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DIRECT MEASUREMENT OF WATER LOSS FROM VEGETATION WITHOUT DISTURBING THE NORMAL STRUCTURE OF THE SOIL

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Introduction

One of the most serious objections to the usual method of determining the water losses from plants is the almost universal use of containers which are quite too small to accommodate the normal development of the root system. But even where containers of sufficient size to overcome this obstacle are employed, the plants are grown in a mass of soil which has been at least fairly recently screened, mixed, aerated and watered and thus its structure is wholly unlike that which occurs in nature. This difference has been noticed for a number of years in connection with investigations of root systems of native and crop plants, as well as the markedly better growth of plants in the loose soil of trenches which have been refilled only one to four years. Just how long a time is required for such soil to assume the structure and take on the physical and chemical properties of that in an undisturbed area has not been determined, but casual observations indicate that many years are required. Undoubtedly the return to the former condition of equilibrium with surrounding soils, and the consequent effect upon the roots of plants, plays no small part in the phenomenon called plant succession, a process often requiring a minimum of 15–25 years for its completion.

Since a disturbance of the extremely complex system of physical, chemical and biological conditions included in soil structure has such profound effects upon the growth of plants, it seems clear that it might also affect the water relations and thus more or less vitiate attempts to determine the normal transpiration rate by use of containers filled with a soil mixture.

To obviate these possible errors and to determine the water losses from native and crop plants already grown under normal field conditions without disturbing the root system, the following experiments were performed.

Methods

A steel cylinder, 12 inches high and with an inner cross-sectional area of one square foot, the edge on one end of which was sharpened, was driven into the soil in the grassland to a depth of about 4 inches. Care was taken not only to select a typical cover of the grassy vegetation but also to cut off none of the over-lapping leaves belonging to the plants in the enclosed square foot. The cylinder was then carefully removed, leaving the column of soil intact, and replaced by one end of a heavy galvanized iron cylinder of similar cross-sectional area 3 feet long and reinforced at both ends by a heavy wire over which the metal was turned back smoothly. After starting a row of these cylinders, the individuals being at least eight inches apart, a trench about two feet wide was dug around them to a depth of over 3 feet. In digging the trench no soil was removed within 3 or 4 inches of the cylinders. As the trench was being excavated the columns of soil in front of the cylinders were carefully pared away with large knives in such a manner that the cylinders could be forced over the columns when considerable pressure was applied from above. By shaping the column only a few inches in front of the descending cylinder it was possible to force the latter into place to a depth of three feet over a tightly fitting soil core. The columns were next undercut so as to break off readily, and the portion extending beyond the lower end of the cylinder cut off smoothly. Next a loosely fitting metal bottom, with edges upturned two inches, was placed over the end of the core and cylinder which was then weighed on a portable Fairbanks scales sensitive to one-fourth pound. In the meantime a long trench just wide and deep enough to receive the cylinders in an upright position had been dug in a nearby undisturbed area, care having been taken not to cover the grass with soil (plate III A). The cylinders with contents were lowered into the new trench and slid into place on a plank in the bottom, after which the bottoms of the cylinders were made water tight by the addition of a measured amount of paraffin-petrolatum wax seal mixture poured while hot into the bottoms from the outside and allowed to congeal. Finally the trench about the cylinders was filled with soil, pieces of sod being fitted around the tops, thus they soon took on normal soil temperatures while the above ground parts were at about the same general level and surrounded by vegetation as before.

In these experiments, which extended throughout a period of 15 days and were repeated at three widely separated stations, the trenches were selected in areas so that surface water could be drained away from them and, moreover, the plants were covered by long wooden roofs at all times when rain was actually falling. This was necessary because the varying amounts and kinds of vegetation in the several cylinders would intercept different amounts of rainfall and corrections calculated from rain gauges would be entirely misleading (Horton, 1919).

By the employment of similar methods water losses in fields of oats and millet were determined. In these experiments, owing to the difficulty of selecting the proper slope for drainage, the usual type of bottom for the cylinders was replaced by one of similar diameter but 3 feet deep. To determine the amount of water lost directly from the soil, the plants from one container in each field were removed. The direct losses from the prairie soil were determined in a similar manner except that the grasses in the container, killed by the addition of a measured amount of boiling water, were left in place.

From time to time during the progress of the experiment, depending upon weather conditions and the demands of the plants, water was added very slowly and in measured amounts to all the containers. As a result of this, very little shrinking of the column of soil away from the container occurred.

None of the plants in the containers died, in fact not even those near the edge showed signs of wilting, indicating that sufficient roots were in the core of soil to abundantly furnish the plants with water. Great care was exercised in watering so that there was little or no runoff down the sides of the core. This was accomplished by pouring the water on slowly and pressing the moist soil firmly against the cylinders where (as occasionally happened) the contact was not water tight. At the end of the period the containers were reweighed and the losses calculated. Data were obtained including kind, size and abundance as well as the dry weight of the grasses and crops, the dead growth of previous years being discarded.

Experiments at Burlington, Colorado

Experiments were conducted in the Great Plains at Burlington, Colorado (altitude 4,160 feet). The type of vegetation is that designated as short-grass (Bouteloua-Bulbilis association). Closed mats of buffalo grass *Bulbilis dactyloides,* usually mixed with grama grass *Bouteloua gracilis,* make up fully 90 per cent of the vegetation, forming a carpet seldom over 4 inches deep, exclusive of flower stalks. These grasses with their widely spreading roots occupy the soil so thoroughly that relatively few subdominants occur. Most conspicuous among these, and increasing in abundance where overgrazing has occurred, are wire-grass *Aristida purpurea,* cacti *Opuntia camanchica, O. fragilis* and *O. polyacantha,* an annual fescue *Festuca octoflora,* wooly plaintain *Plantago purshii,* Texas crab grass *Schedonnardus paniculatus,* a mustard *Erysimum asperum,* wild alfalfa *Psoralea tenuiflora,* buffalo bean *Astragalus crassicarpus,* a mallow *Malvastrum coccineum,* and cone-flower *Ratibida columnaris.* Wheat-grass *Agropyrum glaucum,* is often found in disturbed areas from which vantage points it invades the short-grasses.

