FACTORS AFFECTING THE EVAPORATION OF MOISTURE FROM THE SOIL [1]

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INTRODUCTION

The importance of soil moisture in crop production is well understood. No plant can grow unless moisture is present to help make food available and furnish the water necessary to carry on regular plant functions. In arid regions the growth of crops is limited more by a lack of moisture than by any other factor, and even in regions of high rainfall crop yields are often materially reduced by droughts.

In sections where only a small amount of rain falls, practically all that sinks into the soil returns to the surface and is evaporated directly or passes through plants, from which it is evaporated. In humid regions also, where some of the soil moisture percolates to great depths, there is considerable loss by evaporation from the surface of the soil.

Moisture evaporated from the soil is completely lost and is of no value to crops; hence, it is important to reduce evaporation to a minimum, particularly where the supply of moisture is limited. The best condition would be to have no evaporation of moisture except that passing through the plant and assisting in its functions. Any information, therefore, that will lead to a better understanding of the factors involved in evaporation and a fuller knowledge of methods of controlling these factors will be of considerable practical importance as well as scientific interest.

Surface losses are due to two factors: (1) Capillarity, by which the moisture is brought to the surface, and (2) evaporation. In many of the soil-moisture studies that have been made these two factors have not been clearly separated, but have been considered together in determining loss. This has led to considerable confusion, since a difference in two losses might, in one case, be due to a difference in the rate at which moisture was supplied to the surface by capillarity and, in another case, to the evaporation factors.

In the experiments reported in this paper an attempt has been made to eliminate the factor of capillarity and to confine the studies entirely to evaporation in order to determine, as nearly as possible, the effect of a number of the factors involved in the evaporation of moisture from the soil.

[1] The writers wish to acknowledge their indebtedness to Messrs. George Stewart and N. I. Butt, of the Utah Experiment Station, for their assistance with certain experiments and in preparing this paper for publication.

REVIEW OF THE LITERATURE

Considerable work has been done on various phases of the evaporation problem. One of the important factors influencing water losses is the wetness of the soil, or the initial percentage.

Widtsoe (19, p. 35, Table 20)[1] gives the results of four years' experimental work, as shown in Table I.

TABLE I.—*Total evaporation of water from bare College loam*

Moisture.	Loss in pounds per square foot.				
	1902	1903	1904	1905	Average.
Per cent.					
10	9	32	9	16	16
15	23	.....	10	30	21
20	51	80	38	69	60

Loss increased with the percentage of water up to 20 per cent, which was the highest degree of wetness used. He (19) says: "The evaporation of water from bare soils increased with the increased saturation of the soil. The increase in loss was usually much larger than the increase in saturation. In another treatise (20) he found that "the wetter the soil at the surface, the more rapid is the evaporation of water from it."

This is confirmed by Whitney and Cameron (18) and by Fortier (5). In Whitney and Cameron's work, 26 per cent was the highest humidity, that being used in but one set of experiments. Fortier's highest percentage of water was 17.5. In his conclusions he says, "The rate of evaporation from soils varies directly with the amount of moisture in the top layer."

The work of Cameron and Gallagher (3, p. 45-49) indicates that, after a certain wetness is reached, there is little if any increase in water loss. In their work the soils of different degrees of wetness were placed over sulphuric acid of different concentrations in order to control the humidity. Over 95 per cent sulphuric acid in desiccators, Podunk fine sandy loam gave the most rapid loss by evaporation up to 4 per cent moisture, with a very slight increase in loss up to 28 per cent. Miami black clay loam lost most rapidly up to 22 per cent, with a small increase to 41 per cent, where the loss was highest.

The color of the soil is claimed by King (10) to affect evaporation greatly, since the darker the soil the more heat it absorbs and radiates. He found that the rise in temperature, due to the darker color, is the important factor.

Concerning winds, King (9, p. 16) shows that up to 300 feet from woods the loss gradually increased with the distance. He (11) gives the following

[1] Reference is made by number to "Literature cited," p. 460-461.

data on evaporation for an hour from a wet soil with a surface of 27 square inches:

20 feet from hedgerow the evaporation was 10.3 c. c.
150 feet from hedgerow the evaporation was 12.5 c. c.
300 feet from hedgerow the evaporation was 13.4 c. c.

