MOISTURE RETENTION BY SOME IRRIGATED SOILS AS RELATED TO SOIL-MOISTURE TENSION[1]

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INTRODUCTION

The processes of depletion and replenishment of soil moisture have received considerable attention from agricultural scientists because of the dependence of plant growth on the soil-moisture supply. The maximum amount of moisture that can be stored in soil in the field and the degree of dryness to which plants can reduce the moisture content of soil are the limits that determine the range of moisture available to plants. Numerous single-valued soil-moisture constants, such as moisture-holding capacity, moisture equivalent, field capacity, and the various wilting percentages, have been used for indicating the capacity of soils to retain water. The possible advantages of expressing moisture retention in terms of the physical condition of the moisture in soil or in terms of the security with which the water is retained as expressed by some energy or thermodynamic scale have long been considered (*4*).[2]

Some of the scales that have been proposed for this purpose will be discussed, but it is the main object of this paper to present data on the relation between the equivalent negative pressure or tension in the soil water and the moisture content for **71** soil samples collected by Furr and Reeves. On these samples the collectors[3] made careful determinations of the moisture equivalent, the first permanent wilting percentage, and the ultimate wilting percentage, and stated:

> With few exceptions the soil samples were taken from the top foot of soil, and most of them were from cultivated, irrigated orchards or fields. A few samples were from uncultivated desert or brushlands. The samples were air-dried and screened through a round-hole 2-mm. screen.

APPARATUS AND PROCEDURE

The pressure-membrane apparatus (12) was used to obtain moisture data at tensions above 1 atmosphere. This is a modification of ultrafiltration apparatus which has been used by Woodruff (21) for the same purpose. The extraction cells were the same as those already described (12), consisting of a Visking[4] membrane supported on a brass screen and plate with a cylindrical soil chamber 29 cm. in diameter and 1.3 cm. high. Moisture was extracted by water pumped nitrogen supplied from a storage cylinder.[5]

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[2] Italic numbers in parentheses refer to Literature Cited, p. 234.

[3] Furr, J. R., and REEVES, J. 0. THE RANGE OF SOIL MOISTURE PERCENTAGES THROUGH WHICH PLANTS UNDERGO PERMANENT WILTING IN SOME SOILS FROM SEMIARID IRRIGATED AREAS. 1942. [Unpublished manuscript.]

[4] The Visking Corporation, Chicago, 111.

[5] A small refrigeration compressor, on which tests have just been completed, has been found to supply ample quantities of compressed air for pressure-membrane work and has been operated at pressures up to 420 wounds in.$^{-2}$.

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During moisture extraction most soils undergo a certain amount of shrinkage that tends to pull the soil out of contact with the membrane. To prevent this, a soft-rubber diaphragm actuated by a 5 pound per square inch pressure differential was used to hold the soil against the membrane. This pressure differential was obtained by inserting in the line between the pressure source and the soil chamber a mercury U-tube fitted with a bypass valve.. The diaphragm pressure was obtained from the pressure-inlet side of the U-tube and was applied by closing the bypass valve and venting the soil chamber. To prevent undesired compacting and puddling effects on wet soils, the diaphragm pressure was not applied until the moisture content of the sample was reduced to somewhere near the 1-atmosphere percentage. In future work it is contemplated that the mercury U-tube will be replaced by a water U-tube.

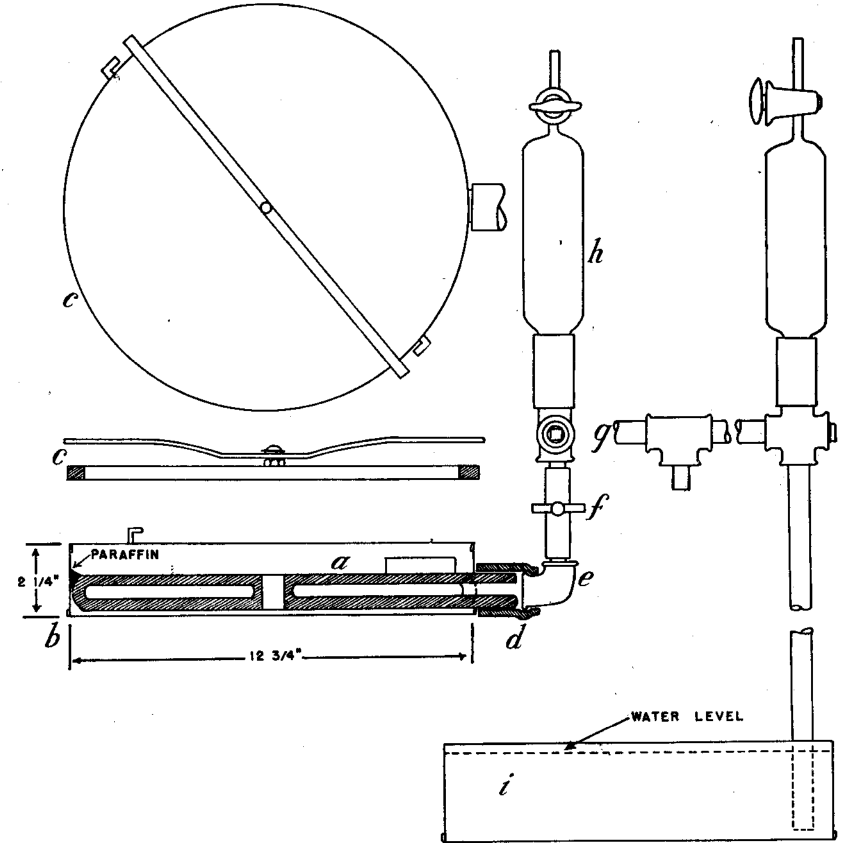

FIGURE 1.-Suction-plate apparatus for determining single moisture-retention values for soils in the 1-atmosphere tension range: a, Ceramic cell with porous upper surface; *b*, galvanized-iron box; c, box lid with spring clamp and sponge-rubber gasket; d, ⅞-inch automobile radiator hose; e, ⅜-inch galvanized pipe L with ⅜- to ¼-inch pipe bushing, which has a section of 7⁄16-inch copper tubing soldered in place; f, ⅜-inch (inside diameter) vacuum rubber tubing with pinch clamp; g, manifold for making connection to a number of cells; h, glass air trap; i, water reservoir.

Moisture-retention data at tensions between zero and 1 atmosphere were obtained either with pressure-plate or suction-plate apparatus. The pressure-plate apparatus is identical in principle with the pressure-membrane apparatus but makes use of a porous ceramic plate instead of the cellulose membrane. The suction-plate apparatus used is shown in figure 1. The porous ceramic cell [6] is of single-piece construction and is mounted in a galvanized-iron box. The lid is fitted with a sponge-rubber gasket -and a spring clamping bar. The cell spout extends from a hole in the box and connects through various fittings to the manifold. This manifold has connections for as many of the suction-plate units as are needed and slopes upward toward the pipe cross and the separatory funnel that is used as an air trap. A pipe extends downward from the air trap to a free water surface, the elevation of which determines the negative pressure at the porous surface. The suction, of course, can be produced when desired by a controlled vacuum system.

The procedure for obtaining all of the moisture-retention data presented in this paper was as follows: A layer of screened, air-dried soil was placed on the porous moisture-extracting surface; the soil was wet thoroughly with an excess of distilled water, and then the moisture was extracted until the moisture tension in the soil increased to a constant predetermined equilibrium value and moisture outflow from the sample ceased. For the determination of single moisture-retention values, a number of soil samples were brought to equilibrium in the same extraction cell, the moisture-content determinations being made by drying to constant weight at 105° C. Moisture retention was expressed as percentage of dry weight so as to be comparable with moisture-equivalent and wilting data.

The soil samples were kept separate on the porous plate by placing them in thin-walled brass rings 5.4 cm. in diameter and 1 cm. high. This permitted 12 to 14 determinations per ground cell. Rings 2 cm. high can be used when larger soil samples are desired.

When moisture-retention curves were desired, the entire pressure-membrane or pressure-plate cell was loaded with one soil sample. The moisture percentage at any desired number of equilibrium-tension values can be calculated from the combined record of the moisture extracted at each succeeding tension increment, the final moisture content, and the total dry weight of the sample.