This rather meager plant cover grows in a rich, brown, very fine sandy loam which is very compact and hard when dry. At a depth of 2 to 2.5 feet it is underlaid with a hardpan caused by the concentration of colloidal clay and carbonates (Weaver and Crist, 1922). An examination of table 1 shows that silt constitutes about one-third of the soil at all depths, while the sand decreases and the clay increases in amount to 4 feet.

In this hard, fine-textured soil water penetrates very slowly and runoff is very high, usually exceeding one third of the rainfall. Water-content determinations during a period of four growing seasons show that the soil is seldom moist below the surface 2–2.5 feet, while even here the moisture is regularly reduced to the hygroscopic coefficient during summer drought.

TABLE I. *Mechanical analyses of soils from Burlington, Colorado*

	Depth of sample, in feet				
	0.0 to 0.5	0.5 to 1.0	1 to 2	2 to 3	3 to 4
	p.ct.	p.ct.	p.ct.	p.ct.	p.ct.
Coarse gravel	0.0	0.0	0.0	0.0	0.0
Fine gravel	0.0	0.0	0.0	0.0	0.0
Coarse sand	0.0	0.0	0.0	0.0	0.0
Medium sand	0.1	0.1	0.2	0.1	0.1
Fine sand	2.6	2.2	1.9	1.5	0.9
Very fine sand	48.6	49.1	46.7	45.5	42.2
Silt	33.4	32.5	32.0	31.0	34.2
Clay	15.3	16.1	19.3	21.9	22.6
Hygroscopic coefficient	10.9	10.9	12.2	12.0	11.4

Six cylinders were used in the grassland and three in an adjoining field of millet. Container 2 was covered with a dense closed mat of nearly pure pistillate *Bulbilis dactyloides* except for about one sixth *Bouteloua gracilis.* They formed a fine green carpet about 4 inches in average height. Only one fifth of the area enclosed by the cylinder was bare. The check container, number 1, in which the vegetation was killed, was similar to number 2 except that one fourth of the area was bare. Container 3 was very much like number 1 except for a mixture of about one third grama which was flowering at a height of 8 inches. The average height of the short-grass foliage was 4.5 inches. Container 4 consisted of nearly pure pistillate *Bulbilis* about 4 inches tall with just a little grama, some of which had flower stalks. Only one sixth of the area was bare. Containers 5 and 6 had a rather dense growth of *Agropyrum glaucum.* The foliage averaged 20 inches in height, most of the stems being dry and yellowish to a height of 6 or 8 inches. There were no flower stalks. The two containers were very similar, number 6 having slightly less vegetation (plate III B).

The millet was about 4 weeks old, of thick stand, and had an average height of 18 inches. It had not begun to head at the beginning of the experiment (July 5), but by the end of the 15-day period it was well headed with an average height of 20 inches. Two containers with millet were used, and one from which the crop had been removed by pulling out the plants.

The soil, as usual at this time of the year, was very dry. About 4 per cent of water in excess of the hygroscopic coefficient was available at 2 to 2.5 feet in the grassland, no excess being present at any other level to 4 feet. This water deficiency was indicated by the rapid browning and rolling of the vegetation outside the containers during July 6 to 10. Slightly more

TABLE 2. *Loss of water from native vegetation and millet at Burlington, Colorado*

Container	Dominant species	Original weight, July 5	Weight of seal	Water added (lbs.), July 5	6	7	8	9	12	17	18	19	Final weight, July 20	Loss	Dry wt. of plants	Loss per gram of dry wt.
		lbs.	lbs.										lbs.	lbs.	grams	grams
1	Control, dead buffalo grass	254.75	2.03	5	0	0	2	0	3	3	0	1	265.75	5.03		
2	Buffalo grass	260.5	1.22	2	2	0	3	0	3	3	0	2	264.25	12.47	15.4	367.3
3	" "	254.0	1.22	2	2	0	3	0	3	3	0	2	259.00	11.22	17.75	286.7
4	" "	265.25	1.22	2	2	0	3	0	3	3	0	2	268.75	12.72	15.75	366.3
5	Wheat grass	251.5	1.22	4	2	2	3	0	4	3	0	2	254.00	18.72	45.31	187.4
6	" "	254.25	1.08	4	2	2	3	0	4	3	0	2	258.50	16.83	40.32	189.3
7	Milllet	274.78	1.22	0	2	2	3	2	3	3	3	2	274.50	21.50	46.95	207.7
8	"	278.75	1.22	0	2	2	3	0	3	3	3	2	279.00	18.97	40.20	214.0
9	Control, bare soil	267.25	1.22	0	1	1	2	0	3	3	0	0	271.50	6.97		

moisture was available in the field of millet, although the leaves rolled daily and many areas in the field were badly wilted until relieved by rains on July 14. Hence it was necessary to water the plants in the enclosed soil columns rather freely to keep them in good condition. The amounts of water added, the original and final weight, dry weight of vegetation, as well as the amounts transpired are given in table 2.

An examination of table 2 shows that the weight of the soil columns varied from 251 to 279 pounds, of which cylinder and bottom weighed about 15 pounds. This variation was due in part to differences in soil structure and water-content and partly to rodent burrows in the deeper soil. The wax seal, which consisted of 80 per cent parowax and 20 per cent petrolatum, was weighed on a small balance, the large one being sensitive to only one fourth pound. The final weights of the columns are only slightly greater than their original weights which means that approximately all of the water added was again lost by transpiration or direct evaporation from the soil and dead plant surfaces. The latter amount was only 5.03 pounds (container 1). The square foot of *Bulbilis* and *Bouteloua* in each of the three containers lost 11 to 13 pounds. The wheat grasses lost 17 to 19 pounds, varying directly with the amount of foliage concerned, while the losses from the millet were even greater, 19 to 21.5 pounds. It is interesting to note that the bare area lost approximately two pounds more water than a similar area covered with dead grasses.

