeper soil layers of the typical locality studied by Livingston were found to contain at the end of the dry season (and, it was assumed, at all times) a water content adequate to the needs of those desert plants which are active throughout the months of drought. On the other hand, there is no evidence in Livingston's report to show that the roots of these plants had the ability to traverse dry soils, a condition which he doubtless would have observed.

With agricultural plants, there seems to be no experimental evidence that roots will be forced through dry soils. While Auchter's[3] evidence concerning the cross transfer of water in the plant was not conclusive, it did suggest that water may move through or around the plant without much difficulty. According to Auchter's statement his evidence strongly suggests that the foods manufactured on one side of a plant are used and stored mainly in that side, or are translocated to the roots beneath, and that mineral nutrients absorbed by the roots on one side of a plant are translocated to and used by the trunk, limbs, and leaves directly above them. The ready cross transfer of water from roots in moist soil to roots in dry would serve to keep the latter turgid, but unless elaborated foods and mineral nutrients were also carried to them or derived from a previously stored supply, elongation would soon cease.

Taking as a basis the assumption that elongation of the roots of agricultural plants at least will not take place in dry soil, the writers give the following hypothetical case, which they believe would be about as extreme as would normally be found under actual farming conditions. When a plant has exhausted the available moisture from most of the soil permeated by roots, if frequent light irrigations or rains keep the upper layers of soil moist, leaving the layers below dry, elongation, if it occurs at all, will take place in the moistened top soil. This should result in an increase in the weight of roots in the upper soil over that in the lower. But it does not necessarily follow that if the whole soil mass is wet again, and the top layers dry out by root absorption, the absorptive area in the lower levels will be insufficient to support the needs of the plants.

Some studies bearing on this question have been made by Beckett and Huberty,[4] under conditions probably not so extreme as that postulated above, but nevertheless with marked variations in irrigation practice and consequently of soil-moisture conditions. Consequently the following description of the experiments taken from their report is given in some detail. At Davis certain plots of alfalfa of about 0.7 of an acre in area, which were planted in 1921, were irrigated for a period of five years, 1921 to 1925, with a total seasonal depth of 30 inches on each plot, but with the number of irrigations varying from 2 to 12. The distribution of frequencies of application and the depths were as follows: twelve 2½-inch; eight 3¾-inch; six 5-inch; four 7½-inch; three 10-inch; and two 15-inch. At Delhi, plots of alfalfa of 1.07 acres were planted in 1921, and all received identical irrigations during that year. During 1922, 1923, 1924, and 1925, each plot received varying amounts of water and different frequencies of applications as follows: six 8-inch irrigations from 1922 to 1925; six 6-inch irrigations, 1922 to 1925; three 4-inch irrigations, 1922 to 1924, and six 6-inch irrigations during 1925; twelve 3-inch irrigations, 1922 to 1924, and four 6-inch irrigations during 1925.

The soil at Davis on which the plots were located is a Yolo fine sandy loam with an average maximum field capacity of from 20 to 22 per cent. The depth to the ground water level was greater than 14 feet throughout the five years of the experiment. The plots at Delhi were on Oakley fine sand which has a maximum field capacity of about 6 per cent at the surface, and 10 per cent and 12 per cent at the lower depths. A hardpan layer practically impervious to water, 10 to 12 inches in thickness, underlies the area at depths of 6 to 9 feet. The water table under the Delhi plots was always more than 25 feet from the surface during the period of observation.

Beckett and Huberty separated the roots from the soil in 6-inch layers, weighed them, and recorded their distribution to a depth of 6 feet. They concluded that "when the winter rainfall was sufficient to moisten the soil to a depth of at least 6 feet, and where the depth to the underground water table was more than 15 feet, variation in depth of application or in frequency of irrigation did not affect the root distribution of the alfalfa.'' Furthermore, these investigators also found that ''variations in number of irrigations, providing the same seasonal total was applied, did not materially affect the yields.''

While Beckett and Huberty do not report soil-moisture contents, undoubtedly the upper layers of soil in the plots which received the more frequent applications had greater amounts of available water, for longer periods during the growing season, than those of the plots which were less frequently irrigated. The quantitative measurements of roots in 6 feet of soil, nevertheless, clearly show that their distribution in this depth of soil was not materially affected. It must be remembered that the soil in these plots was wet by rainfall to the full depth of 6 feet at the beginning of each season.

