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CONTENTS

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MAXIMUM HEIGHT OF CAPILLARY RISE STARTING WITH SOIL AT CAPILLARY SATURATION

CHARLES F. SHAW* AND ALFRED SMITH†

INTRODUCTION

The height to which water will be lifted through a soil by film forces, commonly designated as "capillary rise," is an important factor in many phases of agricultural practice, particularly in determining the depth at which the ground water table should be maintained in order to prevent evaporation from the surface.

In most experiments heretofore reported, the capillary rise has been determined by starting with the soil in an air-dry condition and usually in tubes of relatively small diameter.[3] The experiments of Hilgard[1] have generally been quoted to show a maximum rise of 122 inches in the silt separate with less rise in all the other separates, while the work of Linde and Dupre[2] shows that under ideal conditions, where friction of flow through the soil is eliminated, the total height may reach nearly to thirty feet!

Since most soils in agricultural use are frequently or occasionally wetted to the water table by rain or by irrigation, it was felt that to properly measure the maximum possible "capillary rise" under conditions simulating those in the field, the soils should be started at or near capillary saturation, and the ability of the soil to raise water be measured by the amounts removed from a ground-water reservoir and evaporated from the surface.

* Professor of Soil Technology and Soil Technologist in the Experiment Station.

† Assistant Professor of Soil Technology and Associate Soil Technologist in the Experiment Station.

FIRST EXPERIMENT

Experimental methods.—In the first experiment, conducted in the laboratories at Berkeley, the soil was placed in galvanized iron tubes 8 inches in diameter, and 4, 6, 8, and 10 feet in length. The soil used was Yolo sandy loam from Davis, California. The soil was placed in the tubes by pouring steadily from the top, gently hitting the sides of the tubes to induce settling. There is no doubt but that there was some stratification of the soil in the tube. The tubes were so arranged that their tops were at the same level, just projecting into a tunnel of muslin (on a frame work) through which a constant stream of warm air was drawn by an electric fan. The air entered the tunnel near large steam pipes, and was generally heated to a temperature of from 70° to 85° F. The bottoms of the tubes were placed in closed reservoirs in which a constant water level was maintained by Winchester supply bottles by which the amount of water taken up by each tube could be measured.

The experiment was set up and irrigation water applied on September 1, 1922. Additional water was applied until drainage occurred, when the water in the reservoir was brought to the predetermined level, the constant supply arranged and the reservoir closed to prevent evaporation losses. As drainage occurred first in the case of the shorter tubes, these had a more extended period of evaporation than the longer tubes. Slow drainage from the soil served to add water to the reservoirs and as this was not removed, the quantity from the 8 and 10-foot tubes exceeded the amount lost by evaporation, giving negative results.

Amounts of water evaporated.—The experimental period was completed and the 4 and 6-foot tubes taken down and sampled on November 27, 1922, after 87 days, and the 8 and 10-foot tubes sampled on December 4 and 5, 1922, after 95 and 96 days. During this time the water was used up rapidly by the 4-foot columns of soil and slowly by the 6-foot columns, while one 8-foot column showed a slight loss and the other 8-foot column and both 10-foot columns showed gains in the water reservoir, due to the excess irrigation water draining from the tube. The loss or gain for each tube is shown in table 1.

The tubes were observed daily throughout the experiment, and while the loss of water from the constant-level replenishment reservoir was noticeable and steady for the 4 and 6-foot tubes, none could be observed from the 10-foot tubes and only a little from one of the 8-foot tubes.

TABLE 1

LOSS OF WATER BY EVAPORATION FROM CAPILLARY RISE TUBES CONTAINING YOLO SANDY LOAM (MOISTURE EQUIVALENT = 16), BERKELEY, 1922

Number of tube	Length	Total water evaporated in liters	Water used daily in grams	Equivalent in surface inches monthly
41	4 feet	3.778	43.4	1.5780
42	4 feet	5.027	57.7	2.1000
61	6 feet	1.295	14.9	.5424
62	6 feet	1.700	19.5	.7098
81	8 feet	.361 (gain)	0	.0000
82	8 feet	.423	4.4	.1599
101	10 feet	.084 (gain)	0	.0000
102	10 feet	.334 (gain)	0	.0000

As the soils were dried by evaporation from the surface, water was drawn by film forces from the deeper wet layers. If these forces could maintain a constant film of water from the reservoir to the surface, continuous evaporation would take place, but if the depth to water table was greater than the film forces could lift the water—greater than capillary rise—then no losses from the reservoir could take place.