At the end of the experiment the vegetation was carefully removed at the soil surface by means of a hand grass clipper. The dead foliage of former years was very carefully separated from the living plants and the latter oven dried at 60° C. and weighed. The loss of water in grams per gram of dry weight of the vegetation is shown in the last column of the table. This, of course, is not the water requirement. It is almost identical (about 366 grams) in containers 2 and 4, the smaller ratio in number 3 probably being due to the presence of flower stalks of grama grass which increased the dry weight but transpired little. The relatively low ratio of the wheat-grasses (188 grams) may readily be explained by their large, very fibrous stems. Losses from the millet were intermediate, probably being relatively less than earlier because of the heads.

Considered solely on the basis of total loss per square foot area the millet ranks first, wheat-grass second, and the short-grasses last. Thus, as is shown by the distribution of the native species, wheat-grass is less adapted to this semi-arid region than are the short-grasses, more than one third more water escaping from areas occupied by the former. These data, however, hold only for the conditions of the experiment, *viz.*, plants growing in very dry soil and under unusually humid conditions for the Great Plains. This can readily be seen by an examination of the environmental conditions, and especially by comparing them with conditions of preceding seasons.

The weather during the first five days of the experiment was very characteristic of high plains in July with day temperatures reaching from 90° to 96° F. and falling to 60° or 65° F. at night, the humidity fluctuating from 25 or 30 per cent in the afternoon to 80 or 85 per cent late at night. However, this was followed by ten days during which the atmosphere was cooler and much more humid due largely to an unusual amount of cloudy weather and rain. Rains totaling 2.6 inches fell in the evening or at night on July 11, 14, 16 and 17. Since most of these were general, covering a wide area, the humidity was greatly increased regardless of wind. One day was entirely cloudy, four were cloudy half or more of the time, on three others it was cloudy more than one fourth of the time, while only seven were clear. Temperatures ranged rather uniformly between 55°–60° F. and 80°–85° F., and the humidity nearly always reached 100 per cent at night and except for one day fell only to 50 or 55 per cent during the afternoons. The average day temperatures and humidities for the period (8 A.M. to 6 P.M.) were 80° F. and 57 per cent respectively. While the temperature was nearly the same as the average day temperature for the same period during the three preceding years, as determined by hygrothermographs in the field, the humidity was 11 per cent higher.

Wind movement at a height of 39 cm. during the first four days averaged over seven miles per hour, but during the rest of the time it was much less (3.4 miles), periods of calm not being infrequent. Evaporation from the porous cup atmometers was 35.4 c.c. average daily as compared with an average of 40.5 c.c. for the three (approximately) similar July intervals preceding. Thus, it seems clear that the water lost by the areas of crops and grassland, while high, was probably somewhat below normal.

Experiments at Phillipsburg, Kansas

A similar lot of experiments were conducted on June 18 to July 3 at Phillipsburg in north central Kansas, 180 miles east and somewhat north of Burlington, in an area of grassland (*Stipa-Bouteloua* association) characterized as mixed prairie. Here the precipitation (23 inches mean annual) has increased 5 inches over that in the short-grass country and, moreover, runoff is less, humidity higher and evaporating power of the air lower (*cf.* Weaver, Jean and Crist, 1922). Because of the more favorable growth conditions, the tall-grasses of the true prairies further eastward meet and mingle with the short-grasses, the former alternating with or forming a layer above the shorter ones. Thus the vegetation forms typical mixed prairie. The bluestems *Andropogon scoparius, A. nutans* and *A. furcatus* often form more or less continuous irregular sodded areas varying from 6 inches to 7 feet in diameter where short-grasses may be almost entirely excluded, while wheatgrass *Agropyrum glaucum,* frequently occupies large areas rather exclusively. Side oats grama *Bouteloua racemosa* and wild rye *Elymus canadensis,* are other important tall-grasses. Alternating with these are similar or, on drier slopes, even larger areas of *Bulbilis dactyloides* and *Bouteloua gracilis*, intervening areas often to the extent of one fourth of the surface being nearly devoid of vegetation. Perhaps, more usually, however, the short and tall grasses are intimately mixed, the former often showing strong tendencies towards the bunch habit. Certain sedges *Carex filifolia* and *Carex stenophylla*, supplement the understory of grasses which reach an average height of about 4 inches (before flower-stalk production), as contrasted with the midsummer tall-grass level 4 to 10 inches above. Subdominant herbs are not only more abundant as regards species than in the short-grass plains, but they often form more extensive societies and the individuals reach larger size (*cf.* Clements, 1920).

The soil supporting this vegetation which covers the gently rolling hills is a fertile, mellow, dark-brown, very fine sandy loam of the Colby series. An examination of table 3 shows that it is quite uniform throughout although the clay increases and the very fine sand decreases with depth.

TABLE 3. *Mechanical analyses of soils from Phillipsburg, Kansas*

	Depth of sample, in feet.				
	0.0–0.5	0.5–1.0	1–2	2–3	3–4
	p. ct.	p. ct.	p. ct.	p. ct.	p.ct.
Coarse gravel	0.0	0.0	0.0	0.0	0.0
Fine gravel	0.0	0.0	0.0	0.0	0.0
Coarse sand	0.3	0.0	0.0	0.0	0.0
Medium sand	0.2	0.2	0.2	0.3	0.1
Fine sand	1.2	0.5	0.3	0.6	0.2
Very fine sand	43.5	44.4	39.7	41.2	37.5
Silt	35.8	32.8	34.0	31.9	31.4
Clay	19.0	22.1	25.8	26.0	30.8
Hygroscopic coefficient	10.6	10.6	10.9	10.6	10.7

Six cylinders were used in the mixed prairie grassland and three in an adjoining field of oats. Container 2 was two thirds covered with a dense sod of *Bouteloua gracilis* with a very little pistillate *Bulbilis dactyloides*. The grasses had an average height of 9 inches. The third container was fully two thirds covered with a practically pure growth of *Bouteloua gracilis* with an average height of 9 inches, in which were found a few stalks of *Sporobolus cryptandrus*, and one small *Callirrhoe involucrata*. The control, number 1, bore a vegetative cover of a kind and density almost exactly like that in number 3. About one fourth of the area in container 4 was bare. The rest was covered with a dense sod of mostly pistillate *Bulbilis dactyloides* 4 to 8 inches tall. There were also four small clumps of *Carex filifolia* and a very small amount of *Bouteloua gracilis*. A fine clump of *Andropogon furcatus*, 18 inches in average height, occupied 96 square inches of the area in container 5, the rest being devoid of vegetation. Container 6 also bore a clump of the same grass 91 square inches in extent at the base, and with an average height of 20 inches.