The amount of moisture a soil will retain at a given tension depends somewhat on the time allowed for wetting the air-dried sample. Some sandy soils show no increase in moisture retention for wetting time beyond 15 minutes, but some fine-textured soils require as much as 18 to 24 hours before the moisture retained is independent of the wetting time. An overnight wetting time of 16 to 18 hours was used for the determinations reported in this paper.

For all except very impermeable soils, 4 to 6 hours is ample time for a 1- to 2-cm. layer of saturated soil to come to equilibrium after the pressure differential is applied to the porous ceramic plates used. The time required for outflow equilibrium in the pressure-membrane apparatus is indicated by the curves in figure 8, which will be discussed later.

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[6] Ground cell K 939-B, General Ceramics and Steatite Company, Keasbey, N. J.

Unless otherwise indicated, all the soil-moisture tension data presented in this paper were obtained at a temperature of 21° C., and the following pressure equivalents were used: 1 atmosphere$=1.013\times10^6$ dyne cm.$^{-2}=14.71$ pounds in.$^{-2}=76.39$ cm. of mercury$=1,036$ cm. of water$=34.01$ feet of water.

FIFTEEN-ATMOSPHERE PERCENTAGE AND THE WILTING RANGE

For the soils used in the first tests of the pressure-membrane apparatus it was found that an extraction pressure of 16 atmospheres reduced the moisture content slightly below the wilting percentage, as determined with sunflowers by Eaton and Horton (*6*). In view of this preliminary experience it was decided to determine the 15-atmosphere percentage for the soil samples collected by Furr and Reeves. Table 1 gives the moisture equivalent, the first permanent wilting percentage, and the ultimate wilting percentage as determined by Furr and Reeves, and in addition gives the moisture retained by these soils at five soil-moisture tension values.

TABLE 1.—*Moisture*[1] *retained by soils after moisture-extracting treatments*

Soil type	Soil accession No.	Moisture equivalent	First permanent wilting	Ultimate wilting	Moisture retained at indicated soil-moisture tension				
					Centimeters of water				Atmospheres
					250	345	440	518	15
Coarse soils:									
		Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Washed and screened sand, 10-20 mesh	57	1.3	1.2	0.7	1.2	1.2	1.2	1.1	0.8
Washed and screened sand, 20-30 mesh	56	1.4	1.3	.7	1.3	1.2	1.3	1.2	.9
Washed and screened sand, below 30 mesh	55	1.9	1.4	.9	1.9	1.5	1.7	1.6	1.0
Tujunga sand	52	2.6	1.8	1.2	2.3	2.1	2.2	2.1	1.4
Hanford sand	51	4.8	2.9	1.9	5.0	4.5	4.3	4.1	2.2
Ramona sand	54	5.0	2.9	2.2	5.2	4.4	4.5	4.2	2.0
Indio loam	76	5.2	2.6	1.6	5.3	4.6	4.3	3.8	1.6
Indio very fine sand	48	5.8	3.2	2.0	5.9	5.0	4.7	4.1	1.9
Dune sand	53	6.5	2.6	1.9	6.6	5.6	5.4	5.2	2.9
Superstition (leached) sand	50	6.6	2.4	1.5	6.5	--------	4.8	4.4	1.9
Holland sandy loam	41	6.9	4.2	3.2	7.6	6.4	6.2	5.5	2.7
Indio very fine sandy loam	70	7.3	3.2	1.9	8.2	6.9	6.4	5.7	2.2
Indio loam	75	7.4	2.8	1.9	7.5	6.2	6.2	5.1	1.9
Placentia sandy loam	43	7.4	3.9	3.2	8.1	6.7	6.4	6.0	2.5
Indio fine sandy loam (6 feet)	82	7.7	3.9	2.5	9.2	8.0	7.5	6.6	2.7
Hanford fine sand	47	8.0	3.8	2.5	8.8	7.6	7.3	6.8	2.3
Fresno fine sandy loam	40	8.9	3.7	2.5	10.2	8.5	8.1	7.5	2.3
Ramona fine sandy loam	37	9.2	5.2	3.7	10.1	8.3	8.3	7.8	3.5
Tujunga Stony sand	58	9.8	5.2	3.8	10.2	9.1	8.8	8.1	4.3
Indio fine sandy loam (5 feet)	81	9.9	5.2	3.2	12.3	10.7	10.0	8.8	3.1
Placentia clay loam	17	10.9	6.0	4.7	11.8	10.0	9.8	8.7	5.6
Hanford gravelly sandy loam	26	11.3	5.4	3.5	12.6	9.8	9.5	9.0	3.5
Hanford sandy loam	42	12.4	4.8	3.6	14.2	11.7	10.6	9.7	2.9
San Joaquin sandy loam	46	12.5	5.9	4.1	14.1	12.1	12.2	11.6	4.3
Greenfield loam	N4	12.7	6.3	5.1	17.3	14.5	14.2	13.1	5.4
Tujunga fine sandy loam	39	13.2	5.5	4.1	20.3	15.6	13.8	12.2	3.5
Yolo loam	31	14.3	8.4	6.7	15.1	12.6	12.7	11.6	7.1
Hanford loam	29	14.5	6.0	4.0	16.9	14.0	13.2	11.8	4.4
Placentia loam	28	14.8	7.7	5.3	16.9	14.0	13.4	12.6	5.7
Coachella very fine sand	49	15.2	5.7	4.0	18.1	14.5	13.2	12.1	3.8
Indio loam (4 feet)	74	15.4	6.1	3.3	18.0	--------	14.5	13.2	3.8
Altamont clay	2	15.6	6.8	5.2	19.4	15.4	14.7	13.4	5.7
Yolo fine sandy loam	38	15.4	8.3	6.2	14.7	12.6	12.1	12.0	5.5
Total[2]	--------	279.6	137.8	98.0	318.3	265.3	254.2	233.1	99.6

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[1] Expressed on a dry-weight basis.
[2] Omitting soils 50 and 74.

TABLE 1.—*Moisture retained by soils after moisture-extracting treatments*—Con.

Soil type	Soil accession No.	Moisture equivalent	First permanent wilting	Ultimate wilting	Moisture retained at indicated soil-moisture tension				
					Centimeters of water				Atmospheres
					250	345	440	518	15
Fine soils;		*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Madera sandy loam	45	16.0	6.6	4.8	16.0	13.2	12.9	11.8	4.5
San Joaquin loam	33	16.2	8.1	6.3	18.0	15.1	15.4	14.4	6.5
Ramona loam	27	16.6	8.3	5.6	18.7	15.4	15.1	14.3	6.0
Indio fine sandy loam (5 feet)	79	16.9	6.8	3.8	19.9	17.0	16.0	14.9	4.6
Indio fine sandy loam (1 foot)	77	17.5	5.9	3.5	21.9	17.7	16.3	14.7	4.2
Madera loam	32	17.6	9.9	7.7	22.1	18.0	18.5	16.6	8.4
Hanford fine sandy loam	36	17.8	6.7	4.7	22.5	18.5	16.9	15.2	4.3
Altamont clay loam	14	18.4	10.0	8.8	19.0	16.1	16.4	15.3	9.1
Indio very fine sandy loam (5 feet)	69	19.0	5.6	4.0	21.2	18.3	17.7	15.9	4.8
Ramona clay loam	15	19.0	9.3	6.3	23.1	19.4	18.9	17.5	6.7
Indio loam (3 feet)	73	20.2	7.0	4.2	24.2	--------	19.8	17.9	5.0
Antioch silty clay loam	22	20.9	10.7	9.0	25.2	20.8	20.0	17.9	9.5
Chino loam	30	21.0	10.2	7.5	23.6	19.7	19.8	18.4	8.0
Indio very fine sandy loam (4 feet)	68	21.2	6.9	4.3	23.9	--------	20.1	18.3	5.2
Yolo clay loam	16	21.3	12.3	10.4	23.7	20.4	19.8	18.1	10.2
Madera clay loam	18	21.7	11.7	8.2	24.0	21.3	21.4	20.2	8.8
Indio fine sandy loam (4 feet)	80	22.8	8.8	5.3	27.0	23.7	22.5	20.9	6.4
Indio clay loam	85	22.9	8.9	5.9	29.2	24.6	23.0	20.6	6.5
Indio loam (1 foot)	71	23.2	8.0	5.1	27.1	22.8	21.9	20.0	6.1
Montezuma clay	4	23.4	13.2	10.5	22.8	20.2	19.8	17.6	11.3
Hanford silty clay loam	25	24.4	14.3	12.1	29.5	24.3	25.4	22.8	13.2
Montezuma clay	8	25.9	13.3	10.1	30.0	25.9	27.2	24.9	12.7
Indio fine sandy loam (2 feet)	78	26.1	11.5	5.8	31.2	--------	26.1	24.1	7.0
Fresno loam	34	26.8	14.2	9.6	34.4	30.5	29.3	27.2	10.7
Dublin clay	1	27.4	16.4	13.2	30.7	27.6	27.3	24.0	14.2
Chino silty clay loam	23	27.6	14.4	10.4	30.5	26.8	25.9	24.3	11.0
Antioch clay	5	29.5	17.8	15.5	38.6	28.5	29.0	26.9	16.5
Indio loam (2 feet)	72	30.3	8.8	5.7	37.5	32.5	31.4	27.9	6.7
Yellow clay loam (Stevens No. 2)	20	31.0	20.2	16.9	34.5	31.2	31.1	29.7	18.4
Ducor clay	10	31.2	17.1	14.4	35.3	32.0	32.0	28.7	16.5
Merced loam	35	32.0	16.4	11.7	39.5	36.4	34.9	32.5	13.4
Diablo clay	3	34.1	18.2	15.0	33.1	34.0	33.9	31.0	17.7
Chino silty clay loam (heavy phase)	24	37.1	22.4	19.2	40.5	35.6	36.5	33.9	21.1
Chino silty clay	12	37.6	23.2	20.1	42.8	40.8	39.5	36.1	21.9
Portersville clay	7	40.2	21.2	17.1	46.4	41.5	43.5	41.2	23.2
Olympic clay	9	41.8	24.4	19.9	48.0	42.6	43.1	40.2	23.6
Chino silty clay loam	13	43.2	23.3	14.4	53.1	48.9	47.0	44.0	15.0
Yolo clay	6	45.9	29.6	23.6	52.3	45.1	48.1	43.5	26.2
Total [3]	--------	918.2	476.2	366.3	1,061.7	926.4	917.4	843.1	407.9

