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RELATION OF MINIMUM MOISTURE CONTENT OF SUBSOIL OF PRAIRIES TO HYGROSCOPIC COEFFICIENT[1]

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Introduction

It has long been recognized that the maxima and minima percentages of water found in well drained soils in the field are in general roughly dependent upon the relative fineness of texture, but very few data have been published in such form as to permit of any attempt to compute the actual relations which these extremes bear to the physical constants. In a previous paper (3) we have reported laboratory experiments and field observations showing that when loams, after rains sufficiently heavy to moisten them thoroughly, are protected from losses by evaporation and transpiration, they lose water by downward movement until the ratio of moisture content to hygroscopic coefficient reaches a value between 1.8 and about 2.5; while with coarse sands the ratio is as high as 6.0 or 7.0; and fine sands occupy an intermediate position, the ratio rising with a decrease in hygroscopicity.

While the maxima under field conditions are easily ascertainable anywhere, it being necessary only to await heavy rains or to irrigate a small area, the corresponding minima are developed only when a very scanty rainfall or a prolonged absence of precipitation is

[1] The work reported in this paper was carried out in 1907–1913, while the authors were members of the staff of the Nebraska Agricultural Experiment Station.

accompanied by weather conditions which stimulate both evaporation and transpiration, and so favor a reduction of the soil moisture content. These favoring conditions are high temperature, low atmospheric humidity, high wind velocity, and a high degree of insolation. Even in a semi-arid region several years may pass without the concurrence of the necessary conditions, while in humid regions such intervals are of still greater length.

The results of the greenhouse experiments of BRIGGS and SHANTZ (6) would suggest that after periods of extreme drought the prairie subsoil might be expected to show a moisture content which either approximated the so-called wilting coefficient (1.47 times the hygroscopic coefficient) or which was somewhat lower than the former value but bore no distinct relation to the latter. In the opinion of these authors the wilting coefficient "practically marks the cessation of growth," and after this point has been reached the soils continue to lose water through the tissues of the plants, even after they are dead, the final moisture content of the soil being as low as though the soil and air had been in direct contact. However, pot experiments of any kind, and especially those employing shallow vessels, appear ill adapted to answer the question as to how dry a particular soil may become under field conditions. Accordingly the data obtained in the field at such times as when the weather conditions have been favorable to an extreme reduction of the subsoil moisture should prove of especial interest, provided they are accompanied by determinations of the hygroscopic coefficient or wilting coefficient of the soils.

In regions of winter rains and summer droughts, such as California, one may safely count upon the continuance of hot rainless weather with clear skies for many weeks after the dry season has once set in, but in those with summer rains one never knows when to make preparations for studies that are dependent upon extreme brought conditions, and it may happen that, after all arrangements have been completed, several years may pass before weather conditions favoradle for the work occur. For this reason data on the soil moisture content during unusual droughts in humid regions are most apt to be secured in the course of some less specialized investigation.

Location of prairies sampled

The fields from which we secured the following data form two groups, one in the southwestern corner of Nebraska adjacent to the towns of McCook, Wauneta, Imperial, and Madrid; and the other close to the Nebraska Experiment Station at Lincoln. As all the former were at a distance of 200 miles or more from the experiment station, the sampling of them was feasible only at long intervals, and many of the data from these were secured incidental to the collection of samples for chemical studies. The western group of fields is beyond question well within the semi-arid region, while those at Lincoln lie almost as far to the west as the strictly humid climate extends on the American prairies. Some may consider that even Lincoln falls within the eastern limit of the great semi-arid region, but the composition of the soil (4, p. 414), the growth of vegetation and its agricultural history, as well as the moisture conditions of the subsoil distinguish it from the drier country west of Holdrege. All the factors which determine the difference in climate alter so gradually from east to west that it is impossible to place any definite line of demarcation between the humid and the semi-arid regions, the most that we are justified in assuming being that for every advance of a few miles to the westward of Hastings there is a nearer approach to strictly semi-arid conditions. At Hastings we appear to be still within the humid region, while at Holdrege, 50 miles farther west, most of the characteristics of semi-arid regions are discernible. Also the distribution of carbonates in the subsoil indicates that the district between Hastings and Holdrege is the region of most rapid transition (4, p. 414).

Favorable weather conditions

The weather of the period covering our work proved extremely favorable for the development of dry subsoils in both localities. At Lincoln it included the driest two-year period (1911–1912) of the past 20 years, 1897 to 1916, although in two years, 1895 and 1901, there had been a lower annual precipitation than in either of these (table I). Accordingly the soil moisture conditions we found there may be considered to include those representing the effects of extreme drought.

In southwestern Nebraska our work was begun in seasons, 1907 and 1908, forming the conclusion of a series of wet years. This was followed by a prolonged dry period, reaching its climax in

TABLE I

RELATION OF ANNUAL PRECIPITATION AT LINCOLN, YEAR BY YEAR, TO NORMAL (=100), 27.51 INCHES, SHOWING RELATIVE DRYNESS OF PERIOD OF OBSERVATION (1906 TO 1912).

Year	Percentage	Year	Percentage	Year	Percentage	Year	Percentage
1895....	60	1901....	80	1907....	99	1913....	95
1896....	138	1902....	150	1908....	130	1914....	145
1897....	93	1903....	126	1909....	126	1915....	128
1898....	102	1904....	101	1910....	114	1916....	80
1899....	82	1905....	129	1911....	89	....	....
1900....	123	1906....	124	1912....	81	....	....