The soil at the time of the experiment had a good supply of moisture, the columns being shaped with ease in the mellow loess. The water-content in excess of the hygroscopic coefficient at the several depths was as follows: 0–6 in., 11.3; 6–12 in., 13.3; 1–2 ft., 11.1; 2–3 ft., 12.6 per cent.

The crop of white Kherson oats had been planted on April 12 at the rate of 56 pounds per acre. At the beginning of the experiment (June 18) it was 2 feet high and had headed. The soil had a water supply above the hygroscopic coefficient at the several depths as follows: 0–6 in., 3.3; 6–12 in., 6.5; 1–2 ft., 4.1; 2–3 ft., 1.8 per cent respectively. Notwithstanding considerable watering, by the end of the 15-day period the crop was rapidly ripening, the lower leaves being quite dry and yellow. At the end of the experiment the oats in container 7 had 20 fully grown stalks 29 inches in average height and 7 tillers. Number 8 had 27 stalks about 27 inches tall and 3 tillers. A little undergrowth of *Chaetochloa viridis* and *Eragrostis major* occurred in both containers.

The period during which the experiment was conducted (June 18 to July 3) was one of very typical weather for early summer at this station, when compared with that of the three preceding years during which factor data were obtained. Except for a few floating clouds, 9 days were clear and 4 others were sunny for over half of the time. Only on two days did the sun shine for less than one third of the time. Heavy showers occurred at night on June 18, 21, 26 and 29 as well as during the day on the 21st. June 24 was extremely warm, a temperature of 98° F. being accompanied by a high, drying south wind. The air temperature during the first six days of the period ranged from 65° to 98° F. and the humidity from 41 to 97 per cent. During the remainder of the time the variations were from 42° to 90° F. and 34 to 100 per cent humidity. The average day temperature for the 15-day period was 80.6° F. and the average day humidity 60 per cent. The total wind movement at a height of 39 cm. was 1179 miles, an average of 3.3 miles per hour. However, most of this occurred during the day, several days being very windy. The rather dry conditions are shown by the average daily evaporating power of the air (12 cm. above the soil surface) which was 25.5 c.c.

Under these conditions of prevailing clear, warm weather the losses by transpiration were quite high (table 4).

Uniformity in the weight of the soil columns is marked, the weight being about 20 pounds more than at Burlington. All of those with grasses were obtained from a single long trench. Among the short-grasses the amount of water added slightly exceeded the amount used; it was approximately the same in amount in the oats, but the soil lost 3 to 7 pounds of its original weight in the case of the bluestems. Losses from the control with a dead short-grass cover and from bare soil were 4.4 and 7.2 pounds respectively. Losses from containers 2 and 3, where the dominants were grama grass, were 14.7 and 16.2 pounds per square foot respectively, approximately one pound (pint) of water per day. The buffalo grass sod lost nearly as much, 14.2 pounds, while that from the big bluestem was nearly twice as great, 27 and 28 pounds respectively. The oats even in their late stage of development lost amounts almost identical with those of the columns with short-grasses (14.7 and 16.4 pounds).

TABLE 4. *Water losses from native vegetation and oats at Phillipsburg, Kansas*

Container	Dominant species	Original wt. June 18	Wt. of seal	Water added (lbs.), June					Final weight July 3	Loss	Dry weight of plants	Loss per gram of dry wt.
				18	19	22	26	30				
		lbs.	lbs.						lbs.	lbs.	grams	grams
1	Control, dead *Bouteloua gracilis*	276.25	0.9	7	0	1	2	4	286.75	4.40		
2	*Bouteloua gracilis*	278.75	0.9	2	2	4	4	4	281.00	14.65	19.30	344.3
3	*Bouteloua gracilis*	274.00	1.2	2	2	4	4	4	275.00	16.20	20.42	359.9
4	*Bulbilis dactyloides*	275.50	0.75	2	2	4	4	4	278.00	14.25	21.76	297.0
5	*Andropogon furcatu*	282.50	0.9	2	2	4	4	4	271.25	28.15	53.90	236.9
6	*Andropogon furcatus*	282.30	0.75	2	2	4	7	4	275.00	27.05	53.94	227.5
7	Oats	269.25	2.43	0	2	4	4	4	271.00	14.68	34.30	194.1
8	Oats	267.50	2.43	0	2	4	4	4	267.5	16.43	36.43	204.6
9	Control, bare soil	285.75	2.43	0	2	1	2	2	288.00	7.18		

Thus, a square foot of buffalo grass sod in mixed prairie, rooted in very moist soil and under favorable conditions for transpiration and evaporation, lost only slightly more water than a similar area in very dry soil under rather unfavorable weather conditions in the Great Plains.

The loss of water per gram of dry weight of vegetation (last column) was considerably greater for *Bulbilis* at Burlington (341 grams) than at Phillipsburg (297 grams). *Bouteloua* gave a higher average ratio, 352, while that of the Andropogons was lower (228 to 237) [1]. The oats gave a relatively low loss undoubtedly because of the grain which increased the dry weight but added little to the transpiring area.