Distribution of water.—On taking the tubes down, they were sampled by 1-inch sections by use of a modified King tube, and moisture determinations made. The distribution is shown in table 2.

The rather irregular distribution in places is no doubt due to stratification during filling. The graphs in figure 2 show the distribution when the curves were smoothed.

SECOND EXPERIMENT

Experimental methods.—As the drainage from the longer tubes masked the effects of evaporation and capillary rise, a duplication of this experiment was undertaken at Davis, using care to guard against the errors and difficulties encountered in the original experiment. This work was started in August, 1924, and closed in July, 1925, after a period of over ten months.

Eight-inch galvanized iron tubes were again used, the lengths being the same as before: 4, 6, 8, and 10 feet. The soil was Yolo loam from the Armstrong tract at Davis, a soil heavier in texture than that used in Berkeley. Great care was used in filling the tubes to avoid stratification and to insure even packing and uniform volume weight

TABLE 2

DISTRIBUTION OF MOISTURE IN CAPILLARY RISE TUBES AT THE END OF THE EXPERIMENT. YOLO SANDY LOAM (MOISTURE EQUIVALENT = 16), BERKELEY, 1922

Height above water table *inches*	Per cent of water present (dry basis)							
	41	42	61	62	81	82	101	102
1	23.90	22.99	25.11	25.45	21.90	22.85	22.07	24.55
2	23.93	23.80	25.03	24.19	21.30	23.00	22.70	24.80
3	23.24	24.45	24.70	23.40	20.50	22.18	22.87	25.86
4	24.20	26.25	28.73	24.20	21.30	25.11	22.59	26.39
5	24.95	26.85	16.23	23.20	21.40	21.12	22.80	25.60
6	23.33	27.60	25.79	20.10	22.80	20.24	....	25.22
7	25.62	27.20	26.10	18.80	22.90	23.40	24.60	25.35
8	24.24	23.99	26.45	20.43	21.70	23.26	24.81	24.08
9	23.28	22.40	26.70	21.18	....	23.23	24.10	28.30
10	23.21	21.50	25.20	25.50	22.65	30.50	21.55	26.00
11	22.80	19.75	24.90	22.82	22.55	21.18	21.20	25.30
12	22.20	....	24.00	....	22.50	20.20	22.65	24.18
13	20.81	19.95	24.90	22.01	18.10?	18.56	21.43	27.35
14	19.15	20.40	24.45	21.60	15.62?	20.80	21.42	22.97
15	19.91	22.57	23.50	19.80	15.50?	19.65	....	20.78
16	18.77	20.08	22.35	18.26	15.69?	19.41	20.89	18.87
17	19.53	21.70	22.00	18.71	15.76?	16.36	18.44	16.92
18	....	....	21.41	18.60	16.59?	18.34	18.56	20.38
19	....	19.94	17.84	18.40	....	19.74	19.27	19.52
20	18.51	22.88	19.65	19.50	16.50	19.63	18.43	18.15
21	17.09	20.79	20.05	18.30	17.38	19.00	18.67	17.84
22	18.00	20.30	19.07	17.06	18.22	19.40	17.09	17.70
23	16.21	20.38	19.45	17.13	16.54	19.40	14.95?	17.14
24	16.70	16.27	16.95	17.29	15.56	18.45	20.14?	16.23
25	14.05	17.11	18.43	16.95	14.25	17.71	13.67	16.35
26	12.71	15.82	....	16.95	15.36	19.65	16.95	13.71
27	12.16	15.27	17.51	16.84	14.50	28.10	15.50	15.21
28	10.57	16.89	16.85	17.99	12.72	15.25	17.52	17.17
29	12.02	16.87	17.15	16.45	13.74	14.36	14.65	17.54
30	....	....	17.06	....	13.40	15.23	14.63	15.22
31	11.52	15.32	16.80	14.60	13.56	15.78	14.12	17.16
32	12.03	15.10	16.90	16.75	14.81	12.48	13.40	15.55
33	11.13	14.45	16.57	16.18	14.71	14.72	15.58	15.02
34	11.11	14.61	15.91	....	14.24	14.60	13.30?	13.63
35	....	14.55	15.89	15.42	15.20	15.40	16.40?	14.42
36	....	14.30	....	15.35	13.28	13.80	15.38	15.55
37	11.05	13.52	15.25	15.20	13.90	14.92	15.57	14.70
38	10.65	15.05	15.28	15.75	11.95	14.00	14.27	14.50
39	10.60	12.99	16.45	14.39	11.12	14.68	13.27	14.54
40	11.33	13.01	14.89	13.29	12.44	13.39	14.17	14.18
41	9.81	11.09	14.93	14.21	12.94	13.38	14.93	13.46