1910–1911, the precipitation in 1910 being the lowest recorded since observations were begun at North Platte 42 years ago (table II). By 1911 the subsoil moisture had probably been reduced to as

TABLE II

ANNUAL PRECIPITATION IN INCHES AT STATIONS IN SOUTHWESTERN NEBRASKA

Length of record in years*	McCook 16	Wauneta 27	Imperial 26	H. O. Ranch 11	North Platte 42
Normal	19.71	18.70	20.79	17.80	18.88
1905	33.97	32.24	33.05	....	26.81
1906	20.59	22.82	26.23	20.14	27.99
1907	19.32	20.18	16.76	12.02	19.61
1908	18.08	24.77	26.27	21.01	19.96
1909	22.54	18.46	20.03	16.89	22.41
1910	9.34	13.82	11.77	7.62	10.70
1911	12.15	18.82	17.37	12.76	17.43
1912	14.69	20.00	24.58	20.74	18.69
1913	18.26	16.05	16.60	14.99	19.10
1914	18.24	17.26	16.94	19.42	15.79
1915	30.95	27.04	37.14	35.84	32.70
1916	15.35	14.95	19.33	14.60	12.96
Maximum	33.97	32.24	37.14	35.84	32.70
Minimum	9.34	13.82	11.77	7.62	10.70

* To end of 1916.

low a point as is ever experienced in southwestern Nebraska. The climate of the Nebraska portion of the Transition Region, including both groups of fields, has been discussed in some detail in a previous paper dealing with the composition of its loess soils (2).

Experimental methods

In taking the samples we used augers provided with extensions, commonly employing two sizes, one 1.5 inches in diameter with which to take the sample, and another 2.0 inches in diameter to enlarge and clean out the hole preparatory to sampling the next lower section. In many of the borings in western Nebraska the subsoil in part or in all the levels sampled was too dry to be removable by the ordinary auger, sliding off the bit as this was being withdrawn. In such cases we employed a Tinsley "auger with casing" (11), the sleeve on this retaining the soil loosened by the bit. Except where otherwise indicated, the samples were composites from 3 borings 10–20 yards apart. Composites were made from the first 3 borings only where it could be seen from the behavior of the soil toward the auger that the general moisture conditions in all 3 were similar, but not necessarily identical.

Extremes under semi-arid conditions

After a prolonged drought.—As already stated, 1910 proved the driest year in southwestern Nebraska since observations were begun, the precipitation amounting to scarcely half the normal (table III). The autumn of this year and the following winter and spring were practically without snow or rain until April, the total precipitation at McCook from the end of August 1910 to the first of the following April amounting to only 1.60 inches (table IV), and this fell in such small amounts as to influence the soil moisture content through only a negligible distance. At Imperial and Wauneta the weather was not quite so dry, but the difference was not sufficient to cause an appreciable difference in the moisture content of the subsoil.

The samplings made in fields near McCook and Wauneta near the end of October 1910 showed such low ratios of moisture content to hygroscopic coefficient (table V) that some undiscovered source of error was suspected, and for this reason 6 weeks later we resampled two of them, A and B at McCook, and took sets from two additional fields. These confirmed the correctness of the extremely low ratios. The concordance of the moisture content with the hygroscopic coefficient was very striking, as though the plant roots, while not recognizing the wilting coefficient, practically ceased to withdraw water as soon as the hygroscopic coefficient had been reached. There was little difference in moistness between

TABLE III

MONTHLY PRECIPITATION IN INCHES AT McCOOK, WAUNETA, IMPERIAL, AND THE H. O. RANCH, SHOWING DRYNESS OF SEASONS

MONTH	NORMAL			1910			
	McCook	Wauneta	Imperial	McCook	Wauneta	Imperial	H. O. Ranch
January	0.21	0.26	0.44	0.0	0.0	0.40	0.35
February	0.62	0.69	0.69	0.0	0.0	0.10	0.06
March	0.73	1.03	1.33	0.0	0.0	0.38	0.36
April	1.89	2.04	2.27	0.76	0.82	0.71	0.60
May	2.82	2.54	2.82	2.77	2.00	1.98	2.25
June	3.29	3.34	3.34	1.12	3.44	2.51	1.24
July	3.09	2.47	2.91	0.70	0.77	0.72	0.34
August	2.55	2.74	2.73	2.93	2.64	2.82	0.97
September	1.72	1.35	1.34	0.72	3.20	1.58	1.28
October	1.03	1.13	1.10	0.17	0.0	T	0.0
November	0.56	0.39	0.50	0.0	0.10	T	0.03
December	0.57	0.57	0.72	0.17	0.85	0.57	0.14
Annual	19.08	18.55	20.19	9.34	13.82	11.77	7.62

MONTH	1911				1912			
	McCook	Wauneta	Imperial	H. O. Ranch	McCook	Wauneta	Imperial	H. O. Ranch
January	0.05	0.10	0.42	0.15	0.0	0.20	0.52	0.15
February	0.47	0.70	0.37	0.31	0.24	1.51	1.08	1.00
March	0.12	0.50	0.22	0.03	1.50	2.35	3.61	2.70
April	1.72	3.45	2.55	1.94	2.01	2.82	2.85	1.74
May	1.25	1.75	2.19	1.29	0.0	0.95	1.41	1.53
June	0.66	1.35	1.29	0.92	2.77	1.89	1.82	1.80
July	0.84	1.30	1.10	0.84	2.29	3.26	5.09	5.16
August	4.34	3.07	3.45	1.97	2.11	2.78	4.28	2.49
September	0.59	1.80	1.44	0.86	2.13	2.61	2.01	2.41
October	0.96	3.30	2.92	2.85	1.09	1.43	1.55	1.45
November	0.05	0.0	0.10	0.05	0.50	0.20	0.15	0.0
December	1.10	1.50	1.32	1.55	T	0.0	0.21	0.05
Annual	12.15	18.82	17.37	12.76	14.69	20.00	24.58	20.44

the surface foot and the succeeding 2 or 3 ft., and even the deeper subsoil was but little if at all moister. At no level and in none of the fields was there any growth water, the moisture content being below the computed wilting coefficient, which corresponds to a ratio of 1.47, or approximately 1.5 (6).