Weaver[8][20][21][22] and his co-workers have, however, reached different conclusions. They are of the opinion that changes in lateral spread of roots, depth of penetration, or output of branches are correlated in nearly every instance with changes in water content of the soil. These investigators further believe that by the application of more or less water, the root system may be varied, and yields will be affected.

Since it has been shown[14] that drying of the soil below the surface layer is the result of root activity, and that dry soils must, then, necessarily mean the presence of roots, we believe that if the soil is wet to the full depth to which roots of the particular plant in question would normally go at the beginning of the growing season, then subsequent applications of water during the summer can have little influence on the extent of the distribution of the roots.

It is reasonable to assume that if soils are wet only to a certain depth, either by rainfall or by irrigation, and if the soil below this depth contains less moisture than that at which plants become permanently wilted, the roots will be confined within the moistened area. On the other hand, as far as the writers are aware, no experiments have shown that plants which normally are deep rooted can be made to keep their roots in the upper layers of soil, if those at lower depths have an available supply and if no other adverse conditions for root development are present in the lower strata. In other words, the progressive enlargement of the absorbing surface of the roots will cause them to elongate into the new moist layers, even though the region at present occupied by roots contains readily available water.

A number of references might be cited in which the effect of different soil-moisture conditions on the ratio of tops to roots of different plants has been studied. Most of this work has been with plants in containers, but in all cases, as has been previously[14][18] pointed out, serious objection can be raised to the conclusions drawn from studies on the water relations of plants, because of the inability to bring about or to maintain the predetermined moisture contents in the soil which the operators had presumed were maintained.

Studies on the water relations of deciduous fruit trees conducted at this station[14][17] have shown that apparently among the soils tested a *moist* soil has no optimum moisture content at which the trees grew best or at which the use of water was affected. Optimum moisture conditions for growth may therefore be taken to cover a range of soil moisture from the maximum field capacity to about the wilting coefficient. By analogy it might be reasoned that optimum conditions for root growth are covered within the same range as that found for the portion of the plant above ground, especially if a direct proportionality exists between top and roots.

It is certain that adverse conditions for root growth may be brought about by extreme variations in moisture conditions. Temperature and oxygen supply have been studied most in this connection. In the greater part of the work dealing with this subject, it is extremely difficult to gain an idea of the relative wetness of the soil under test, because there has been no uniformity in the manner of stating the soil-moisture conditions, and because no information is generally given to enable one to reduce the data to an understandable basis. There appears, however, to be in the literature on the subject of soil moisture and oxygen relations no conclusive evidence that favorable oxygen conditions for the growth of roots of agricultural plants would not be satisfied within the range of moisture contents from the moisture equivalent to about the wilting coefficient. The same statement may be made with regard to temperature conditions. Exceptionally frequent applications of water might, of course, result in filling the pore space of the soil for so long a time that unfavorable conditions for root growth would be established. The approximate equality of moisture equivalent to the maximum field capacity holds only for soils of fairly uniform texture throughout the depth considered. A decided change in texture (for instance, as Alway and McDole[1] have shown, a loam or clay above a sand) may result in the establishment, for some time after rain or irrigation, of a moisture content considerably higher than the moisture equivalent in the same zone just above the coarse soil. This moisture content may sometimes be too great to permit root growth.

The curves in figure 3 and part of figure 2 suggest the probable history of the use of soil moisture by a single isolated row of sorghum. At the time of planting, we may assume that the soil to a depth of at least 6 feet was wet to the maximum field capacity, except that part composing the surface mulch. The developing seedlings send their roots into the soil, absorbing moisture as they go. Possibly because the roots near the crown are usually more abundant and have been in contact with the soil there for a longer time, more moisture has been absorbed from this region of the soil. The roots of the plants extending into the unplanted soil find no competition from roots coming from the opposite direction, as they would between adjacent rows in a normally planted field; in consequence, the moisture is absorbed progressively.

If, at some time during the growing season, the points of equal relative wetness in the soil, say 50 per cent, be joined, they will approximate part of the surface of a cylinder whose central axis would ideally (except for surface evaporation) coincide with the line of the border row. If a surface of relative wetness of 60 per cent were formed, it would be farther from the crowns of the plants, and roughly concentric to the other surface of 50 per cent; the same condition holds for surfaces of higher relative wetness. As growth takes place, more and more soil moisture is absorbed; and under conditions when there is usually a negligible amount of precipitation during the summer, this absorption will result in the gradual enlarging of all cylindrical surfaces of equal relative wetness. This process would be continued until the plants were matured or until the roots used up all of the readily available moisture in the depth of the soil possible of exploration by the roots of the plants growing there.