[3] Omitting soils 68, 73, and 78.

Figure 2 is a scatter diagram showing the relation of the 15-atmosphere percentage to the wilting range. Vertically placed pairs of points give the position of the ultimate and the first permanent wilting percentage of each soil on the moisture scale. The intersection of a vertical line connecting a pair of points with the diagonal locates the 15-atmosphere percentage with respect to the wilting range. It is seen that with but comparatively few exceptions for the soils tested the 15-atmosphere percentage lies in the wilting range. It is estimated that if the complete root system of the wilted plant had been removed from the soil the wilting percentages would have been reduced by 0.2 to 0.3 percent. This reduction would bring the 15-atmosphere percentage of all but 7 of the 71 soils within the wilting range.

The location of the 15-atmosphere percentage in the wilting range may be indicated by another method. The soils in table 1 have been divided into a coarse group (moisture equivalent less than 16 percent) and a fine group (moisture equivalent 16 percent or higher). Totals of the data are given for all of the soils in the two groups except the five for which the data are incomplete. From these totals it is seen that for the coarse group the 15-atmosphere percentage lies in the wilting range and only 0.04 of the wilting range from the ultimate wilting percentage,and for the fine group the 15-atmosphere percentage is 0.38 of the wilting range from the ultimate wilting percentage.

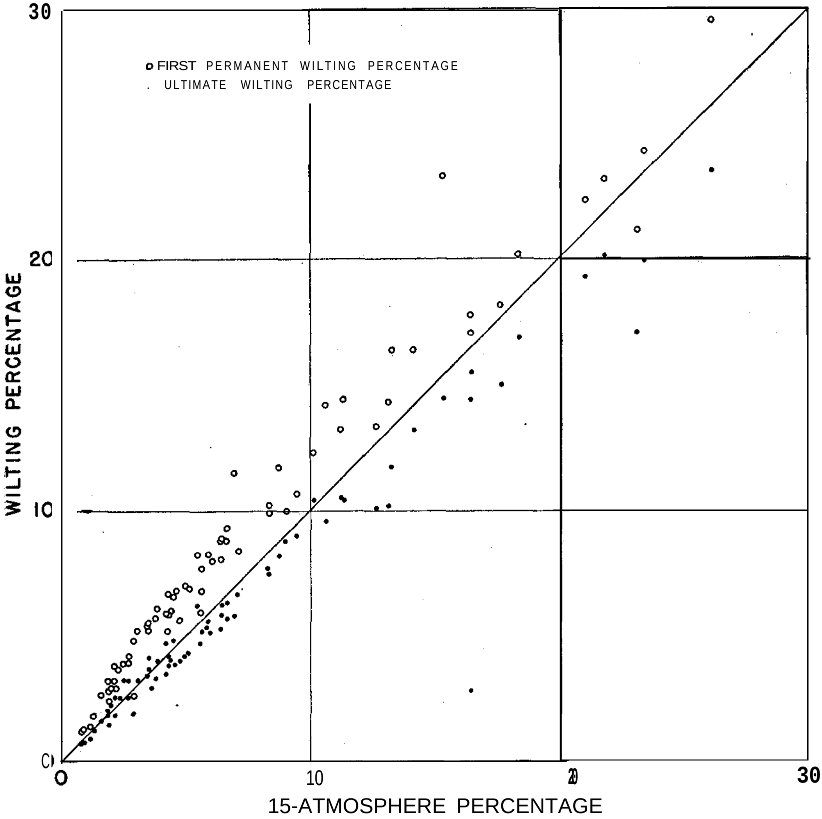

FIGURE **2.-A** scatter diagram showing the relation of the 15-atmosphere percentage to the wilting range.

The-problem of getting representative samples was given particular attention. Subsamples were taken in such a way as to cause a minimum of particle-size segregation after “pulling” all of the original sample on a Koroseal-coated cloth. The 15-atmosphere percentages shown in figure 2 and table 1 are the average of triplicate determinations. The coefficient of variation [7] for the determinations was larger for the coarse soils, running as high as 5.0 in some cases, but the average coefficient of variation for the whole group of soils was 1.46.

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[7] Standard deviation expressed as percentage of mean.

Determination of the 15-atmosphere percentages was made on 21 individual soil samples in one extraction unit at one time by placing the samples in rubber rings 4.1 cm. in diameter and 1 cm. high. The rings were cut from the inner tube of a bicycle tire. The samples were covered with individual squares of waxed paper when placed in the cell so as to minimize vapor losses during transfer to moisture boxes at the end of a run.

SOIL-MOISTURE TENSION AND THE MOISTURE EQUIVALENT

The scatter diagrams in figure 3 show the relation between moisture equivalent as determined by Purr and Reeves and the moisture retained when these soils are wetted and then brought to equilibrium on the suction plate at the four tension values 250, 345, 440, and 518 cm. of water. The determinations were made in triplicate. The coefficients of variation calculated for the 51%cm. determinations were not related to texture and had an average value of 1.50. It is evident that on an average there is a fairly close relation between moisture equivalent and the moisture retained at the moisture tension of 345 cm. of water (⅓ atmosphere).

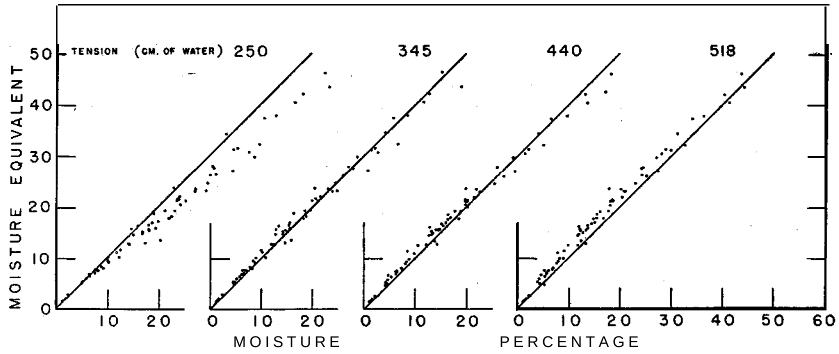

FIGURE 3.-Scatter diagrams showing the relation of the moisture equivalent to the moisture retained by the same group of soils at soil-moisture tensions of 250, 345, 440, and 518 cm. of water. Comparison of the change produced by the various tension increments is aided by the 45° reference lines,

The totals in table 1 indicate that the g-atmosphere percentage is slightly lower than the moisture equivalent for the coarse soils and slightly higher than the moisture equivalent for the fine soils.