[1] In these calculations total loss from the column, *i.e.*, transpiration and evaporation, is used, for it seems clear that a dead cover of short-grass, for example, would have a very different effect upon evaporation from the soil than a living cover of *Andropogon.*

EXPERIMENTS AT LINCOLN, NEBRASKA

Similar experiments were also performed in the prairie at Lincoln, Nebraska. The vegetation is distinctly of the tall-grass sod type. Little bluestem *Andropogon scoparius,* spear grass *Stipa spartea,* June grass *Koeleria cristata,* side oats grama *Bouteloua racemosa* and goldstem *Andropogon nutans* are the chief grasses of the uplands, although some big bluestem

A. furcatus occurs with bluegrass *Poa pratensis*. Wild rye *Elymus canadensis* and grama *Bouteloua gracilis* are of much less importance. A host of other herbs occurs, forming extensive societies and indicating the presence of better conditions as regards soil moisture than occur in the mixed prairie. These mostly overtop the grasses and give tone to the landscape, the aspects changing with the season. An average height-level of grasses of 6 inches and an upper story of herbs at 15 to 22 inches occurs by June 1, although the flower stalks of *Stipa* and later blooming grasses and herbs are 2.5 to 3.5 feet tall.

This luxuriant plant cover grows in a soil composed of glacial drift. It is a silt-loam belonging to the Carrington series, with a water-holding capacity of about 60 per cent. Table 5 shows that it is fine in texture, being composed mostly of silt and clay. It is sufficiently supplied with calcium to lack acidity, and is usually well supplied with water to great depths. The native vegetation is deeply rooted.

TABLE 5. *Mechanical analyses of soils from Lincoln, Nebraska*

	Depth of sample in feet.				
	0.0–0.5	0.5–1.0	1–2	2–3	3–4
	p. ct.	p. ct.	p. ct.	p. ct.	p. ct.
Coarse gravel	0.0	0.0	0.0	0.0	0.0
Fine gravel	0.0	0.0	0.0	0.0	0.0
Coarse sand	2.0	1.2	2.7	5.6	7.0
Medium sand	1.9	2.2	2.9	6.9	8.8
Fine sand	6.0	3.8	4.8	10.1	12.8
Very fine sand	26.1	21.8	19.6	23.1	23.5
Silt	39.3	38.4	45.6	32.8	28.3
Clay	24.7	32.6	24.4	21.5	19.6
Hygroscopic coefficient	12.7	15.6	13.1	11.0	10.0

Six cylinders were used at the upland station during May 31 to June 15, 1923 (plate III C). The vegetation in container 2 consisted of 4 bunches of *Koeleria* flowering profusely at a height of 16 inches, one *Solidago rigida* about 8 inches high, with 6 leaves, one bunch of *Sisyrinchium angustifolium* and a very little *Andropogon scoparius*. Except for about one sixth bare area, practically the whole container was covered with a sod of *A. nutans* and *Bouteloua racemosa* mixed with a little *Andropogon furcatus, Carex pennsylvanica* and *Poa pratensis* and having a general height-level of 9 inches.

The vegetation in container 1, which had been killed with hot water, was very similar to that in 2, having been taken within 18 inches of it. Container 3 had 2 clumps of *Koeleria* flowering abundantly at 16 inches, one third of the area was occupied by *Andropogon nutans* 10 inches high mixed with a little *Poa, Carex* and *Bouteloua racemosa,* one sixth by *A. scoparius* 8 inches tall, while the remaining area was bare.

Container 4 held one fine bunch of *Koeleria cristata* with 9 flower-stalks 10–11 inches tall, while one half of the area was occupied by a sod of *Andropogon nutans*, 7 inches high intermixed with a little *Poa pratensis*. Two small clumps of *Bouteloua racemosa*, 5 *Carex pennsylvanica*, one *Panicum scribnerianum* with a seedling of *Brauneria pallida* 7 inches high completed the list. Only one fifth of the soil was bare.

Container 5 had three large and two small bunches of *Stipa spartea* about 18 inches tall, 4 small clumps of *Bouteloua racemosa*, 3 small areas of *Andropogon scoparius*, 1 small clump of *A. nutans*, 3 *Amorpha canescens* stems with scarcely any leaves, one *Carex pennsylvanica* and one *Solidago missouriensis* about 4 inches tall. One third of the soil was bare.

Number 6 had two medium-sized bunches of *Stipa spartea* each about 15 inches tall; one half of the surface was covered with a sod of *Andropogon scoparius* about 7 inches high. Other plants included one small clump of *A. nutans*, one *Panicum scribnerianum* and two stems of *Aster multiflorus* about 8 inches tall. Approximately one fourth of the area was bare.

The soil at this time had the following percentage of water above the hygroscopic coefficient, at the several levels: 0–6 in., 10.4; 6–12 in., 16.6; 1–2 ft., 16.7; 2–3 ft., 11.5.

The period (May 31–June 15) was exceptionally cool and wet. Only one entire day was sunny and on only two others did the sun shine over half of the time. During a four-day period the sun did not appear, while the total sunshine over the entire interval was approximately 5.5 days. Four and nine tenths inches of rain fell distributed over 8 days. Rains occurred during the daylight hours on 6 days, during one of which it was necessary to keep the plants sheltered for the entire day. In fact they were under cover for a total period of 30 hours of daylight when rain was falling.

The air temperature during the first 7 days ranged from 55° to 91° F. while the humidity was never lower than 55 per cent. Then followed a period of four days when the temperatures remained at 58° to 65° F. and the humidity above 80 per cent. The remaining time was similar to that of the first seven days. The average day temperature for the entire period was 70.1° F. and the day humidity 75 per cent.

The total wind movement during the period at a height of 39 cm. was 1,196 miles, an average of only 3.3 miles per hour. Except for a single day the wind was low. The very mesophytic conditions are shown by the average daily evaporating power of the air which was only 8.4 cc. per day, a loss of 20 to 30 cc. per day not being unusual during this portion of the growing season.

Under such conditions of cool cloudy weather and high humidities the water losses were very low (table 6).