TABLE 2—(*Continued*)

Height above water table *inches*	Per cent of water present (dry basis)							
	41	42	61	62	81	82	101	102
42	10.12	10.50	15.10	13.91	11.46	14.80	14.03	13.99
43	8.95	8.10	15.04	13.82	12.06	14.00	14.20	12.00
44.	8.47	10.05	14.40	13.70	13.34	14.43	13.04	13.20
45	7.58	8.62	16.40	14.08	13.50	14.25	13.21	13.98
46	6.03	6.09	14.94	13.85	11.89	14.33	12.75	13.53
47	3.33	....	15.78	13.83	12.74	14.31	12.29	11.64
48			15.43	13.60	12.16	13.87	14.81	13.64
49			13.86	13.12	....	13.31	14.53	13.51
50			14.46	12.15	10.70	14.01	13.92	11.45
51			14.06	11.96	....	14.00	13.50	13.78
52			....	12.83	12.05	13.25	12.65	14.52
53			12.90	12.70	12.50	13.96	13.10	13.56
54			13.67	12.20	12.61	10.38	13.43	13.40
55			13.60	12.52	11.20	13.10	13.82	13.10
56			....	11.53	12.04	11.86	14.78?	12.82
57			13.20	11.89	11.33	13.25	14.00	13.73
58			12.68	13.10	12.26	14.43	13.73	13.07
59			11.75	12.12	12.40	13.04	14.26	13.13
60			11.54	12.11	12.55	13.32	13.51	13.46
61			12.35	14.57	11.75	13.90	13.83	12.60
62			9.15	11.37	12.38	12.46	15.23?	12.32
63			....	....	12.90	13.01	13.90	12.56
64			11.20	8.92	11.44	13.28	14.82	12.20
65			10.57	8.31	11.22	13.37	14.39	....
66			10.10	8.72	11.23	13.92	14.62	12.43
67			10.05	4.64	11.60	13.81	14.23	12.85
68			9.36	6.32	....	13.50	14.03	12.58
69			5.77	3.56	11.05	13.61	13.60	12.76
70			7.90	....	10.54	12.70	14.20	....
71			4.16	....	11.07	11.85	14.04	11.77
72					10.34	13.50	12.83	15.14
73					11.22	13.44	13.52	20.66
74					11.52	11.71	13.92	12.54
75					....	12.05	14.45	13.64
76					10.85	11.60	12.81	11.46
77					11.22	12.16	13.58	12.11
78					11.62	12.27	12.51	19.35
79					11.62	12.05	13.21	12.78
80					11.37	11.15	12.84	13.15
81					11.80	11.28	13.59	12.10
82					11.90	10.24	13.21	12.00
83					11.42	13.35	13.02	13.18
84					....	11.71	14.75	10.94
85					11.61	10.85	11.25	12.26

TABLE 2—(*Continued*)

Height above water table *inches*	Per cent of water present (dry basis)							
	41	42	61	62	81	82	101	102
86					11.05	10.63	11.73	12.26
87					9.92	11.18	12.31	12.67
88					11.22	10.54	12.38	11.95
89					10.52	10.41	12.29	11.33
90					10.52	8.90	12.57	12.01
91					9.12	6.40	11.89	11.71
92					9.22	7.99	12.36	11.67
93					8.65	6.10	11.82	11.13
94					7.40	4.52	12.17	11.38
95					5.36	3.74	12.10	11.80
96					3.30	....	11.23	12.66
97							12.15	11.70
98							12.35	11.67
99							12.09	10.92
100							11.85	11.38
101							13.95	11.72
102							11.29	11.37
103							12.02	10.95
104							13.93	10.68
105							11.37	11.12
106							12.70	11.11
107							9.12?	11.27
108							12.07	10.85
109							11.23	10.57
110							12.22	10.80
111							10.61	11.23
112							11.91	10.56
113							11.39	10.40
114							9.84	9.55
115							8.82	8.40
116							8.26	7.85
117							7.50	2.26
118							7.32	6.75
119							4.85	4.94
120							2.77	3.30