It will be noted that there are inconsistencies in table 1. At moisture tensions of 345 and 440 cm. of water, a lower moisture content was found at the lower tension for some of the soils. The authors feel that these inconsistencies were caused by sampling error and do not indicate an inherent lack of precision in the suction-plate procedure, since there was excellent agreement among the triplicate determinations (coefficient of variation, about 1.5). Chronologically the moisture-retention values for the soils at 345 cm. of water tension were the last data determined in the table, and although considerable care was used in subsampling, the inconsistencies in the table seem to indicate that repeated subsampling shifted the texture of some of the stock samples toward lower moisture retention.

TEMPERATURE EFFECT ON MOISTURE RETENTION

Because of the evidence in the literature that temperature has a definite effect on moisture retention, it was felt that part of the scatter in figures 2 and 3 might arise from the fact that the various moisture-equivalent and wilting determinations were made at different temperatures. To get information on this point, **12** soils, covering a wide texture range, were selected from the laboratory-stock samples and the Furr and Reeves collection. Triplicate determinations of the ½-atmosphere percentage and the 15-atmosphere percentage were made for each soil at 4 different temperatures. The results of these measurements are given in table 2 and figure 4. Slope and intercept values for least-square straight lines are given in table 2, and these lines are shown in figure 4 along with the experimental points. With but one exception the slopes were negative, as would be expected from the effect of temperature on surface tension. The change in moisture retention per degree of change in temperature increased from coarse to fine texture, but appeared not to be linearly related to the moisture retention of the various soils at any given temperature and tension.

TABLE 2.—*Effect of* temperature on *moisture retained at ½ and 16 atmospheres*

Soil type	Accession No.	Moisture retained at ½ atmosphere and indicated temperature (°C.)					$\frac{dPw}{dt}$ [1]	Moisture retained at 15 atmospheres and indicated temperature (°C.)					$\frac{dPw}{dt}$ [1]
		[1] 0	12.2	21.2	29.7	37.2		[1] 0	12.4	21.1	29.5	37.5	
		Percent	*Percent*	*Percent*	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	
Tujunga sand	52	2.76	2.47	2.42	2.23	1.99	-.0193	1.66	1.46	1.25	1.23	1.00	-.0167
Placentia sandy loam	43	6.10	5.94	5.80	5.63	5.60	-.0144	3.49	3.15	3.03	2.78	2.55	-.0244
Hanford gravelly sandy loam	26	8.49	8.28	8.50	8.30	8.46	.0041	3.88	3.45	3.49	3.31	2.82	-.0245
Placentia loam	28	12.62	12.48	12.41	12.16	12.24	-.0118	6.36	5.79	5.72	5.39	[2] 4.88	-.0363
Sagemoor fine sandy loam	S-40-10	11.90	11.68	11.64	11.28	11.35	-.0163	6.92	6.18	5.80	5.25	4.79	-.0563
Indio very fine sandy loam	S-40- 4	18.99	18.31	17.86	17.98	16.87	-.0494	6.80	6.49	6.23	6.00	5.83	-.0264
Chino loam	30	18.78	18.45	18.39	17.78	17.96	-.0252	8.91	8.20	7.94	7.41	6.94	-.0614
Billings clay	S-40- 7	22.92	22.15	20.66	20.82	19.81	-.0823	9.41	8.77	8.56	8.13	7.66	-.0448
Altamont clay loam	14	15.36	15.32	15.28	14.86	15.28	-.0070	10.28	9.27	9.46	8.74	[2] 7.90	-.0572
Meloland clay	S-40- 2	28.25	28.00	27.60	27.51	27.32	-.0257	17.11	15.63	14.93	14.13	12.8;	-.1082
Antioch clay	5	28.29	27.67	26.67	26.31	26.00	-.0649	20.33	18.28	16.79	15.76	14.06	-.1634
Yolo clay	6	44.73	44.37	41.80	42.83	41.81	-.0808	30.75	28.20	26.04	24.96	22.69	-.2102

[1] Values taken from least-square equation having the form $Pw=a+bt$, where Pw represents moisture percentage, t represents temperature, $a=Pw$ for $t=0$ and $b=dPw/dt$.

[2] Values calculated by C. H. Wadleigh, using the missing-plot technique.

SOIL-MOISTURE RETENTION CURVES

Curves showing the relation between the security with which water is held by soil and the amount of water in the soil are being increasingly used in soils work because of their relation to pore-size distribution, structure, and the nature and extent of the soil surface (5, 9).

The curves shown in figure 5 were obtained on air-dried and screened soil samples, this being the normal preparation for moisture-equivalent and wilting-point determinations. The jog in the curves at the 1-atmosphere percentage occurs at the juncture between pressure-plate and pressure-membrane data. With one exception for the curves shown, the discrepancy is less than 0.5 percent and is

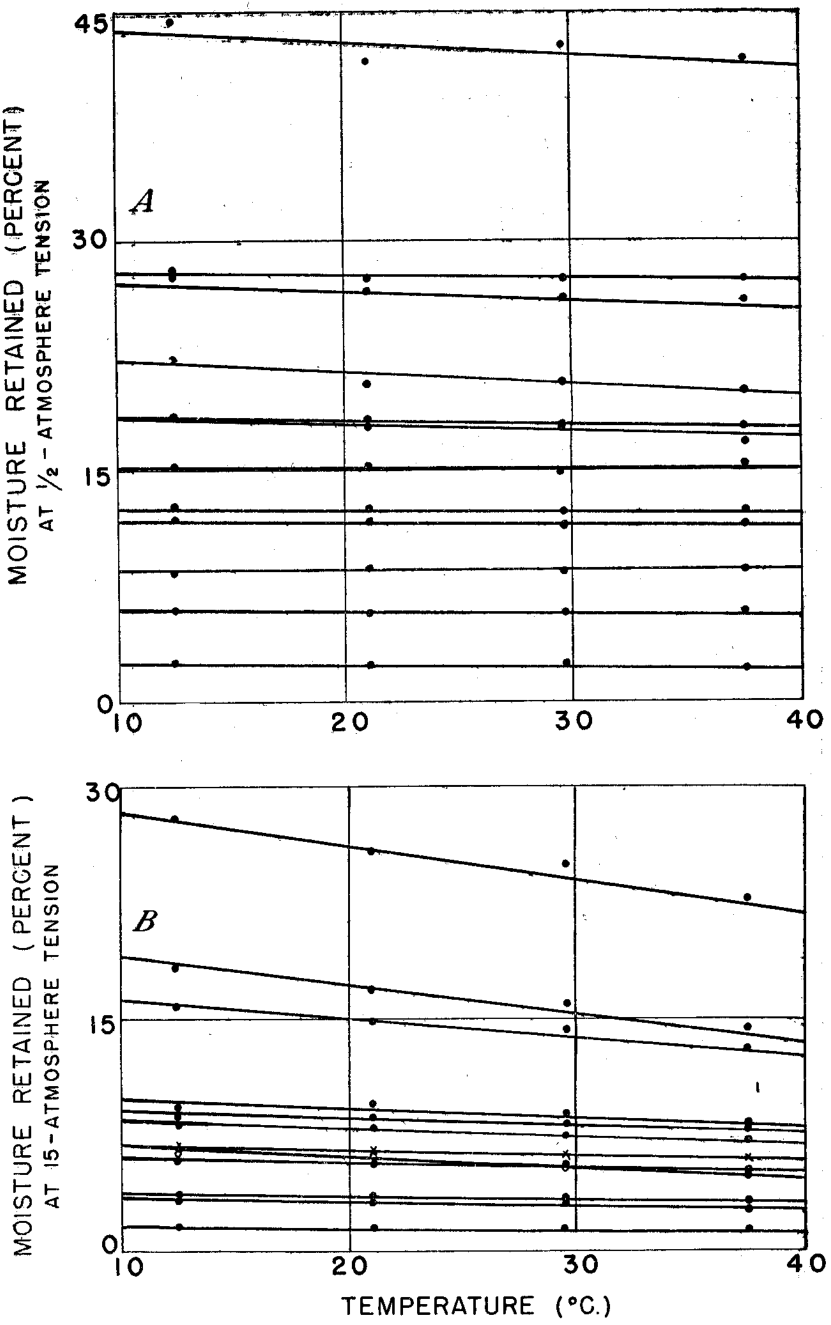

FIGURE 4.—Effect of temperature on the moisture retained by a group of soils at one-half atmosphere (*A*) and 15 atmospheres (*B*) of soil-moisture tension.