TABLE IV

DAILY PRECIPITATION AT MCCOOK FROM SEPTEMBER 1, 1910, TO JUNE 30, 1912

	1910				1911												1912					
	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June
1					0.05														T			
2		0.17										0.57							0.80			
3								0.89		0.36												
4								0.09			0.07	0.57	0.12									
5	0.15			0.10							0.07	0.47			T							
6												0.22		0.06								0.15
7												0.20										0.05
8																		T				0.95
9											0.27											0.33
10										0.12												
11												0.31			T							0.47
12												0.77						0.08	0.60			0.10
13				0.07							0.07											
14																						
15														0.41								
16						0.25				0.18				0.49	0.05							0.38
17						0.08		0.18														0.27
18												0.43				T						0.07
19											0.09											
20												0.73	0.19			0.95				0.55		
21	0.23								1.10										0.10			
22											0.27											
23	0.34																			0.08		
24																						
25								0.42								0.15		0.11				
26							0.12					0.07										
27									0.15													
28						0.14												0.05		1.38		
29													0.28									
30								0.14														
31																						
Total	0.72	0.17	0.0	0.17	0.05	0.47	0.12	1.72	1.25	0.66	0.84	4.34	0.59	0.96	0.05	1.10	0.0	0.24	1.50	2.01	0.0	2.77

TABLE V

MOISTURE CONDITIONS AT McCOOK AND WAUNETA, AUTUMN 1910

A: McCOOK

Depth	October 24		Oct. 26	Oct. 27	December 9		December 10	
Foot	Field A	Field B	Field C	Field D	Field A	Field B	Field D	Field E
	HYGROSCOPIC COEFFICIENTS							
1	9.2	9.5	10.2	8.8	9.1	10.0	9.3	10.6
2	10.7	11.4	11.3	10.9	10.4	10.1	10.9	9.9
3	10.4	9.1	10.2	10.7	10.2	9.1	10.7	8.2
4	10.1	8.6	8.4	10.8	9.3	7.8	9.6	8.1
5	9.4	8.5	8.6	....	8.7	8.2	9.7	7.9
6	8.7	8.4	9.0	8.5	8.2	8.2	11.7	7.5
Average	9.8	9.1	9.6	9.6	9.3	8.9	10.3	8.7
	RATIOS							
1	0.8	0.8	0.8	0.8	1.1	0.9	0.9	0.9
2	0.9	0.8	0.9	0.8	1.0	0.8	0.8	0.9
3	0.9	0.8	0.8	0.8	1.0	0.9	0.8	0.9
4	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0
5	0.9	1.1	1.0	....	1.1	1.0	1.0	1.0
6	1.2	1.1	0.9	1.0	1.1	1.1	0.9	1.1
Average	0.9	0.9	0.8	0.9	1.0	0.9	0.9	1.0

B: Wauneta

Depth	October 31	November 1		November 2	November 3
Foot	Field A	Field B	Field C	Field D	Field E
	HYGROSCOPIC COEFFICIENTS				
1	8.8	9.9	9.5	8.5	8.1
2	9.5	10.1	9.4	9.3	9.5
3	8.7	10.6	7.7	9.7	9.7
4	8.9	10.7	8.6	9.5	8.7
5	10.0	9.8	7.6	8.7	7.3
6	10.3	8.7	7.6	8.0	6.4
Average	9.4	10.0	8.4	8.9	8.3
	RATIOS				
1	0.9	0.8	0.9	1.0	0.9
2	0.8	1.0	0.9	0.8	1.0
3	0.9	0.9	1.0	0.8	0.9
4	1.0	1.0	0.9	0.8	1.0
5	1.0	0.9	1.0	0.9	1.1
6	1.1	1.2	1.1	1.1	1.3
Average	0.9	1.0	1.0	0.9	1.0

Some 4 months later 3 of the fields at McCook and Wauneta were sampled again and one added at the latter place. The

TABLE VI

MOISTURE CONDITIONS IN WESTERN NEBRASKA IN LATE SPRING OF 1911, FOLLOWING VERY DRY AUTUMN, WINTER, AND EARLY SPRING

DEPTH	McCOOK		WAUNETA		IMPERIAL				
	Mar. 24	Mar. 25	April 4		April 1	April 3	April 12	April 12	April 14
Foot	Field B	Field E	Field E	Field F	Field A	Field B	Field C	Field D	Field E
	HYGROSCOPIC COEFFCIENTS								
1	9.6	8.7	8.7	9.0	6.4	8.3	3.0	2.0	3.6
2	10.5	10.1	9.2	9.6	7.9	10.7	2.6	2.2	4.6
3	9.1	9.6	9.1	10.9	8.1	9.0	2.4	2.0	5.9
4	8.3	9.0	9.2	10.0	6.8	7.8	4.1	2.0	4.8
5	8.1	8.6	9.6	8.8	4.2	6.8	4.5	2.1	4.4
6	8.1	9.0	8.3	7.7	3.9	6.8	4.5	2.0	3.6
7	8.1	7.9	6.6	6.7	4.0	......	5.1	1.9	4.2
8	8.3	8.6	5.7	7.3	5.3	......	4.3	2.5	8.4
9	8.1	8.4	4.9	7.0	6.0	......	3.5	2.0	5.4
10	8.1	8.4	4.4	7.0	......	......	......	......	......
11	8.1	8.6	4.0	7.9	......	......	......	......	......
12	8.1	8.6	3.7	7.4	......	......	......	......	......
13	......	......	4.3	6.6	......	......	......	......	......
14	......	......	4.2	6.5	......	......	......	......	......
15	......	......	5.1	6.4	......	......	......	......	......
Average	8.9	9.2	9.0	9.3	6.2	8.2	3.5	2.1	4.5
	RATIOS								
1	0.8	0.8	1.0	1.0	0.8	0.9	1.2	1.1	0.7
2	0.8	0.9	0.8	0.9	0.9	0.9	1.5	1.1	0.9
3	0.9	0.9	0.9	0.8	0.9	0.8	1.2	1.1	0.9
4	0.9	0.9	1.1	0.8	0.9	0.8	1.1	1.2	0.9
5	1.0	1.0	1.3	0.9	1.0	1.0	1.2	1.0	0.9
6	1.1	0.9	1.2	1.0	1.0	1.0	1.0	1.1	1.0
7	1.1	1.1	1.5	1.1	1.1	......	1.1	1.4	1.4
8	1.1	1.1	1.5	1.0	1.2	......	1.2	1.2	1.2
9	1.1	1.1	1.5	1.1	1.3	......	1.2	1.4	1.3
10	1.2	1.1	1.5	1.1	......	......	......	......	......
11	1.2	1.0	1.6	1.0	......	......	......	......	......
12	1.2	1.1	1.8	1.1	......	......	......	......	......
13	......	......	1.6	1.2	......	......	......	......	......
14	......	......	1.7	1.1	......	......	......	......	......
15	......	......	1.7	1.2	......	......	......	......	......
Average 1–6	0.9	0.9	1.0	0.9	0.9	0.9	1.2	1.1	0.9

sampling was carried down to the twelfth or fifteenth foot on this occasion (table VI). The subsoil was not found appreciably drier than when first sampled. As 4 or 5 months of rainless weather had intervened, it would appear that the loss of moisture by transpiration during the winter must have been very slight.