within the tubes. That this effort was successful is shown by the weight of the soil in the duplicate tubes, and by the volume weight (table 3). The average volume weight was 1.276, with ranges from 1.262 to 1.293, or expressed as pounds weight per cubic foot, an average of 79.66 lbs. with ranges from 78.76 lbs. to 80.73 lbs. A representative sample of this soil had a specific gravity of 2.55, indicating a pore space of almost exactly 50 per cent. The close agreement in the moisture content of the duplicate tubes at the close of the experiment also indicates a uniform packing of the soil.

In this experiment the bottoms of the tubes were set at the same elevation, as shown in figure 1, the tops varying by two-foot intervals. No forced air circulation was attempted, the normal ventilation and circulation of air in the laboratory being relied upon to give comparable evaporation conditions.

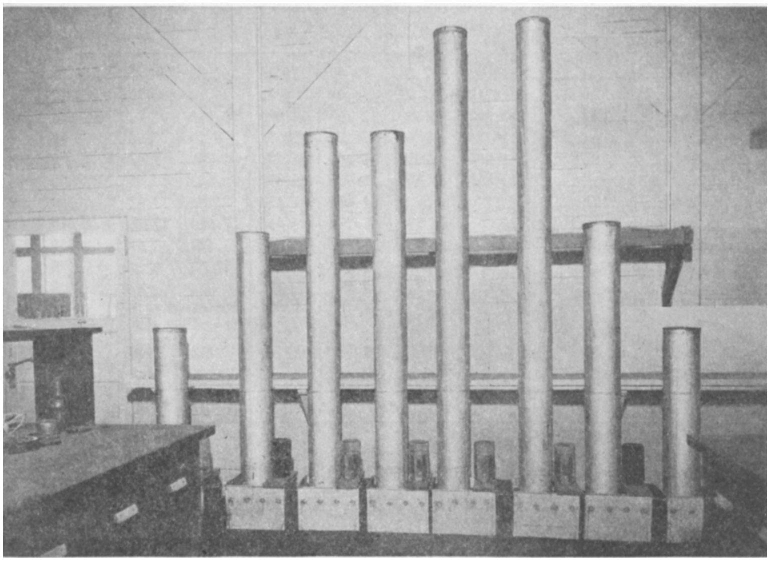

Fig. 1. The eight tubes used in the second experiment, at Davis, showing the reservoirs and the bottles that maintained the constant water level. In the first experiment, at Berkeley, the tubes were so placed that the tops were all at the same elevation and enclosed in a muslin tunnel through which warm air was constantly drawn.

Water was applied to the 10-foot tubes on August 9, to the 6, 8, and 10-foot tubes on August 11, and to all the tubes on August 13, and daily thereafter until August 16. As the soil within the tubes settled, more soil was added to keep them filled to within $1\frac{1}{2}$ inches of the top, and when drainage started, soil was added to completely fill the tubes, a small amount of water being added to wet this soil to the normal moisture condition. Drainage began on August 18 from all except the 10-foot tubes, which began to drain on August 20 and 21. By September 2 drainage from all tubes had apparently ceased.

The water level in the reservoirs was adjusted during the drainage period by removing the excess water and after that period by adding water to the Winchester supply bottles.

Amounts of water evaporated.—The experiment was concluded on July 21, 22, 23, and 24, 1925, when successive tubes were sampled and the distribution of water within the soil columns determined.