believed to be due to soil differences or other imperfection in experimental procedure and is not to be attributed to the change from the ceramic plate to the cellulose membrane. Curves obtained on

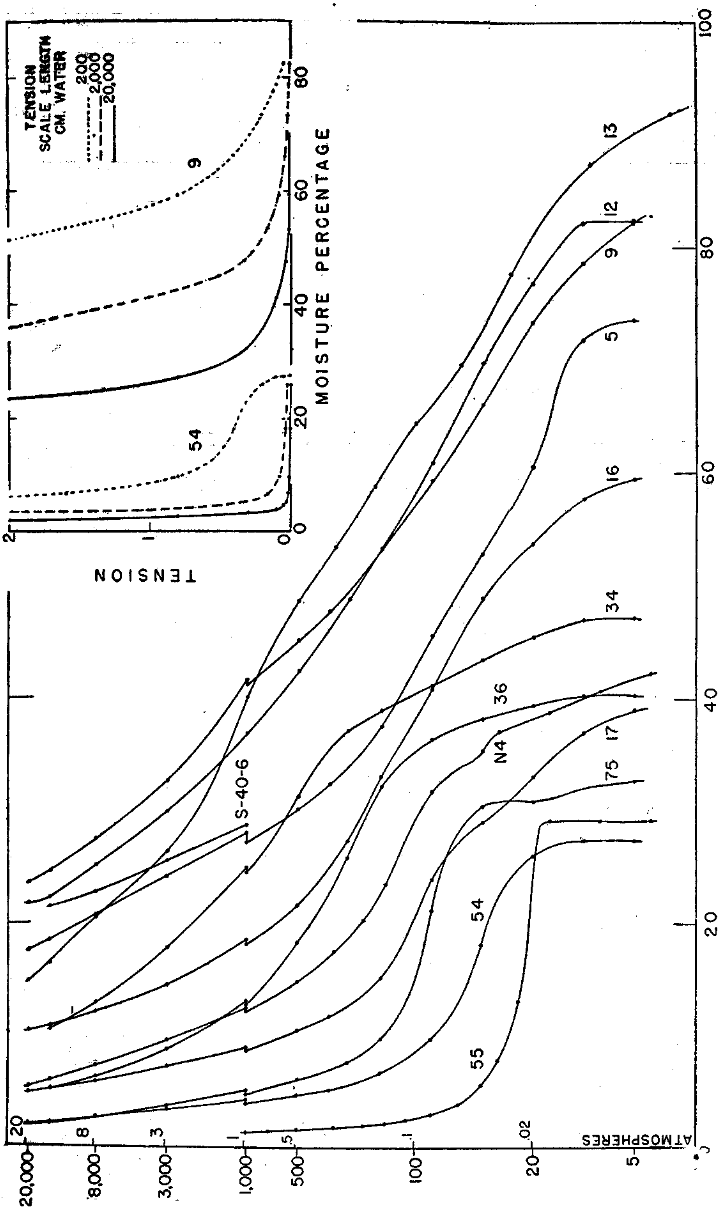

FIGURE 5.—Moisture-retaining properties of soils. The logarithmic scale is helpful for giving a visual comparison over a wide tension range. To show the effect of the kind of scale on the apparent slope of the retention curve, data from the logarithmic curves for soils 54 and 9 are each replotted on three different linear scales in the upper right-hand corner.

duplicate samples agree closely, if care is taken to insure that the samples are as nearly as possible identical. The high-tension parts of the curves were obtained by spreading approximately 420 gm. of dry soil on a circular Visking membrane *29* cm. in diameter, whereas for the low-tension data approximately 55 gm. of soil was spread on a ceramic plate 8.9 cm. in diameter.

A number of interesting facts are brought out by the curves plotted on the logarithmic scale. The marked differences in slope and the crossing of the curves in the high-tension range discourage any attempt to find a general relation between moisture equivalent and the wilting percentage. It is apparent that some of the curves that coincide at the 15-atmosphere tension axe widely separated at lower tensions. Since the position and slopes of the curves at the higher tensions are determined largely by the kind and amount of soil colloid, it is likely that moisture-retention data on the extracted colloid will have some use in colloid identification work. The Aiken soil is known to have predominantly kaolinitic colloid and in the field has *a* very narrow range of moisture available for plants, as indicated by the steepness of the moisture-retention curve for the Aiken soil, which is marked S-20-6 in figure 5.

The smooth curves between the experimental points might be somewhat altered if additional points were determined. In the low-tension range the curves are shifted considerably by small changes in the history or physical condition of the sample, but this sensitivity increases the usefulness of the curves for studying the stability of structure as proposed by Childs (5). Since the determinations were made on air-dried and screened samples, the curves differ from those that would have been obtained with field structure.

The moisture-retention data shown by the logarithmic curves for soils 54 and 9 in figure 5 are replotted in the upper right-hand corner of the figure on linear scales. This was done to illustrate the effect of the method of plotting on the apparent shape of the curves. The same moisture scale was used for all of the inset curves, but the dotted curves show the retention data for O-200 cm. of water; the broken curves, for 0-2,000 cm.; and the solid-line curves, for 0-20,000 cm. It is at once apparent that the position of the “knee” of the curve on the moisture axis depends on the scale and the amount of the retention curve being examined. The appearance of rapid change in the slope of the curve in this region has no special biological or physical significance as far as the moisture-retaining characteristics of the soil are concerned.

SOIL-MOISTURE RELATIONS IN THE l-ATMOSPHERE RANGE

The moisture equivalent has been widely used as an index of moisture retention by soil, and it is interesting to see how this constant is related to the moisture-retention curve.

The work of Schaffer, Wallace, and Garwood (16) indicates that the pressure in the soil moisture is zero at the periphery of the moisture-equivalent centrifuge sample. From this boundary condition, the soil-moisture-tension values at successive l-mm. distances from the periphery or moisture-outflow surface of the centrifuge sample may be calculated (15) from the equation $T = (\omega^2/2g)(r_1^2 - r_2^2)$ and are found to be successively 0, 101, 201, 301, 400, 498, 596, 692, 789, 884, and 979 cm. of water. Quantities represented by the symbols in the equation are T, tension; ω, angular velocity of centrifuge; g, acceleration of gravity; r_1 and r_2, distances from center of rotation. The depths of the soil after cenfrifugation for a number of 30-gm. moisture-equivalent samples were carefully measured, and the majority were found. to range from 9 to 10 mm. deep.

TABLE 3.--Moisture-retention *data as related to moisture equivalent,* tensiometer range, and *field*

Item	Soil accession No.											
	55	54	75	17	N4	36	16	34	5	12	9	13
(1) Moisture equivalent..	1.9	5.0	7.4					26.8	29.5	37.6	41.8	43.2
(2) Average *Pw*[1] from curves in figure 5 over 0.1- to 1.0- atmosphere tension range_.	1.6	5.0	6.5	10.9	15.5	19.6	23.0	31.5	30.6	43.3	45.9	43.9
(3) Ratio between numbers in item 2 and item 1....	.84	1.00	.88	1.00	1.22	1.10	1.08	1.16	1.04	1.15	1.10	1.13
(4) Tension value on curve at *Pw* in item 2	450	400	420	410	420	442	415	483	450	450	450	475
(5) Pw at 40 cm. of water tension_	5.5	18.1	30.4	29.0	35.4	38.2	48.9	43.4	52.8	69.8	68.3	72.7
(6) Ratio of Pw at 40 cm. of water tension to the moisture equivalent multiplied by 2.	1.42	1.81	2.05	1.33	1.39	1.07	1.15	.81	.89	.93	.82	.84
(7) Difference between Pw at 0.1- and 0.85-atmosphere tension..	1.25	4.5	11.6	12.1	16.3	21.0	19.6	13.8	12.8	19.3	16.3	21.1
(8) Difference between Pw at 0.1- and 15-atmosphere tension..	1.7	6.7	14.9	15.7	23.4	31.0	28.4	29.8	23.8	36.1	33.7	49.4
(9) Ratio between numbers in item 7 and item 8	.74	.67	.78	.77	.70	.68	.69	.46	.54	.53	.45	.43

[1] The symbol *Pw* represents percentage of water in the soil expressed on a dry-weight basis.