A striking character of the soil columns is their rather uniform weight. Cores 1 to 4 were obtained from a single trench, the extreme distance between

TABLE 6. *Water losses from square-foot areas of grassland at Lincoln, Nebraska*

Number	Original weight May 31	Weight of seal	Water added May 31	Final weight June 15	Loss	Dry wt. of foliage	Loss per gram of dry wt.
	lbs.	lbs.	lbs.	lbs.	lbs.	grams	grams
1, control...	309.50	0.60	5.5	312.5	3.1		
2..........	307.00	0.60	4.0	303.0	8.6	19.18	203.4
3..........	305.25	1.20	4.0	302.0	8.45	18.95	202.3
4..........	303.75	1.00	4.0	302.5	6.25	13.88	204.3
5..........	313.00	0.80	4.0	311.0	6.8	18.95	162.8
6..........	308.00	1.20	4.0	308.0	5.2	15.18	155.4

the containers not exceeding 6 feet. The weight of the three cubic feet of soil (exclusive of container) varied only from 289 to 295 lbs. Soil columns 5 and 6 were obtained about 50 feet distance from the first trench.

In table 6 it may be seen that the water losses though low, are fairly consistent ranging from 2.1 to 5.5 lbs. per square foot in excess of that of the area covered with dead grasses. Moreover the variations are directly proportional to the extent of the grassy cover, as expressed in dry weight. In the last column of table 6 it may be seen that the mixture of grasses (chiefly *Andropogons* and *Koeleria*) lost about 203 grams of water per gram of dry matter, which was somewhat more than that from *Stipa spartea* (average 159 grams). The latter was not only more mature but was growing in soil 6–10 per cent drier.

An experiment was begun in a field of white Kherson oats on June 5 when the crop was beginning to head (plate III D). It had been planted on April 4 at the usual rate of 56 lbs. per acre, after preparing the soil, which had been broken for many years, by plowing and harrowing. At the end of the 10-day experiment (June 15) the plants had an average height of 34 inches and were past the blossoming stage. In container 1 there were 72 large stalks and 24 smaller tillers, while container 2 had only 59 large stalks and 28 small ones. The water-content of the silt loam was so nearly optimum (about 20 per cent in excess of the hygroscopic coefficient) that little water was added throughout the experiment. The losses and other data are given in table 7.

TABLE 7. *Water losses from square-foot areas of oats at Lincoln, Nebraska*

No.	Original weight June 5	Weight of seal	Water added June 13	Total weight	Final weight June 15	Loss	Dry wt.	Loss per gram of dry wt.
	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	grams	grams
1..........	326.75	2.0	4	332.75	323.00	9.75	65.03	68.0
2..........	323.50	2.0	4	329.50	320.00	9.50	60.88	70.8
3, control...	333.00	2.0	2	337.00	335.25	1.75		

Notwithstanding the unfavorable atmospheric conditions for transpiration as well as the late stage in the development of the crop, the losses are fairly high, about 8 lbs. in excess of the bare area or 0.8 lbs. per day. The daily loss from the bare soil (0.18 lbs. per day) was similar to that (0.21 lbs.) covered with dead grasses.

Because of the unfavorable weather conditions the experiments were repeated during July and August. On July 24, five containers were installed in the high prairie station and four others in an adjoining low prairie. In container one a mixture of *Andropogon nutans, Koeleria cristata* and *Poa pratensis* with a single plant of *Amorpha canescens* (*Andropogon* being most abundant) covered half of the area. These had an average height of 12 inches. The surface of three-fourths of the second container was covered principally with *Andropogon nutans,* but also with a mixture of *Koeleria cristata, Bouteloua racemosa,* and a little *Poa pratensis* with an average height of 15 inches. The grasses in container three were chiefly *Andropogon scoparius,* with a third as much *A. nutans* and a very little *Bouteloua racemosa.* The height was 14 inches. In container four one-fifth only of the area was bare, the rest being occupied with a mixture of the grasses named above, *Andropogon scoparius* dominating. *Amorpha canescens* and *Antennaria campestris* were each represented by a single small clump. The control container, number 5, in which the grasses were killed as usual. was very similar to number three.

In the low prairie two clumps of *Andropogon furcatus,* 22 inches in average height, occupied slightly less than half of the area in container 6, the rest being bare. Nearly two thirds of the area in container 7 was bare, the rest being occupied by a large clump of *A. furcatus* 16 inches in height. *Spartina cynosuroides* with a little *Panicum virgatum,* with an average height of 38 inches, filled about one third of container 8, the remainder being destitute of plants. The remaining cylinder was sunk and a soil core obtained in a field of alfalfa where the plants were 21 inches high and beginning to blossom freely. A single clump in the center of the core was obtained which occupied only one fourth of the area.

Because of a prolonged period of hot dry weather the grasses on both high and low prairie had rolled leaves and some were wilted during the afternoons, a phenomenon seldom seen among true prairie vegetation. Water-content on the high prairie in excess of the hygroscopic coefficient was as follows: 0–6 inches, 3.0 per cent; 6–12 inches, 4.3; 1–2 feet, 5.4; 2–3 feet, 7.1; and 3–4 feet, 7.5 per cent respectively. The soil in the low prairie was somewhat more moist. After selecting the soil cores and before they were excavated, a hole about an inch in diameter and eight inches deep was made in the center of each. After excavating but before weighing several liters of water were poured slowly into the hole in each core and the water-content thus increased at least to a depth of a foot. These holes were kept tightly corked except when more water was added from time to time during the course of the experiment.

Weather conditions throughout the following 15 days were below normal as regards amount of sunshine and heat. Only two days were entirely clear, three were cloudy for one third of the time, seven for half or more of the day, while on three days there was no sunshine. Rains totaling 3.6 inches fell on eight different days, usually occurring at night, early in the morning, or late in the evening, but on one day it showered intermittently throughout. The showers necessitated covering the plants which were thus protected approximately 30 daylight hours and even longer during the nights. The average day temperature for the period was 79° F. which was 3° F. lower than the average of a similar period for the three years preceding. The average day humidity was 80 per cent as contrasted with 66.6 per cent average for approximately similar dates of three preceding years. The wind velocity averaged 3.4 miles per hour; the evaporating power of the air 22 c.c. per day, the cups being placed at a height of about 4 inches above the soil surface.