It is of interest that in the spring of 1911 the subsoil at depths of 7–15 ft. in field E at Wauneta was found quite moist, showing an average ratio of 1.6. The explanation of this will be discussed in a later paragraph.

On the last occasion samples were taken from near Imperial also. While the soil and subsoil in all of the fields at McCook as deep as sampled, and in all those at Wauneta except in the lower levels of E and F, were derived from the loess, and showed hygroscopic coefficients between 7.5 and 11.0, all the soils and subsoils at Imperial were residual in origin with hygroscopic coefficients varying all the way from 2.0 to 10.7. At Imperial, in contrast to McCook and Wauneta, we sampled some fine sandy loams as well as the more numerous fine textured soils, none of the latter, however, being of loessial origin. Comparing the ratios it will be seen that the prairies with the finer soil, A, B, and E, were as dry in the first 6 ft. as those at Wauneta and McCook, and that the one of the two with sandy soil and subsoil, C and D, was but slightly more moist. Below the sixth foot they were distinctly moister, but in none of them was the ratio much above 1.0. The reduction of the moisture content to the hygroscopic coefficient was general and was independent of the relative hygroscopicity.

After a wet winter following a prolonged drought.—Until the spring of 1912 no more sampling was done at McCook, Wauneta, or Imperial. The weather of the intervening months had been unfavorable for any marked increase in the moisture content of the deeper subsoil, although very favorable for moistening the surface foot. April and May of 1911 had a rainfall somewhat below normal, June and July were very dry, while during August and the first few days of September considerably more rain than usual fell. The rest of September was dry, but the precipitation of October was 3 times the normal and of such a character that there was little chance for run-off; as vegetation had become dormant the loss by transpiration must have been slight. November was very dry, but the precipitation of December was twice the normal, a heavy rain on December 20 further moistening the surface soil. January and February together had a precipitation somewhat below normal at McCook, but above at both Wauneta and Imperial, while March at all 3 places had a precipitation 2 or 3 times the normal. April was rainless until the 20th, between which date and the 28th from 2 to 3 inches of rain fell.

Sampling was carried out at McCook on May 7 and 8, no rain having fallen since April 28; at Imperial on May 11, 13, and 14, 0.45 inch having fallen there in 4 light showers; and at Wauneta on May 16 and 17. At the last place the only rain since April 28 had been one of 0.10 inch on May 10. Thus conditions had been ideal for the downward movement of the water into the subsoil, while at each place an interval of 8–19 days had elapsed between the last good rain and the date of sampling.

The generally favorable weather of autumn, winter, and spring was evidenced by the circumstance that in the early spring the outlook appeared unusually promising for the farmers. Wheat had come through the winter in fine condition and preparations were being made for seeding a large acreage to spring grains, the prospects being considered so favorable that local merchants were willing to furnish seed grain in return for a reasonable share of the crop. Conditions appeared ideal for a study of the degree to which the ratio in the surface soil had to be raised before water could pass downward into the deeper portions of the subsoil, where during the previous year the moisture had been reduced to the hygroscopic coefficient or even slightly below.

In the fields with heavier soil we found that the moisture content had been distinctly affected at McCook (table VII) to only 2 ft., at Wauneta in the one field to 3 ft., in the other to 4 ft. or more, and in the only one sampled at Imperial to 5 ft.

In normal seasons.—That the low ratios prevailing throughout the subsoil of the prairies after severe droughts, as illustrated in the preceding tables, are not entirely absent even in favorable seasons, may be seen from table VIII reporting conditions at the H. O. Ranch. There, as at McCook, Wauneta, and Imperial, after periods of drought the ratio was found not far from 1.0 at all depths, while under more favorable conditions, as in July 1908, the low ratio was still to be found at some level within the first 6 ft.

While after protracted droughts and probably also after extremely wet periods the moisture conditions in the subsoil are quite uniform, they vary much from place to place under more normal weather conditions, as illustrated by table IX.

TABLE VII

MOISTURE CONDITIONS IN WESTERN NEBRASKA IN MAY 1912, AFTER WET WINTER AND SPRING

DEPTH	McCOOK			WAUNETA		IMPERIAL					
Foot	May 7	May 7	May 8	May 16	May 17	May 11			May 13		May 14
	Field A	Field B	Field E	Field B	Field C	Field E	Field G	Field H	Field I	Field J	Field K
	HYGROSCOPIC COEFFICIENTS										
1	8.4	9.6	10.1	9.2	7.5	8.2	1.6	2.6	7.1	5.8	3.2
2	9.6	10.3	10.1	10.4	9.1	10.2	2.6	3.7	7.5	6.3	3.2
3	8.1	8.3	....	10.0	9.0	8.9	1.9	3.5	9.7	7.1	5.4
4	8.7	7.5	....	9.6	9.5	5.3	1.5	3.5	9.0	5.1	3.7
5	8.4	7.8	7.3	8.4	8.4	4.7	1.3	1.6	......	......	3.4
6	7.2	7.6	....	7.6	6.8	4.9	1.3	1.3	......	......	3.0
Average	8.4	8.5	....	9.2	8.4	7.0	1.7	2.7	......	......	3.7
	RATIOS										
1	2.6	2.1	2.1	2.0	2.3	2.0	2.5	2.9	2.4	2.1	2.4
2	1.4	1.4	1.3	1.9	2.2	1.7	2.1	2.8	2.4	2.3	3.5
3	1.1	1.1	....	1.4	1.6	1.3	4.2	2.7	1.5	1.3	2.0
4	1.0	1.1	....	1.0	1.3	1.2	4.6	2.3	1.1	1.2	1.1
5	1.1	1.0	1.0	1.1	1.2	1.2	4.5	3.1	......	......	1.1
6	1.3	1.1	....	1.2	1.3	1.0	4.7	3.4	......	......	1.2
Average	1.4	1.3	....	1.4	1.6	1.4	3.8	2.9	......	......	1.9

Computations from data of Shantz and of Burr

The only data reported by other investigators that may be used for comparison with our own appear to be those secured by SHANTZ at Akron, Colorado, in 1909, and by BURR at North Platte, Nebraska, in 1912. While neither of these authors reports the hygroscopic coefficients of the soils, each gives the wilting coefficients for a representative set of samples, these having been computed from the determined moisture equivalents. From these data we have computed the hygroscopic coefficients by means of the Briggs-Shantz formula (**6**, p. 65): hyg. coef. = wilt. coef. $\times 0.68$.