It is difficult to say exactly where in the centrifuge soil-cup system the zero-pressure boundary condition applies. If this is taken to be the surface between the screen and the centrifuge case, then about **1** mm. is taken up by the screen and the filter paper, and on the basis of the above calculations this would give a tension of 100 cm. of water at the outer surface of the soil. The moisture equivalent is the average moisture content for the whole centrifuge sample and, therefore, should be the average of moisture values taken from a retention curve at points corresponding to the tension and packing at successive 1-mm. layers of the sample. Since the departure from linear tension distribution is small, it should be possible to approximate the moisture equivalent by averaging the moisture-content values on the moisture-retention curve for the centrifuged sample between the tension limits determined by the distances of the inner and outer soil boundary from the water-outflow surface. The average moisture percentage for the 100 to 1,000 cm. of water-tension range of each of the curves in figure 5 was determined, and these values are given in item 2 of table 3. The ratios of these average values to the corresponding moisture equivalents are given in item 3. The average value ratio is 1.06. These results are about what might be expected, since for most soils centrifugation produces denser packing and less pore space than existed in the uncentrifuged pressure-plate samples. The curves in figure 5, particularly at lower tensions, show higher moisture retention than would be found if the samples had been compacted in the centrifuge. The foregoing analysis, therefore, supports the view that the moisture equivalent is the average value over approximately the 0.1- to 1.0-atmosphere tension range for a moisture-retention curve that. takes into account centrifuge packing effects.

It is becoming increasingly clear that the moisture equivalent cannot be generally used as an index of either the upper (3, 11) or the lower [8] (20) limit of moisture usable by plants in the field. Moisture equivalent has the advantage of being a definite reproducible quantity not too difficult to determine, but this is insufficient justification for its continued use provided something more closely related to the available moisture range can be found. It is apparent from figure 3 that moisture-retention values in the ¼- to ½-atmosphere ranges are too closely related to moisture equivalent to be of appreciably greater use or significance, except that (1) they are less expensive to determine and (2) they do represent a more definite physical property of the soil moisture. This latter is some advantage since it makes the determination independent of the kind of apparatus used, provided, of course, that the procedure does not alter the condition of the sample. As a substitute for moisture equivalent the 1/3-atmosphere percentage appears to merit some consideration, but the authors feel that the expression “moisture equivalent” should be used only in connection with determinations made with the Briggs and McLane equipment.

From tensiometor data now available for several soils it appears that field capacity may correspond to a tensiometer reading somewhere near 0.1 atmosphere, but there seems to be no distinctive feature of the tension-time curve following irrigation that can be associated with the condition of field capacity. If further field measurements should indicate that there is a certain tension range that approximates field capacity, it would be possible, by adjusting the height of the sample, the thickness of *a* standard porous pad under the sample, and the speed, to set up a centrifuge method that would give the average moisture percentage for any section of a moisture-retention curve. The fact that the field capacity depends on the nature and condition of the whole profile, including the initial moisture distribution! the moisture-transmitting properties of the soil, the moisture-retaining properties of the soil, and the amount of water applied, increases the difficulty of basing a field-capacity estimate on a soil sample isolated from the profile.

It might be expected that an estimate of field capacity could be more readily based on a soil sample having field structure than on one that is dried and screened, but the advantages of the latter for routine work are obvious. Centrifuge packing may partly overcome the structural disruption caused by screening, but the ratio of field capacity to moisture equivalent is considerably higher for coarse than for fine soils (3, 11). The possibility that *a* moisture-retention value at a lower tension than the j&atmosphere percentage may be a better indication of field capacity is suggested by the fact that this tension empties a relatively larger fraction of the pore space for the

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[6] See footnote 3, p. 216.’

coarse-textured soils than for the fine-textured soils. The numbers given in item 6 of table 3 were obtained by dividing the moisture retained at 40 cm. of water tension (item 5) by twice the moisture equivalent. These numbers when plotted against moisture equivalent correspond closely to Browning's (3) field-capacity moisture-equivalent ratio curve when the latter is corrected for the difference between the Gooch crucible and the standard. moisture-equivalent procedure. This correspondence indicates that for these 12 soils half the water retained at 40 cm. of water tension by a sample that has been air-dried and screened closely approximates the field capacity as determined by Browning. This agreement may be only fortuitous, but it is possible that further work along this general line may yield a useful field-capacity index.

The curves in figure 5 give basis for an estimate of the fraction of the available range of moisture over which tensiometers can be used. Item 7 in table 3 gives the difference between the O.l-atmosphere percentage and 0.85-atmosphere percentage, these being common limits between which field tensiometers (13) have been found to operate. The figures in item 8 are the difference between 0.1-atmosphere percentage and 15-atmosphere percentage and are a measure of the available range of moisture for the various soils. Item 9 gives the ratios of the numbers in item 7 to those in item 8 and indicates the fraction of the available range over which tensiometers can be used. This fraction is seen to vary from less than 0.5 in the fine soils to about 0.8 in the coarse soils. Under conditions of restricted drainage, this fraction is appreciably increased. For a soil having a permanent wilting percentage of 3.7, which was used in 20-gallon culture cans provided with free drainage, it has been found that the moisture range over which tensiometers operate comprises 0.9 of the available range.[9]

SOIL-MOISTURE TENSION IN THE WILTING RANGE

Since it is not yet possible to measure directly the soil-moisture tension in a sample of soil in the wilting range, some information on the range in tension that corresponds to the wilting range may be obtained indirectly by placing the wilting percentages on the moisture-retention curves (14, 21).

In figure 6 the first permanent wilting percentage and the ultimate wilting percentage as determined by Furr and Reeves have been located on moisture-retention curves determined with the pressure-membrane apparatus. Broken lines indicate where the curves were extrapolated beyond the experimentally determined points. From these results it would seem that neither the first permanent wilting percentage nor the ultimate wilting percentage is closely related to soil-moisture tension.

To get information on the free energy, or pF, at wilting for the Furr and Reeves samples requires consideration of soluble salt content as well as soil-moisture tension. The osmotic concentration of the soil solutions at the wilting points could have been determined by measuring the freezing points on soil solutions extracted from samples in which the sunflowers were wilted. This was not done,

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[9] Correspondence with C. S. Scofield concerning work in progress at the Rubidoux Laboratory, Riverside, Calif.

but an estimate of the osmotic pressures involved can be obtained by another method. Column 2 of table 4 gives the moisture percentage of the soils at the beginning of the extraction process used for the determination of the curves in figure **6.** The amounts of dissolved solids in the extracts were determined, and the soluble salt content of the soils, expressed as percentage on a dry basis, is given in column 3. Column 4 gives the osmotic concentration of the extracted solution. This latter was obtained by dividing the electrical conductivity expressed in micromhos (at 25° C.) by 28.5.[10] Multiplying these values by the ratios of the initial extraction percentage to the wilting percentages gives an indication of the osmotic pressures at the wilting points.” The remainder of the table gives the soil-moisture tension, the osmotic concentration, and the sum of these two at first permanent wilting and ultimate wilting.

TABLE 4.--Soil-moisture *tension and osmotic concentration of the soil solution at wilting*

Soil accession No.	*Pw* before extraction	Soluble salt in soil	Osmotic concentration of extract	First permanent wilting			Ultimate wilting		
				Soil-moisture tension	Osmotic concentration	Soil-moisture tension + osmotic concentration	Soil-moisture tension	Osmotic concentration	Soil-moisture tension + osmotic concentration
		Percent	*Atmos.*	*Atmos*	*Atmos.*	*Atmos*	*Atmos.*	*Atmos*	*Atmos.*
49	65.3	0.06	0.37	*8.8*	4.2	13.0	23.7	6.0	29.7
74	61.2	.06	.34	*8.0*	3.4	11.4	35.5	6.3	41.8
79	58.7	.04	.26	*7.0*	2.2	9.2	28.9	4.0	32.9
73	74.2	.08	.31	*9.2*	3.3	12.5	27.0	5.5	315
33	45.8	.04	.33	7.7	1.9	9.6	18.4	2.4	20.8
38	53.7	.10	.71	5.0	4.6	9.6	16.4	6.7	23.1
80	76.0	.05	.30	7.8	2.6	10.4	27.0	4.3	31.3
72	89.3	.08	.35	8.8	3.5	12.3	20.5	5.5	26.0
15	62.0	.36	1.47	5.9	9.8	15.7	20.9	14.5	35.4
14	66.7	.06	.22	8.7	1.5	10.2	16.0	1.7	17.7
22	71.9	.07	.36	9.7	2.4	12.1	21.4	2.9	24.3
78	83.7	.06	.31	5.8	2.3	8.1	24.8	4.5	29.3
18	70.7	.11	.76	7.2	4.6	11.8	21.9	6.6	28.5
16	85.6	.07	.33	7.2	2.3	9.5	24.0	2.7	26.7
8	72.5	.06	.34	12.9	1.9	14.8	42.2	2.4	44.6
25	82.9	.07	.37	7.0	2.1	9.1	25.2	2.5	27.7
23	88.7	.26	.91	6.3	5.6	11.9	18.4	7.8	26.2
1	88.3	.16	.73	8.2	3.9	12.1	23.2	4.9	28.1
10	79.4	.04	.21	13.2	1.0	14.2	27.6	1.2	28.8
3	87.9	.08	.37	11.2	1.8	13.0	27.6	2.2	29.8
20	102.8	.11	.40	8.9	2.0	10.9	21.9	2.4	24.3
7	92.4	.08	.33	7.2	1.4	8.6	58.2	1.8	60.0
24	114.0	.13	.40	5.6	2.0	7.6	23.7	3.0	26.7
6	126.2	[1] 1.60	3.77	7.5	16.0	23.5	24.0	20.1	44.1