TABLE 3

WEIGHT OF SOIL, WATER APPLIED, AND LOSS OF WATER BY EVAPORATION FROM CAPILLARY RISE TUBES CONTAINING YOLO LOAM (MOISTURE EQUIVALENT = 20), DAVIS, 1924–25

Number of tube	41	42	61	62	81	82	101	102
Depth, in inches	48.00	47.00	72.50	72.25	96.50	96.50	119.88	121.00
Average diameter, in inches	8.12	8.07	8.06	8.04	8.12	8.08	8.07	8.06
Kilograms soil	48.120	48.100	72.450	72.080	96.074	97.024	120.054	120.800
Weight per cubic foot, in pounds	78.83	80.46	78.76	80.73	79.26	79.65	80.02	79.62
Volume weight	1.263	1.288	1.262	1.293	1.269	1.276	1.282	1.275
Water applied, in liters	15.850	15.850	22.850	22.850	30.850	30.850	40.850	40.850
Drainage, in liters	.520	.530	1.640	1.410	3.290	3.420	6.280	6.570
Net water retained, in liters	15.330	15.320	21.210	21.440	27.560	27.430	34.570	34 280
Total evaporation, in liters	12.000	12.650	6.350	6.890	3.440	3.550	.550	.600
Period of evaporation, months	10.7	10.8	10.73	10.8	10.73	10.73	10.76	10.8
Period of evaporation, days	321	324	322	324	322	322	323	324
Evaporation per day, in grams	37.38	39.04	19.72	21 26	10.68	11.02	1.70	1.85
Total evaporation in surface inches	37.47	39.92	19.91	21.71	10.42	11.07	1.72	1.88
Evaporation in surface inches monthly	3.50	3.69	1.85	1.99	.97	1.03	.16	.17

The water used, rate of evaporation and other data are given in table 3. The Winchester supply bottles held two liters of water, and only a little over 0.5 liter each was used by the 10-foot tubes. The supply bottles for the 8-foot tubes were renewed on March 9, these tubes using about 3.5 liters each. It was necessary to renew the supply for the 4 and 6-foot tubes at frequent intervals, though the rate of evaporation decreased considerably during the rainy season. The 6-foot tubes used between 6 and 7 liters each, while the 4-foot tubes used over 12 liters.

When the total use of water is expressed as surface inches evaporated monthly, the 4-foot tubes show an average loss of 3.595 inches, the 6-foot tubes an average loss of 1.92 inches, the 8-foot tubes an average loss of 1.0 inch, and the 10-foot tubes an average of only .165 inch. It is felt that ten feet is approximately the maximum height to which this soil can raise water.

Distribution of water.—The distribution of water within these columns was determined by careful sampling by 3-inch sections to a height of 36 inches and by 6-inch sections above that height. The results are given in table 4.

TABLE 4

DISTRIBUTION OF MOISTURE IN SOIL COLUMNS AT END OF EVAPORATION PERIOD. YOLO LOAM (MOISTURE EQUIVALENT = 20)
(Percentage on oven dry basis)

Distance from base	Tube numbers							
	41	42	61	62	81	82	101	102
inches								
0– 1	35.19	34.99	35.28	35.19	33.71	33.37	33.76	33.58
1– 3	34.13	35.18	34.03	34.56	33.36	33.11	34.06	34.32
3– 6	34.01	35.36	31.01	33.01	34.03	34.21	34.17	34.61
6– 9	31.88	32.96	30.97	31.38	32.50	33.88	33.14	33.16
9– 12	30.45	30.21	29.83	30.22	32.11	30.42	32.81	33.13
12– 15	30.09	28.82	28.09	30.32	31.97	29.19	32.31	31.81
15– 18	27.85	28.92	27.64	28.26	29.83	28.77	30.49	29.12
18– 21	27.68	26.67	26.00	25.75	28.85	28.25	28.64	28.44
21– 24	26.64	27.27	25.80	25.73	27.97	26.38	28.12	27.79
24– 27	24.02	25.13	24.49	24.23	27.47	25.87	27.29	27.73
27– 30	22.74	23.51	23.88	24.19	26.39	25.00	26.64	27.31
30– 33	22.56	22.22	24.00	24.26	24.50	24.38	25.43	26.61
33– 36	21.00	21.73	22.80	23.00	23.99	23.69	25.38	25.41
36– 42	19.62	19.59	22.55	22.51	22.28	23.03	23.66	24.08
42– 48	16.94	16.74	21.82	21.77	22.15	22.22	22.62	22.60
48– 54			20.13	20.88	21.17	21.09	21.22	21.55
54– 60			18.50	19.31	20.64	20.81	21.15	20.47
60– 66			17.16	17.60	20.23	20.71	20.03	20.02
66– 72			13.55	13.62	20.22	20.28	20.01	20.03
72– 78					19.63	19.19	19.19	19.57
78– 84					16.84	17.81	18.51	18.82
84– 90					15.27	16.28	18.46	18.49
90– 96					11.22	11.38	18.23	18.45
96–102							17.96	17.66
102–108							16.14	16.41
108–114							15.05	15.38
114–120							10.20	10.77
Drainage during sampling...	100 cc.	70 cc.	None	40 cc.	50 cc.	50 cc.	40 cc.	30 cc.