For the period June 7–September 27, 1909, SHANTZ determined the moisture content twice a day in a grama-buffalo grass association, recording it in 6-inch sections to a depth of 3 ft. and in foot sections through the succeeding 3 ft. From his data we find that on August 7–8 and 10–11 the ratio of the moisture content to the

TABLE VIII

DATA FROM H. O. RANCH IN DIFFERENT YEARS, INCLUDING THE FAVORABLE SEASONS OF 1907 AND 1908

DEPTH	1907	1908		1910		1911	1913
Foot	Nov. 22	April 30	July 29	March 24	Sept. 21	April 21	July 13
	HYGROSCOPIC COEFFICIENTS						
1	7.7	8.5	8.0	8.7	8.8	8.9	8.4
2	10.3	9.8	9.7	9.7	11.5	11.1	
3	10.1	9.8	11.3	10.4	9.2	10.5	
4	7.7	8.3	7.7	8.7	7.9	8.6	8.6
5	7.1	6.9	6.4	7.9	7.5	8.5	
6	7.2	7.4	6.3	7.5	6.5	7.5	
7	6.4	....	5.9	6.8	....	7.2	
8	....	....	5.1	6.1	....	6.8	6.4
9	8.3	....	5.9	6.0	....	7.7	
Average 1–6	8.3	8.4	8.2	8.8	8.6	9.2	7.6
	RATIOS						
1	1.9	1.2	2.1	2.1	1.2	0.7	0.9
2	1.1	1.1	2.0	1.2	0.8	0.8	
3	1.1	0.9	1.1	1.0	0.8	0.8	
4	1.3	1.0	1.4	1.0	0.9	0.9	0.9
5	1.5	1.1	1.6	1.0	0.9	1.0	
6	1.8	1.1	1.8	1.1	1.1	1.1	
7	1.8	....	1.5	1.1	....	1.1	
8	....	....	1.6	1.1	....	1.2	1.2
9	....	....	1.3	1.1	....	......	
Average 1–6	1.5	1.1	1.7	1.2	0.9	1.0	1.0

hygroscopic coefficient in the 7–12 and 13–18 inch levels fell to approximately 1.0 (**10**, p. 35); while from July 22 to September 9 the ratio at the latter depth was almost continuously much below 1.5. From August 7 to 13 the sixth foot, and to a less extent the fifth, showed ratios close to 1.0. In each of the 4 months included in the study the rainfall was much above the normal for Akron, the excess varying from 25 to more than 100 per cent (**8**), and averaging at least 50 per cent above the normal. There was no actual drought at any time during the season, but there were two rather dry periods, June 14–July 6 and July 11–25, in which light rains gave totals of 0.20 and 0.09 inch respectively.

When the subsoil at Akron, even in that unusually wet summer, had its moisture content reduced to such a low point, it is probable

TABLE IX

DATA FROM 6 INDIVIDUAL BORINGS ON THE H. O. RANCH, NOVEMBER 22, 1907, ILLUSTRATING VARIATIONS FROM BORING TO BORING

Depth	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	Average	Maximum	Minimum
Foot	HYGROSCOPIC COEFFICIENTS								
1	6.9	7.4	7.8	7.6	7.2	6.1	7.1	7.8	6.1
2	8.4	8.6	10.4	10.2	8.3	6.7	8.8	10.4	6.7
3	7.3	6.7	10.2	10.0	8.1	7.5	8.4	10.2	6.7
4	8.5	5.1	7.0	8.4	9.9	7.7	7.9	9.9	5.1
5	7.3	4.2	7.0	7.1	11.8	6.7	7.3	11.8	4.2
6	7.2	5.3	7.8	6.5	9.9	5.4	7.0	9.9	5.3
7	7.9	6.7	6.9	6.0	9.2	5.2	7.3	9.2	5.2
Average 1–7	7.6	6.5	8.1	8.0	9.2	6.5	7.6	9.2	6.3
	RATIOS								
1	1.6	1.7	1.8	1.9	1.7	2.0	1.8	2.0	1.6
2	1.3	1.1	1.2	1.1	1.2	1.5	1.2	1.5	1.1
3	1.3	1.1	1.1	1.1	1.2	1.1	1.2	1.3	1.1
4	1.2	1.1	1.5	1.1	1.1	1.2	1.2	1.5	1.1
5	1.2	1.3	1.7	1.3	1.4	1.2	1.3	1.7	1.2
6	1.3	1.4	1.7	2.0	1.4	1.3	1.4	2.0	1.3
7	1.3	1.7	1.9	1.8	1.2	1.4	1.5	1.9	1.2
Average 1–7	1.3	1.3	1.6	1.5	1.3	1.4	1.4	1.6	1.3

that in a really dry season the ratios would be found as low as those we encountered in southwestern Nebraska.

The root systems of the native plants were studied by SHANTZ, but the penetration of the grama and buffalo grasses he indicates (10) would not account for the removal of available moisture from below the first foot or two.

BURR (7) reports data from a prairie sampled in the spring, summer, and early autumn of 1912 (table X). In the spring high ratios were shown in the first 2–3 ft., but by the end of June the ratios at all levels sampled had fallen to practically 1.0 and so remained through the remainder of the season, there being no evidence of further drying of the subsoil.

Thus the data of both SHANTZ and BURR confirm our findings regarding the stage of dryness to which the subsoil may be reduced in a dry season by the short grass vegetation, while those of the latter author agree also with our view that after the subsoil moisture content has been reduced to approximately the hygroscopic coefficient it suffers but little, if any, further lowering through a continuation of the drought conditions, and not with that of BRIGGS and SHANTZ that the subsoil continues to lose water through the plant tissues until it approaches an air-dry condition (**6**, p. 8).