[1] This soil was leached before determining the wilting percentages.

The frequency diagrams in figure 7 summarize the moisture-retention data at the two wilting values. It is seen that first permanent wilting for these soils occurred in the tension range **5** to **13** atmospheres, with **14** out of the **24** soils wilting in the 7- to g-atmosphere range. When osmotic effects are added to soil-moisture tension it is seen that at first permanent wilting these soils are distributed fairly

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[10] MAGISTAD, O. C., AYERS, A. D., WADLEIGH, C. H., and GAUCH, H. G. EFFECT OF SALT CONCENTRATION KIND OF SALT, AND CLIMATE ON PLANT GROWTH IN SAND CULTURES. Plant Physiol. 18: 151-166. 1944.

[11] This calculation is only an approximation, since it involves the assumption that the total dissolved solids and the degree of ionization remain unchanged as the plants dry the soil from the initial extraction percentage to the wilting points. Also the factor 28.5 is not constant but depends on the composition of the salts present.

uniformly over the equivalent pressure range from 7.5 to 16 atmospheres.

Ultimate wilting occurs over a much wider tension range than first permanent wilting. The soil-moisture tension at ultimate wilting was below 30 atmospheres for all but 3 of the soils, and 17 out of the 24 soils underwent permanent wilting in the tension range from 20 to 30 atmospheres. Combining osmotic pressure with soil-moisture tension at ultimate wilting causes no significant rearrangement or grouping of the points in the frequency diagram.

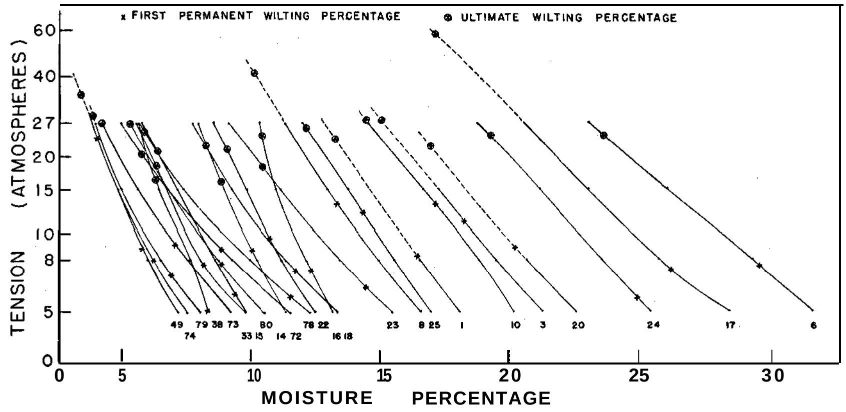

FIGURE 6.-Moisture-retention curves in the wilting range as determined with pressure-membrane apparatus. The ultimate and first permanent wilting percentage' points provide an indirect indication of the range in tension.

One conclusion that might be drawn from figure 7 is that the phenomena of first permanent and ultimate wilting occur over a range in tension or free energy. Unfortunately these results must be regarded as tentative, because the moisture-retention curves in figure 6 were determined when many of the soil samples were nearly exhausted from subsampling by different people, and it is possible that the final samples were not entirely representative of the original samples in which the sunflowers were grown.

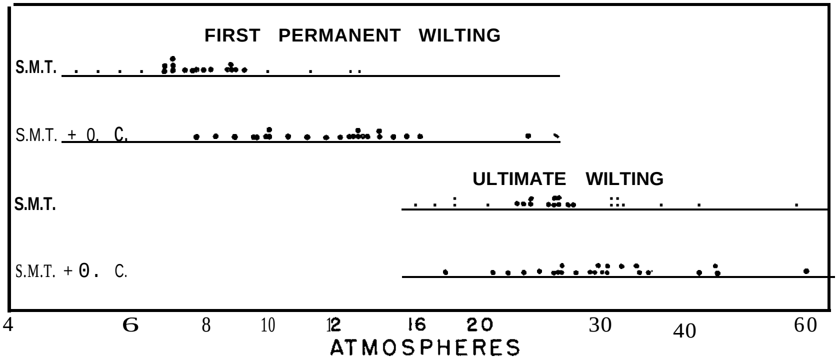

FIGURE 7.-Soil-moisture tension and sum of soil-moisture tension and osmotic concentration at first permanent wilting and ultimate wilting.

MOISTURE MOVEMENT IN THE WILTING RANGE

The pressure-membrane apparatus appears to provide a useful means for studying moisture movement in'relatively dry soils, The curves in figure S show typical summation extraction data from which the curves in figure **6** were determined. The zero of the water-extracted scale was taken at the 5-atmosphere equilibrium, and to conserve space in graphing the curves were returned to the zero of the time *scale* at each pressure increment. The extraction pressures are indicated on the curves.

A burette clamp was used to mount an ordinary 100-ml. stopcock burette on one of the tripod legs of the extraction cell, and the extracted solution was led to the burette tip through a 0.16-mm.-bore copper tube which was closely coupled with rubber tubing. With this arrangement, the gas diffusing through the membrane keeps the extracted solution transported to the burette and a solution outflow of 0.10 ml. or less is easily detectable. The cross on each curve indicates the burette reading at which equilibrium was attained and beyond which no further outflow took place. It is significant that when the 15-atmosphere equilibrium was attained no further outflow took place during a 10- to 15-hour period, but when the extraction pressure was stepped up to 27 atmospheres outflow immediately commenced and continued until a new equilibrium was reached.

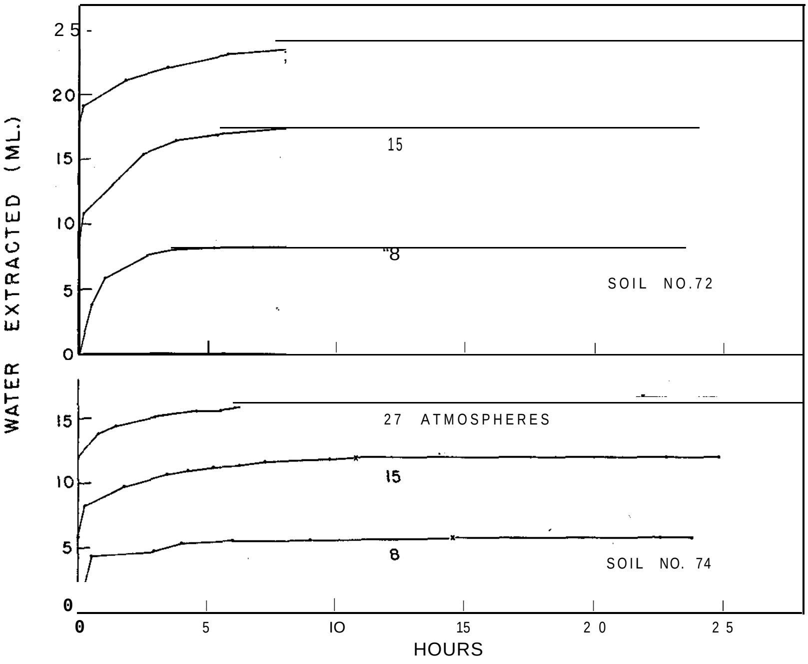

FIGURE S.-Summation extraction data for two soils, indicating rate of water movement in the 5- to 27-atmosphere tension range. The data were obtained from 400 gm. of soil on a Visking membrane having an area of 660 cm.^{2}

There is no indication that 27 atmospheres is anywhere near the limit for this type of experiment either for the satisfactory operation of the membrane or the moisture-transmitting properties of the soil. Moisture extraction through a Visking membrane has been continued at 15 atmospheres for periods as long as a month with no apparent weakening of the membrane or development of leaks. There is a steady diffusion of gas through the membrane during extraction, and this diffusion rate for nitrogen is approximately 1.3×10^{-6} ml. cm.$^{-2}$ sec.$^{-1}$ atmos.$^{-1}$. Apparently iron rust has a decidedly deteriorating effect on the membrane and will cause leaks in a short time. Trouble from this source can be prevented by a protective coating on the cylinder of the extraction cell.