At 300 feet the evaporation was 30 per cent greater than at 20 feet and 6.7 per cent greater than at 150 feet, due largely to the vessels closer to the hedge having protection from the wind.

McDonald (12) gives this terse summary:

> Evaporation depends upon the temperature of the evaporating surface, the dryness of the air, and the velocity of the wind. The hotter the day, the greater the evaporation; the drier, the greater the evaporation—the ceaseless sucking up of moisture.

Bowie (1) claims that loss due to wind is caused by the more intimate contact of the air with the moist soil surface. He says:

> With average wind velocities of from 2.4 to 4.0 miles an hour, and with an average water temperature of 70 F., the increased evaporation rate due to wind was about 0.5 per cent a day for each mile of wind.

Payne (13), in giving the advantage of windbreaks in retarding evaporation, shows that a sod wall 4 feet high and 20 feet long, running east and west, reduces the loss from buckets placed in the ground level with the field. On the north side, buckets 1, 3, 5, 7, and 10 rods distant lost in 62 days moisture the equivalent of 677, 633, 700, 703, and 712 tons to the acre, respectively; on the south side, buckets 1, 3, 5, 7, and 8 rods distant gave losses of 647, 686, 738, 764, and 761 tons to the acre, respectively.

In work done by Principi (14) the conclusions reached were—

> That evaporation is most rapid from the materials which have the largest pore spaces, and that it remains almost the same whether it arises from a free water surface or from thin films covering the particles of wet material.

Woolny (21) claims that capillarity ceases when the diameter of the particles is more than 2 mm. and that it varies with smaller particles in proportion to their fineness—the finer the particles, the greater the lifting power, but the slower the movement.

In regard to moisture movement through a column of dry soil not in direct contact with the moisture but with a saturated atmosphere between, Buckingham (2, p. 9–18) says that moisture escapes probably by pure diffusion and that the loss in this way is proportional to the square of the porosity, following the same law as the diffusion of air and carbon-dioxid gas through soils.

Whitney and Cameron (18) showed that loams over a saturated atmosphere gave a greater diffusion of moisture through the pore spaces than through those of clay.

Fortier (5) shows, in the measurement of losses from water surfaces kept at different temperature, that reducing the temperature from 88° to 80.4° F. lessened evaporation 20 per cent; reducing it to 73.5° decreased evaporation 40 per cent; to 61.3° decreased it to 67 per cent; and to 53.4° reduced it to 85 per cent.

Shade, which is a great protection from heat, aids in preventing evaporation. Seelhorst (16) shows that a loam soil shaded by dry rye plants evaporated 13.9 per cent less of the rainfall than the same kind of soil unshaded.

Widtsoe's (20) work on the influence of shade on evaporation gives a loss of 22 pounds to the square foot as against 32 pounds for the unshaded portion; that is, there was 29 per cent greater loss in sunshine than in shade.

Fortier (6) shows that in actual experiments on Mount Whitney evaporation decreased with altitude. The decrease was rather regular, except at the summit (14,502 feet), where greater evaporation took place than at either 10,000 or 12,000 feet.

According to Carpenter (4), diminished barometric pressure tends to increase evaporation to the extent of 14 per cent at 9,000 feet and 18 per cent at 10,000 feet over that at 5,000 feet.

Mulching the surface of the soil a few inches by stirring it is the most common practice in use for the preservation of moisture under field conditions. Ridgaway (15) shows that stirring the surface to depths of 2, 4, and 6 inches in different tanks once a week, with the water level kept 22 inches below the surface of the soil, lessened evaporation by 19, 23, and 45 per cent, respectively, of the amount lost from unstirred soil. His work also shows that where water is maintained at 6, 12, 18, and 22 inches below the surface, the losses were 95, 70, 45, and 35 per cent of evaporation from a free-water surface. This bears out Wollny's (21) statement that "if there is water underneath the soil the evaporation decreases as the distance between the surface of this water and that of the soil increases."