TABLE X

RATIO OF MOISTURE CONTENT TO HYGROSCOPIC COEFFICIENT IN A PRAIRIE FIELD AT NORTH PLATTE IN 1912, COMPUTED FROM DATA OF BURR

Depth foot	Hygroscopic coefficient*	April			May		June		July		Aug.	Sept.
		18	22	29	11	25	10	29	25	26	22	12
1.....	6.8	2.5	3.3	3.3	3.1	2.0	1.4	0.8	1.0	1.8	0.8	1.5
2.....	6.8	1.9	2.2	3.2	2.6	2.2	1.3	0.8	0.9	0.9	0.8	0.9
3.....	6.8	1.2	1.2	1.7	2.3	2.0	1.6	0.9	0.9	0.9	0.8	0.9
4.....	6.8	1.1	1.2	1.2	1.4	1.5	1.4	0.9	1.0	1.1	0.9	0.9
5.....	7.5	1.1	1.1	1.2	1.2	1.2	1.3	0.8	1.0	1.1	0.8	0.8
6.....	7.5	1.1	1.2	1.2	1.0	1.1	1.2	0.7	0.9	1.1	0.8	0.9

* Computed from wilting coefficients of a representative set of samples (7).

Extremes in eastern Nebraska

The periods of extreme drought at Lincoln were not numerous, and usually when these came an examination with the soil auger showed that the moisture content of even the surface foot or two was well above the hygroscopic coefficient, and as it was only the minimum moisture content that we were seeking in these prairie fields we report data from only a few sets of samples. On only 3 occasions in the 6-year period (1906–1912) did we find in the surface 2–3 ft. the dry condition which indicates the approaching exhaustion of available moisture (table XI).

The first sampling, on August 23, 1909, had been preceded by a comparatively dry period of 42 days, during which only 1.57 inches of rain had fallen; none had fallen in the last 20 days, while the weather had been unusually hot and windy. The time of the season was that at which the draft upon the subsoil moisture might be expected to show the most marked effect. In the soil of the first foot we found a ratio of 1.0 and in that of the next 3 ft., an average ratio of 1.4; but the sixth foot, with a ratio of 1.9, appeared to have lost but little of the moisture which it could retain against downward movement.

TABLE XI

MOISTURE CONDITIONS IN PRAIRIE FIELDS NEAR LINCOLN AFTER UNUSUALLY DRY PERIODS

August 23, 1909			August 3, 1911			June 7, 1912		
Depth foot	Hygroscopic coefficient	Ratio	Depth foot	Hygroscopic coefficient	Ratio	Depth foot	Hygroscopic coefficient	Ratio
1.....	10.9	1.0	1.....	10.5	1.4	1.....	13.4	1.5
2.....	10.8	1.3	2–5...	13.1	1.3	2.....	15.2	1.3
3.....	11.5	1.5	6–8...	12.3	2.0	3.....	14.1	1.2
4.....	14.0	1.5	9.....	12.8	2.1	4.....	13.9	1.2
5.....	12.5	1.6	......	....	......	5.....	12.5	1.5
6.....	11.8	1.9	......	....	......	6.....	12.2	1.9

On the second occasion, August 3, 1911, a dry period of 65 days had just been ended by a rain of 0.84 inch. Compared with a normal precipitation of 9.0 inches for this period, only 2.68 inches of rain had fallen, and this in light showers, while both the mean temperature and the wind velocity had been somewhat above the normal. As the subsoil of the second to the fifth foot appeared uniformly dry it was combined into a single sample, the ratio proving to be 1.3, but in the sixth to ninth foot it was 2.0 to 2.1. The moister condition in the surface foot indicated in the table was due to a shower of the day before having moistened the immediate surface layers.

From the time of the preceding to the next and last sampling, June 7, 1912, the weather on the whole was very unfavorable to the accumulation of any moisture in the subsoil, and the spring of 1912 was exceptionally favorable to the exhaustion of whatever available water was within reach of the plant roots. The moisture conditions found were quite similar to those on the preceding occasion.

Thus the samplings, taken at times of drought when one might have expected almost the lowest moisture content in the subsoil ever to be found in prairie fields at Lincoln, showed dry subsoil only within the first 5 ft., below this depth the ratios lying between extremes of 1.9 and 2.7, or in general between 2.0 and 2.4, the moisture retaining capacity of the subsoil. On only one occasion, and then only in the first foot, was the moisture content found reduced as low as the hygroscopic coefficient, and there it is to be attributed to the surface few inches of the foot section having been dried by evaporation to a point much below this value, with the result that the average for the whole foot section shows a low ratio.

In this connection it is of interest to know the ratios which normally prevail in the deeper subsoil of the eastern prairies. In April 1911, a field situated on a gentle slope and 50 ft. or more above ground water was sampled to a depth of 18 ft. (table XII). Below the fifth foot ratios ranging only between 2.1 to 2.4 were found.

TABLE XII

MOISTURE CONDITIONS IN PRAIRIE NEAR LINCOLN, APRIL 13, 1911, SHOWING NORMAL CONDITION OF DEEPER SUBSOIL

Depth foot	Hygroscopic coefficient	Ratio	Depth foot	Hygroscopic coefficient	Ratio	Depth foot	Hygroscopic coefficient	Ratio
1.....	11.8	2.5	7....	13.0	2.2	13....	12.3	2.2
2.....	15.3	2.0	8....	12.8	2.2	14....	12.0	2.4
3.....	14.3	1.8	9....	13.6	2.1	15....	12.3	2.3
4.....	14.2	1.8	10....	12.1	2.4	16....	10.3	2.3
5.....	13.6	1.9	11....	13.4	2.1	17....	9.8	2.3
6.....	13.1	2.1	12....	13.0	2.2	18....	10.9	2.2