SUMMARY AND CONCLUSIONS

In all studies on the water relations of plants in which soil moisture is involved, much greater care should be given to the manner of taking the samples and to the interpretation of the results. The use of the moisture equivalent for the reduction of moisture contents to a common basis is suggested. Variations in soil texture that are not interpreted by moisture equivalents or by any other of the so-called soil-moisture constants may be great enough to make the results unreliable unless many samples are taken for each condition investigated.

The data in this paper indicate that moisture under rows of grain-sorghum plants is apparently extracted in successive zones and the extraction is progressive whenever no material additions of moisture occur during the growing season.

The percentages for relative wetness expressed as ratios of soil-moisture contents to their respective moisture equivalents, may be used to indicate the development of roots, and the results of adequate moisture samples, taken at proper times, indicate with a fair degree of accuracy the presence or absence of roots of plants growing on the soil tested.

A correlation has been shown to exist under the conditions of this study between the amount of roots and the extent to which the soil has been dried by root activity. The writers reason that if the soil is wet at the beginning of the growing season to the full depth to which roots of plants would normally penetrate, subsequent additions of water by rain or irrigation, unless adverse conditions for growth are brought about thereby, can have but little influence on the extent of the root system developed.

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The titles of the Technical Papers of the California Agricultural Experiment Station, Nos. 1 to 20, which HILGARDIA replaces, and copies of which may be had on application to the Publication Secretary, Agricultural Experiment Station, Berkeley, are as follows:

1. The Removal of Sodium Carbonate from Soils, by Walter P. Kelley and Edward E. Thomas. January, 1923.

4. Effect of Sodium Chlorid and Calcium Chlorid upon the Growth and Composition of Young Orange Trees, by H. S. Reed and A. R. C. Haas. April, 1923.

5. Citrus Blast and Black Pit, by H. S. Fawcett, W. T. Horne, and A. F. Camp. May, 1923.

6. A Study of Deciduous Fruit Tree Rootstocks with Special Reference to Their Identification, by Myer J. Heppner. June, 1923.

7. A Study of the Darkening of Apple Tissue, by E. L. Overholser and W. V. Cruess. June, 1923.

8. Effect of Salts on the Intake of Inorganic Elements and on the Buffer System of the Plant, by D. R. Hoagland and J. C. Martin. July, 1923.

9. Experiments on the Reclamation of Alkali Soils by Leaching with Water and Gypsum, by P. L. Hibbard. August, 1923.

10. The Seasonal Variation of the Soil Moisture in a Walnut Grove in Relation to Hygroscopic Coefficient, by L. D. Batchelor and H. S. Reed. September, 1923.

11. Studies on the Effects of Sodium, Potassium, and Calcium on Young Orange Trees, by H. S. Reed and A. R. C. Haas. October, 1923.

12. The Effect of the Plant on the Reaction of the Culture Solution, by D. R. Hoagland. November, 1923.

13. Some Mutual Effects on Soil and Plant Induced by Added Solutes, by John S. Burd and J. C. Martin. December, 1923.

14. The Respiration of Potato Tubers in Relation to the Occurrence of Blackheart, by J. P. Bennett and E. T. Bartholomew. January, 1924.

15. Replaceable Bases in Soils, by Walter P. Kelley and S. Melvin Brown. February, 1924.

16. The Moisture Equivalent as Influenced by the Amount of Soil Used in its Determination, by F. J. Veihmeyer, O. W. Israelsen and J. P. Conrad. September, 1924.

17. Nutrient and Toxic Effects of Certain Ions on Citrus and Walnut Trees with Especial Reference to the Concentration and Ph of the Medium, by H. S. Reed and A. R. C. Haas. October, 1924.

18. Factors Influencing the Rate of Germination of Seed of Asparagus officinalis, by H. A. Borthwick. March, 1925.

19. The Relation of the Subcutaneous Administration of Living Bacterium abortum to the Immunity and Carrier Problem of Bovine Infectious Abortion, by George H. Hart and Jacob Traum. April, 1925.

20. A Study of the Conductive Tissues in Shoots of the Bartlett Pear and the Relationship of Food Movement to Dominance of the Apical Buds, by Frank E. Gardner. April, 1925.