The transpiration and other data are given in table 8.

TABLE 8. *Water losses from square-foot areas of native vegetation and alfalfa at Lincoln, Nebraska*

Container	Original weight July 24	Wt. of seal	Water added (lbs.)						Final weight Aug. 8	Loss	Dry wt. of plants	Loss per gram dry wt. of plants
			July				August					
			25	26	28	30	1	3				
	lbs.	lbs.							lbs.	lbs.	grams	grams
1.....	294.75	0.61	2	2	3	3	2	2	300	9.36	12.77	332.5
2.....	294.50	1.22	2	2	3	3	2	2	296.0	13.72	32.07	194.1
3.....	291.25	1.08	2	2	3	3	2	2	295.0	11.33	23.12	222.3
4.....	286.25	0.81	2	2	3	3	2	2	291.25	9.81	22.70	196.0
5[1]....	293.75	0.81	4	2	1	3	1	0	300.75	4.81		
6.....	308.75	2.03	5	4	5	2	2	2	313.25	17.53	66.53	119.5
7.....	291.00	0.81	5	4	5	2	2	2	296.5	15.31	42.17	164.7
8.....	322.00	2.03	5	4	5	2	2	2	331.75	12.28	56.07	99.4
9.....	307.50	2.03	5	7	5	3	2	2	312.0	21.53	22.09	442.1

[1] Check.

An examination of the table shows that the losses per square foot in the upland prairie ranged from 9.4 to 13.7 pounds as compared with 4.8 pounds from the control. In the low prairie the losses varied from 12.3 to 17.5 pounds, owing to the more luxuriant growth of the vegetation, while that from alfalfa was 21.5 pounds. Based on amount of water lost per dry weight of the vegetation, the upland prairie grasses show a relatively higher loss (maximum 332.5 grams) than the coarser, larger-stemmed, lowland species where a maximum loss of only 165 grams of water per gram of dry matter was found. On this basis the woody stemmed *Spartina* transpired less even than the upland grasses. Alfalfa lost 442 grams of water per gram of dry matter.

Water loss in relation to rainfall

These data on the direct measurement of water losses from the stabilized grassland furnish an excellent basis for the calculation of the water thus made available for precipitation. Using in all cases very conservative estimates we may safely assume that the short-grass plains vegetation loses water at the rate of .96 lb. per day (average of containers 2 to 6, table 2) during a minimum period of 60 days required for the development of the short-grasses (for example, May 15 to July 15). If we further assume that the losses for the remainder of the season (April 1 to May 15 and July 15 to September 15) are only one third as great, then the total water given off per square foot of vegetation is 91 pounds. Since the average precipitation is 17 inches annually, the total amount of water required (5.2 lbs. for each square foot for one inch rainfall) is only 88 pounds. Thus it may be seen that sufficient water is given off from the vegetation and soil to furnish the total supply.

In the mixed prairie, where the precipitation is 23 inches mean annual the average daily losses of one and one third pounds per square foot per day (average of containers 2 to 6, table 4) probably occur from May 15 to August 15. Assuming one third of this loss for the remainder of the season (April 1 to May 15 and August 15 to September 15) the total is 153 pounds, which far exceeds the 120 pounds per square foot required for precipitation.

Similar calculations in the true prairie show (containers 1 to 4 and 6 to 8, table 8) that the .85 pound daily loss from May 15 to September 15, with one-half this amount during the other 60 days of the growing season, provides 128 of the necessary 146 pounds of water per square foot needed for a 28 inch precipitation. Undoubtedly there is an excess actually since the data on water losses were secured during a period rather unfavorable for high transpiration. These data further indicate that the losses from crops are greater than from the native grassland and in such perennials as alfalfa with recurrent new foliage (after mowing) it may be even two or more times as great.

Discussion

These experiments were undertaken in connection with an extended problem (Clements and Weaver, 1924) on the causes of the present distribution of certain grassland associations and time has not yet been found to check plant behavior in soil columns as compared with that from similar soil with its structure destroyed. As already pointed out it seems clear that the breaking down of soil structure, since it has such a profound effect upon water-content and aeration, would also greatly influence the activities of the soil flora and fauna. Even if no other differences in the chemical and physical conditions, including the colloidal make up, took place, the development of the root system, undoubtedly in part due to new conditions for absorption, would be greatly modified and the stature and activities of the above ground parts somewhat changed in proportion. Thus, the water requirement, fundamentally the transpiration-photosynthetic ratio, might be quite different from that found under the usual experimental conditions.

This method lends itself readily to a number of phases of work of ecological-agronomic importance. Among these is the movement of water by capillarity. Just as the older ideas rather over emphasized the importance of this phenomenon and its rôle in supplying the soil about roots with water, so, it seems to the writers, present opinion rather under emphasizes the importance of capillary movement. As far as we are aware all experimental data have been obtained by the use of soils with the natural structure destroyed. Until this is worked out with soil columns left undisturbed and in unbroken contact with the subsoil the question as regards field conditions remains unanswered. A study of water movement in soil columns such as have been described with and without plants would throw much light upon what actually happens in nature.

Fundamentally this method furnishes a means of determining the water relations of stabilized vegetation. The size of the soil column in such experiments necessarily varies with the species used. For pure growths of *Koeleria* containers 18 inches in diameter and of a similar depth would include practically the entire root system, while with *Andropogon scoparius* a cylinder of the diameter used (about 13.5 inches) and 3.5 feet deep would ordinarily be ample in hard soil. Little is known about the absorbing abilities of roots but it seems clear that the entire root system of a plant is needed for maximum absorption only when the soil is very dry and the above ground parts are subjected to extreme conditions of dessication. Ordinarily the water supplying power of the root far exceeds the demands of the shoot, as is evidenced by the behavior of bunches of grass near the edges of the cylinders which showed no signs of wilting even where at least half of the root system was cut away. In most of the containers, especially in the more moist soil, a vigorous root growth took place over the bottom of the containers, those of alfalfa and *Spartina* reaching lengths of several inches.