Thus as near the surface as the sixth foot, when conditions were such as to develop the driest subsoil, the ratio was not much below that found in the deep subsoil under normal conditions. This failure of the natural vegetation of the prairies of eastern Nebraska to exhaust the free water of the deeper subsoil is in sharp contrast with the conditions found on the short-grass prairies of the southwestern part of the state, as previously described. That this moist condition is due to a difference in the conduct of the native plants and not to any peculiar properties of the humid subsoil is evident from the fact that in the alfalfa fields adjacent to the prairies kept under observation the ratios were quite commonly found reduced as low as 1.2 to 1.4 to a depth of 15 or 20 ft., or even more (table XIII). In an oak grove planted on the prairie some 30 years before and sampled on practically the same dates

TABLE XIII

MOISTURE CONDITIONS IN EASTERN NEBRASKA ALFALFA FIELD, ADJACENT TO PRAIRIE REPORTED IN TABLE XII, SHOWING FAILURE OF PRAIRIE VEGETATION TO REDUCE MOISTURE CONTENT OF DEEPER SUBSOIL NOT DUE TO ANY PECULIARITY OF SUBSOIL

April 13, 1911			September 12, 1912			
			Boring 1		Boring 2	
Depth foot	Hygroscopic coefficient	Ratio	Hygroscopic coefficient	Ratio	Hygroscopic coefficient	Ratio
1..............	11.6	2.4	13.2	1.4	12.9	1.3
2–6............	13.4	1.7	13.7	1.1	13.5	1.1
7–12...........	11.0	1.5	12.4	1.1	12.1	1.1
13–18..........	8.5	1.5	10.5	1.1	10.8	1.1
19–21..........	11.5	1.4	11.8	1.2	12.1	1.1

as the prairie fields, the subsoil moisture was found to be affected to a greater depth than in the latter, the drying effect extending apparently to at least 15 ft. (table XIV).

TABLE XIV

MOISTURE CONDITIONS IN AN OAK GROVE NEAR LINCOLN

August 23, 1909			August 2, 1911			July 5, 1912		
Depth foot	Hygroscopic coefficient	Ratio	Depth foot	Hygroscopic coefficient	Ratio	Depth foot	Hygroscopic coefficient	Ratio
1......	10.1	1.1	1.....	9.1	1.8	1....	10.0	0.7
2......	11.7	1.3	2–9...	12.4	1.3	2....	11.8	1.7
3......	14.2	1.3	10–14.	11.9	1.6	3....	14.2	1.4
4......	14.1	1.2	15....	12.0	1.6	4....	14.1	1.2
5......	13.9	1.2	....	....	......	5....	14.0	1.2
6......	13.4	1.2	....	....	......	6....	13.5	1.2

Discussion

The moisture conditions in the deeper subsoil of the prairies are very dissimilar according to whether we deal with humid or with semi-arid fields. In the former at depths below 6 ft. the subsoil appears always moist, even after the severest drought, while in the latter the extreme dryness indicated by ratios of 1.0–1.2 is in general persistent in the deeper subsoil, extending to a depth of

12 ft. or more after prolonged droughts, and even in wetter seasons is commonly found in one or more foot levels within the first 6 ft. That the lack of dryness in the deeper subsoil of the humid prairies is not due to any peculiarity of the subsoil is evident from the observation that a fair stand of alfalfa may in the course of a few years reduce the moisture content almost to the hygroscopic coefficient to a depth of 20 ft. or more.

In our deep cylinder experiments (1) the exhaustion of free water was observed only within the zone of root development, and in our recently reported study of the movement of water in the absence of plants (3) we found no appreciable transfer of water from a moister to a drier portion of a soil when the ratio in the former was as low as 1.5 and that in the latter between 1.5 and 1.0.

If we assume that movement of water through a soil ceases when the ratio in the moistest portion has fallen as low as 1.5; that the deeper subsoil loses water through upward movement only when it is penetrated by plant roots; and, lastly, that plants are able to develop roots into a soil layer only when this has a moisture content above the computed wilting coefficient (5), the ratio 1.5, we must conclude that the roots responsible for the dry condition (indicated by ratios of 1.1–1.4) encountered in any subsoil level either will be found surviving or that they have died only since this level of the subsoil was last reduced to the dry condition.

In order to explain how the dry condition of the deeper subsoil is first established and how it is renewed after wet periods, it seems necessary to assume that among the shallow rooted grasses there are distributed a considerable number of very deep rooted perennials. After this dry condition of the deeper subsoil has once been established it may be maintained through a dry period of several successive years without the presence of any roots in it, the moisture from the rains and snow being held near the surface until it either evaporates or is transpired by the shallow rooted plants, while the upward movement of water from the moist zone beyond the extreme reach of plant roots is at least too slight to show a distinct effect. The absence of the dry condition in the deeper subsoil after prolonged droughts, such as illustrated by field E at Wauneta (table

VI), may be attributed to a temporary absence of the deep rooted perennials or to their fewness. The factors just mentioned are sufficient to account for the maintenance of a dry upper subsoil through which no roots could develop into the moist zone.

The question of whether the living roots are to be found in the deeper subsoil only during each successive wet period, they following the downward extension of the moist zone, continuing to withdraw water until the ratio approximates 1.0, and then dying off, or whether they continue alive but withdrawing practically no moisture throughout the dry periods of several years which intervene between the successive wet periods, is to be answered only by detailed field investigations, involving the use of pits or trenches 12–20 ft. deep.

The present moisture conditions of the deeper subsoil of the prairies, like their plant population, are to be regarded as the result of a slowly established equilibrium, and any alteration of the plant cover may greatly affect the subsoil moisture conditions. The complete suppression of plant life over an acre or more, a condition approached in young orchards and groves kept in clean cultivation, might during a series of wet years raise the moisture content of the deeper subsoil to its water-retaining capacity and maintain this with little change during the ensuing dry period. If such a field were neglected, however, it would soon be taken possession of by many species, most of them shallow rooted annuals, but some deeper rooting perennials, which, meeting little competition for moisture in the deeper subsoil, could develop an extensive root system there and gradually reduce the moisture to approximately the hygroscopic coefficient. Then, as on the prairie, this dry condition would be maintained except at such times as unusually wet seasons extended the moist zone far below its normal limits.