It will be noted that the moisture content at the top of the column was greatest in the shorter tube, the average for the 4-foot columns being 16.84 per cent, for the 6-foot columns 13.59 per cent, for the 8-foot columns 11.60 per cent, and for the 10-foot columns only 10.49 per cent. This was not evident in the Berkeley experiment, where the soils were sampled by *one*-inch depths, and the immediate soil surface was air-dry and, in the case of the 4-foot tubes, considerably crusted.

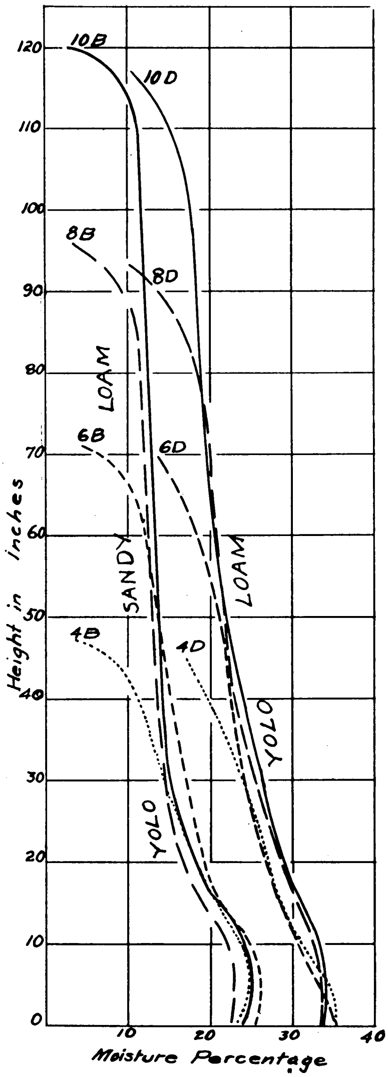

Fig. 2. The distribution of water in the soils at the close of the experiments, after 95 days (B) and 321 days (D) of free evaporation from the surface. (Each curve represents the average of two tubes.) 4B, four-foot tubes at Berkeley; 4D, four-foot tubes at Davis; 6B, six-foot tubes at Berkeley; 6D, six-foot tubes at Davis; 8B, eight-foot tubes at Berkeley; 8D, eight-foot tubes at Davis; 10B, ten-foot tubes at Berkeley; 10D, ten-foot tubes at Davis.

The graphs in figure 2 show the moisture distribution within the tubes from both experiments. The higher water-holding capacity of the Yolo loam as compared to the Yolo sandy loam is shown by the difference of from 8 to 10 per cent of water at any given height. The parallelism of the curves, however, is very striking, although those of the Yolo sandy loam tend to have a steeper slope than those of the loam.

CONCLUSIONS

The Yolo sandy loam and the Yolo loam, wetted to the water table by rains or irrigation, will lift water to the surface at a fairly rapid rate where the water table is within four feet, and at a slowei rate if the water table is at six feet below the surface. Some water will be raised to the surface if the water table is at eight feet, but this appears to be close to the limit of such rise, little water being lost from the soil with the water table at ten feet below the surface.

From this it is concluded that with a water table at a depth of more than ten feet below the surface, no losses by evaporation from the surface would occur from a soil having a capillary capacity similar to that of the Yolo sandy loam or Yolo loam. It might be further concluded that for sandy loams and loams in general, water tables at ten feet or more below the surface would be below the maximum height of capillary rise and would result in no movement of water to the surface.

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[3] WADSWORTH, H. A., AND A. SMITH.
1926. Some observation upon the effect of the size of the container upon the capillary rise of water through soil columns. Soil Science 22:199–211.

Transmitted October, 1926.

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.
3. The Formation of Sodium Carbonate in Soils, by Arthur B. Cummins and Walter P. Kelley. March, 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.
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