Summary

A method has been devised for determining the water losses from square-foot areas of native grassland and cultivated crops without disturbing the soil structure. It consists in excavating soil columns a square foot in cross-sectional area and three feet deep and forcing galvanized iron cylinders over these tightly as they are formed. The columns are then smoothly cut off and bottoms sealed to the cylinders, which, after weighing, are replaced in trenches of appropriate width and depth so that after refilling the interspaces between the cylinders in the trench the vegetation in the containers is completely surrounded by undisturbed grassland or a crop similar to that enclosed

in the soil column. The containers are covered during rain and water added to the soil as needed for a 15-day period after which they are reweighed and the losses calculated. Direct losses from the soil and from soil covered with dead plants are determined by control soil columns.

Experiments were conducted in the short-grass plains of Colorado, in mixed prairie in north-central Kansas, and in true prairie in eastern Nebraska. Data for native vegetation are summarized in the following table:

Station	Dominant grasses	Date of experiment	Approximate sunshine	Ave. day temp.	Ave. day humidity	Ave. daily, evaporation	Ave. daily loss from sq. foot of native vegetation
			per ct.	°F.	per ct.	c.c.	lbs.
Burlington, Colo......	*Bulbilis, Bouteloua, Agropyrum*.....	July 5–20	71	80	57	35.4	0.96
Phillipsburg, Kansas...	*Bouteloua, Andropogon*..........	June 18–July 3	75	80.6	60	25.5	1.33
Lincoln, Nebr.....	*Andropogons, Stipa, Koeleria, Bouteloua*............	July 24–Aug. 8	47	79	80	22.0	0.85

From these data it has been shown that sufficient water is thus afforded to furnish the mean annual precipitation in the several plant associations. Crop plants give off more water than native vegetation.

The method is applicable to the solution of a number of important ecological-agronomic problems among which are water requirement, capillary movement of soil moisture, and non-available water, all of which should be determined under natural conditions, *i.e.*, in the field with soil of an undisturbed structure.

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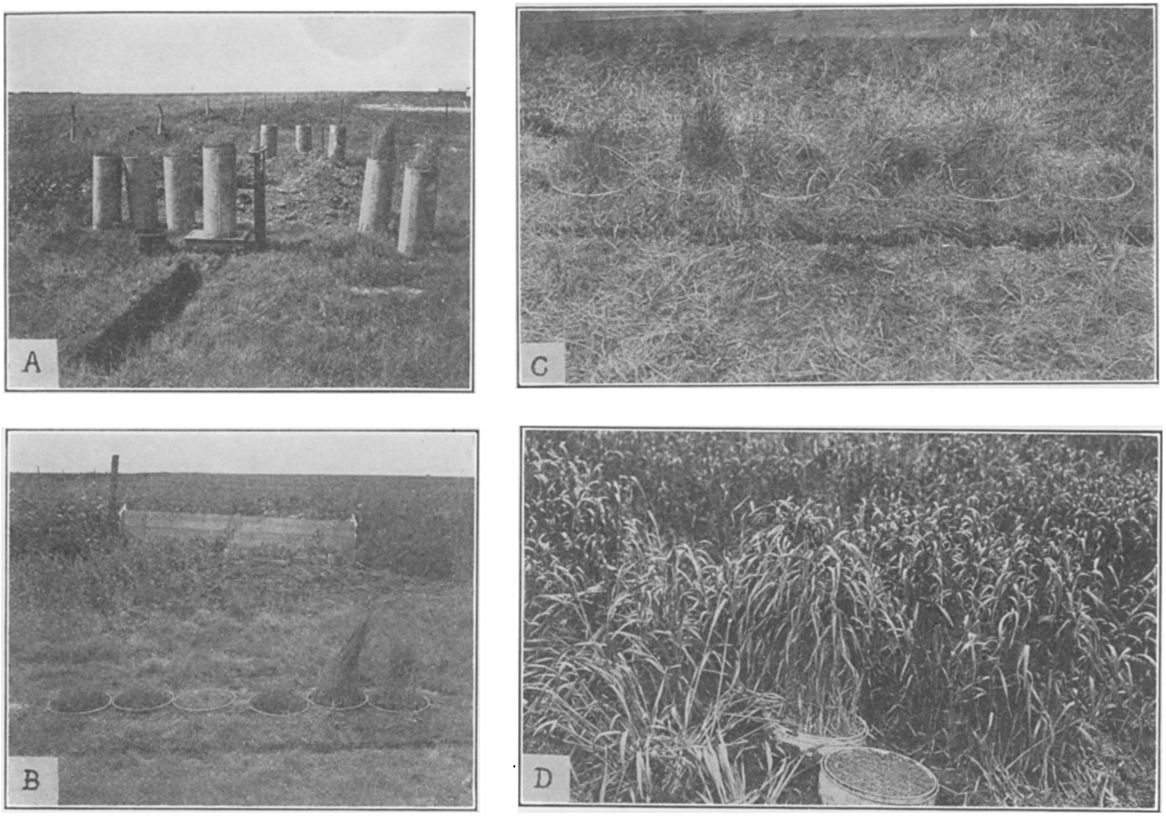

A. Beginning of the experiment at Burlington, Colorado, showing the steel cutter (at left of balance), the enclosed cores of soil containing short grasses and wheat grass, and the narrow trench to receive the containers. One of the pits from which the soil columns were secured may be seen in the background.

B. General view of six containers with native vegetation in the short-grass sod at Burlington. The vegetation in the third from the left has been killed by the addition of hot water. Shelter used during rains is shown in the background.

C. General view of containers with native vegetation in the prairie at Lincoln, Nebraska. The vegetation in number 1 at the right has been killed by hot water.

D. Columns of soil from an oat field at Lincoln surrounded by containers and left in the field for measurement of water loss. The plants have been removed from the container in the foreground.