On the basis of experiments by Lewis (10), it is inferred that moisture movement of the type illustrated in figure 8 is over the *surface* of the soil and that vapor transfer plays a minor role in the absence of temperature gradients.

The statement is repeatedly made in the literature that moisture movement in unsaturated soil ceases at some moisture content not far below the field capacity. This is substantially true for practical purposes when dealing with such problems as the motion of a 12-inch irrigation into a B-foot layer of dry soil, but one would hesitate to say that moisture movement of the magnitude shown by the 27-atmosphere curves in figure 8 is of no practical importance in time of drought to plants with established root systems.

SOIL-MOISTURE ENERGY RELATIONS

Various means have been used in the past [12] (4, 17) for expressing the energy of retention of *water* by soil, or the physical condition of water in soil at various moisture contents. The work involved per unit mass in the transfer of a small element of water between a reference state such as a free flat water surface and the moisture system in soil can be expressed in terms of the thermodynamic function partial molal or partial specific free energy. Edlefsen (7) and Edlefsen and Anderson (8) have recently discussed this function and its usefulness in connection with soil moisture and plant work. Various physical processes and mechanisms contribute to the retention of water by soil, but the free-energy function seems to be suitable for the most, general treatment of soil-moisture problems from the energy standpoint. Unfortunately, convenient and accurate methods for measuring the free energy of soil moisture over the plant-growth moisture range are not now available. Vapor-pressure methods do not yet have sufficient precision. Free-energy determinations from freezing-point depression measurements have been made with some success by Schofield and Botelho da Costa (18), Bodman and Day (I), and Edlefsen and Anderson (8), but results appear to depend on the experimental procedure used and difficulties are encountered at moisture contents in the wilting range. As improvements in measuring methods are made (IQ), it is likely that correct use of the theory in calculating the free energy of soil water from freezing-point data will become easier.

On the basis of experimental results obtainable with pressure-membrane apparatus, it is convenient to divide the forces contributing to the energy of retention of moisture by soil into two classes: (1)

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[12] DAY, P. R. THE MOISTURE POTENTIAL OF SOILS BY THE CRYOSCOPIC METHOD. 132 PP. 1940. [Thesis on file at Univ. Calif., Berkeley, Calif.]

Those arising from dissolved materials as expressed in terms of osmotic concentration of an-extracted sample of the soil. solution and (2) all other forces. Force action of the second class can be measured by the use of membranes permeable to the soil solution. The physical quality that is determined experimentally by such membranes is the negative pressure to which a solution must be subjected to be at equilibrium through the membrane with the same solution in the soil.

Past discussions of soil-moisture energy relations have often been confused or ambiguous in their handling of osmotic effects. In spite of its historical significance, the usefulness of capillary potential is considerably lessened by its indefiniteness and by the fact that it is sometimes used as including and sometimes as excluding osmotic effects. It is clear that soil-moisture retention data obtained with tensiomcter, suction-plate, pressure-membrane, or centrifugation apparatus are independent of and do not involve solution concentration effects except insofar as the presence of soluble material changes such physical properties of the system as surface tension and density of. the soil solution or hydration and flocculation of the soil colloid. Schofield (17), in a fruitful and stimulating paper, proposed the pF as a free-energy scale, specifying vapor-pressure and freezing-point methods for its determination.. But in the same paper he expressed suction-plate and centrifugation data in terms of pF, thereby neglecting without comment the effect of soluble salts on pF. Many other. writers have perpetuated this error in the literature (9, 15, ***21).***

If pF is to bc accepted as a free-energy scale it should be correctly used and should be clearly distinguished from pressure deficiency or soil-moisture tension. In leached soils, of course, the osmotic component of the pF can be negligible, but in normal soils from semiarid or irrigated regions, dissolved material may account for the major part of the free energy of the soil water. For example, Botelho da Costa (2) measured freezing points for 14 California soils supplied by Veihmeyer and found that the average pF at the moisture equivalent was 3.07. Day.,[13] using'a different freezing-point technique on another set of **14** California soils, found the average value of the pF at the moisture equivalent to be 2.97. If osmotic effects are disregarded, the calculation of tension values from these pF values gives 1,175 and 987 cm. of water, whereas both theoretical and experimental results in a preceding section of this paper indicate that the soil-moisture tension at a moisture percentage equal to the moisture equivalent will account for less than half of these energy values.

At this laboratory, where the effects of salt on the growth and yield of plants are being studied, attempts are being made to segregate and evaluate the effects of soil-moisture tension and osmotic concentration as they operate to determine the availability of moisture to plants. Apparently, considerable work must be done before the energetics of wilting will be well understood, because at present, information on salt effects related to this phenomenon are fragmentary and conflicting.

There is a simple but significant experiment that seems to have a direct bearing on the relation of salt to moisture movement in soil. If a tensiometer is filled with distilled water and the manometer is allowed to attain an equilibrium reading with the porous cup standing in distilled water at a fixed level above the porous surface, it is found

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[13] See footnote 12, p. 232.

that the manometer indicates practically no change in pressure (less than 0.003 atmosphere) when saturated sodium chloride or other strong salt solution is substituted for the distilled water surrounding the cup. From this it is inferred that in soils in the absence of semipermeable membranes, moisture flow is produced primarily by gravity and gradients in soil-moisture tension and not directly by solution concentration gradients. The semipermeable characteristic of the plant root with its discriminating action against the uptake of most of the common salts must cause a build-up of the salt concentration at the root surface during moisture absorption, and it is possible that a correct appraisal of the root environment with regard to osmotic effects may be even more difficult than with respect to soil-moisture tension.

SUMMARY

By means of porous ceramic and cellulose membranes, a study of soil-moisture retention has been made on samples of 71 southern California soils for which Burr and Reeves determined the moisture equivalent, the first permanent wilting percentage, and the ultimate wilting percentage.

It was found that for 64 of the 71 soils studied the 15-atmosphere percentage lies in the wilting range somewhere between the first permanent wilting percentage and the ultimate wilting percentage. The soil-moisture tension at first permanent wilting for sunflowers was found to range from 5 to 13 atmospheres, but the majority of the soils showed first permanent wilting in the 7- to 9-atmosphere range. The soil-moisture tension at ultimate wilting was below 30 atmospheres for all but 3 of the soils, and 17 out of the 24 soils tested underwent permanent wilting in the range from 20 to 30 atmospheres. Moisture transfer in soils at moisture contents in the wilting range, as indicated by the rate of extraction of moisture from soil in the pressure-membrane apparatus at 15 and 27 atmospheres, is apparently more rapid than can be accounted for by vapor diffusion and should be of practical importance to plant-root systems under drought conditions.

The moisture equivalent is the average value over approximately the O.l- to l.O-atmosphcro tension range for a moisture retention curve that takes into account centrifuge packing effects. From determinations made on a suction plate it was found that, on an average for the 71 soils studied, the moisture retained by an air-dried and screened but uncentrifuged sample at a tension of one-third of an atmosphere corresponds closely to the moisture equivalent. A set of moisture-retention curve?, covering the tension range from 2 to 20,000 cm. of water and for a wide range of soil textures, shows considerable intercrossing of the various curves throughout the whole tension range.

Tensiometer, suction-plate, pressure-plate, pressure-membrane, or centrifugation apparatus may be used for determining equivalent negative pressure or soil-moisture tension, but,, without disregarding osmotic effects, none of these can be used for determining pF if the latter is to be taken as a free-energy scale as originally proposed.

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