While it is evident from table VI that the lower limit of the dry zone in the deep loessial soils in the semi-arid region is more than 12–15 ft. below the surface we have no data showing its maximum depth. ROTMISTROV (**9**), from his studies near Odessa, concluded that there permanently moist subsoil in waste land occupied by weeds, etc., is first encountered at 14–30 ft. The depth to which the root systems of the deeper rooted prairie plants indicated by

SHANTZ (10) extend would not suffice to explain the dry condition of the deeper subsoil which we encountered.

The persistently moist condition of the deeper subsoil of the humid prairies is to be attributed to the fewness of the roots developed in them. When deep rooted perennial plants such as alfalfa or forest trees are introduced, their subsoil moisture is utilized to a much greater depth. It is evident that on these a forest once established should be able to maintain itself if protected from fires. The subsoil moisture conditions in general would indicate that the natural condition of grassland in eastern Nebraska is due to other causes than soil moisture conditions, while in western Nebraska it may be fully accounted for by those alone.

The distribution of carbonates in the first 6 ft. of soil in the prairies at McCook and Wauneta indicates that in prehistoric times the climate was similar to that now prevailing (4). Carbonates are found in the surface foot or two only in almost negligible quantities, while in the fourth, fifth, and sixth feet they constitute from 3 to 6 per cent of the weight of the soil..

Summary

1. During a 6-year period, in which the weather was exceptionally favorable for a study of the minimum moisture content of the subsoil, moisture studies were carried out on Nebraska prairies, both in the buffalo-grass formation in the southwestern part of that state, where the climate is typically semi-arid, and in the prairie-grass formation near Lincoln, which lies within the limits of the humid region. The fields were sampled to a depth of 6 ft. or more, and in the case of every sample the hygroscopic coefficient as well as the moisture content was determined, and the moisture condition is expressed as the ratio of moisture content to hygroscopic coefficient, this having the advantage of expressing the *relative moistness* while at the same time indicating whether either free water (1.1 or above) or growth water (1.6 or above) is present, and if so the amount of each.

2. The subsoils of the semi-arid prairies were characterized by their persistent dryness. Usually throughout more or less of the

first 6 ft. a ratio of 1.5 or lower was found, and commonly in one or more of the foot sections a ratio as low as 1.1 was encountered. After droughts of unusual severity the whole of the subsoil to a depth of 6 ft., and in some cases of 12 ft., showed a ratio of approximately 1.0.

3. There was no appreciable further reduction of the moisture content when, after the subsoil had been reduced to this very dry condition, there followed a 4 or 5-month period of practically rainless autumn and winter weather. After such droughts the surface foot was found but little drier than the subsoil.

4. The subsoils of the humid prairies, on the contrary, showed no distinct reduction of the moisture content through a greater depth than 5 ft., and even in this a ratio as low as 1.2 or 1.3 appeared only under the severest drought conditions. The normal moisture condition in the deeper subsoil (6–20 ft.) appears to correspond to a ratio lying between 2.0 and 2.4.

5. The dry condition of the deeper subsoil so common in the semi-arid prairies is to be attributed to the presence of perennials with a vertical root range of 15 ft. or more, while the moist condition characteristic of that of the humid prairies is regarded as evidence that the roots of the native vegetation are but little developed below the fifth foot. The occurrence of areas in the semi-arid prairies, even after a severe drought, in which the subsoil below the sixth foot is quite moist, is to be attributed to the absence or fewness of deep rooted perennials in such places.

6. After the subsoil at any level has been exhausted of the water in excess of the hygroscopic coefficient it remains in this dry condition until the precipitation conditions are sufficiently favorable to raise the ratio to 2.0 or upward throughout the whole distance from the surface down to the level in question. Accordingly during many wet periods following droughts the upper moistened portion of the subsoil will be isolated from any deeper lying moist layer by a zone in which the subsoil is too dry to permit of the penetration of plant roots.

7. While in the semi-arid prairies after protracted droughts the moisture conditions in the first 6 ft. are quite uniform, under more

normal weather conditions they vary much from place to place, thus rendering the results obtained in single borings unreliable as an index of the general moisture conditions.

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LITERATURE CITED

1. ALWAY, F. J., Studies on the relation of the non-available water of the soil to the hygroscopic coefficient. Nebr. Agric. Exp. Sta. Research Bull. 3. pp. 122. *figs. 37.* 1913.
2. ALWAY, F. J., and MCDOLE, G. R., The loess soils of the Nebraska portion of the Transition Region. I. Hygroscopicity, nitrogen, and organic carbon. Soil Science **1**:107–238. *pl. 3. figs.* 2. 1916.
3. ———, Relation of the water-retaining capacity of a soil to its hygroscopic coefficient. Jour. Agric. Research **9**:27–71. *figs. 4.* 1917.
4. ALWAY, F. J., and ROST, C. O., The loess soils of the Nebraska portion of the Transition Region: IV. Mechanical composition and inorganic constituents. Soil Science **1**:405–436. *figs. 2.* 1916.
5. BRIGGS, L. J., Dry-farming investigations in the United States. Rep. 84th Meeting Brit. Assn. Adv. Sci., 1914. pp. 263–282. *pl. 5. fig. 7.* 1915.
6. BRIGGS, L. J., and SHANTZ, H. L., The wilting coefficient for different plants and its indirect determination. U.S. Dept. Agric., Bur. Pl. Ind. Bull. 230. pp. 83. *pl. 2. figs. 9.* 1912.
7. BURR, W. W., The storage and use of soil moisture. Nebr. Agric. Exp. Sta. Research Bull. 5. pp. 88. 1914.
8. GRACE, O. J., The effect of different times of plowing small grain stubble in eastern Colorado. U.S.D.A. Bull. 253. 1915.
9. ROTMISTROV, V. G., The nature of drought according to the evidence of the Odessa Experiment Field. pp. 48. *figs. 20.* Odessa. 1913.
10. SHANTZ, H. L., Natural vegetation as an indicator of the capabilities of land for crop production in the Great Plains Area. U.S. Dept. Agric., Bur. Pl. Ind. Bull. 201. pp. 100. *pl. 6. figs. 23.* 1911.
11. TINSLEY, J. D., and VERNON, J. J., Soil and soil moisture investigations in the season of 1901. N.M. Agric. Exp. Sta. Bull. 38. pp. 94. *pl. 11. fig. 1.* 1901.