Fortier (7) sums up the results when dry soil coverings were substituted for stirred surfaces, as shown in Table II.

TABLE II.—*Losses by evaporation from soil surfaces variously treated*

Locality.	Loss from unmulched soil.	Loss from 3-inch mulch on soil.	Loss from 6-inch mulch on soil.	Loss from 9-inch mulch on soil.	Number of days run.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	
Davis, Cal.	35.00	14.71	5.94	0.78	32
Wenatchee, Wash.	14.33	3.98	2.10	1.06	21
Reno, Nev.	20.39	8.26	2.74	1.96	21
Average	23.24	8.98	3.59	1.27	24.7

Using enough water to cover the surface with 3.14 inches, this author (5) found that no mulch gave a 0.72-inch loss; a 4-inch mulch, 0.21 inch; an 8-inch mulch, 0.1 inch; and a 10-inch mulch, 0.03 inch in 14 days—that is, the various mulches saved in 14 days 16.24, 19.75, and 21.97 per cent of the amount applied.

The advantage of deep furrows as a saving in furrow irrigation is brought out by Fortier (5). When the same quantities of water were applied to tanks in furrows 3, 6, 9, and 12 inches deep, he found that the losses at the end of 10 days were 25, 18, 10.2, and 6 per cent of the total water applied. The loss was most rapid for the first 2 days, and at the end of 5 days 77 per cent of the total loss for 10 days had occurred.

Widtsoe's (19) work shows that in the two treatments, sand containing 15 per cent, sandy loam containing 20 per cent, and Sanpete clay containing 25 per cent moisture, the average loss from the soil receiving surface irrigation was more than three times as great in the same length of time as that from a subirrigated soil. Fortier (5) shows that soil subirrigated 2 feet underground by pipes lost only 25 per cent as much water in 20 days as when irrigated by surface flooding.

According to Stigell (17), bacterial growth retards evaporation. He says that this is attributed to utilization of moisture by the organisms in their metabolic products, and reduction of the porosity of the medium by the metabolic products of the organisms. Hoffman's (8) work shows that after the bacteria in various culture media were added to the soil, evaporation was increased except in the case of manure. In drawing his conclusions he leads one to believe that if the experiment is of long duration the results may be reversed, due to the accumulation of carbon dioxid from the organism being taken up by the soil moisture, thereby increasing the surface tension of the water. Gelatin was found to retard evaporation and for that reason could not be used as a culture media.

EXPERIMENTAL WORK

INITIAL QUANTITY OF SOIL MOISTURE

To find, if possible, the specific influence of varying percentages of water in soils, a series of experiments was conducted at the Utah Agricultural Experiment Station in the years 1912 to 1916, inclusive. The preliminary tests show that evaporation losses increased rapidly with the increased wetness of the soil, or with the initial quantity. The latter studies were so arranged as to locate as many points of variation in the losses as possible.

PRELIMINARY STUDY

Late in June, 1913, a study of the effect of initial quantity of moisture in the soil was begun. One hundred gm. of dry Greenville loam were put in small, weighed tin plates about 5 inches in diameter, and puddled

with water. The soil was then set aside to dry. When the condition of dryness was approached, the moisture was made up to the desired content. Twelve percentages—5, 7½, 10, 12½, 15, 20, 25, 30, 35, 40, 45, and 50—were run in triplicate. The pans were set on a table in a large laboratory room. Weighings were taken daily to the nearest one-tenth of 1 gm. and water was added to make up the loss. This experiment continued for 42 days, at the end of which time the losses were computed for each week and for the entire period. Table III gives the losses for each period.

TABLE III.—*Effect of initial quantity of water on evaporation*

Soil moisture.	Water evaporated.	Soil moisture.	Water evaporated.
Per cent.	*Gm.*	*Per cent.*	*Gm.*
5	96.4	25	956.1
7½	229.2	30	1,013.3
10	363.0	35	1,048.1
12½	484.8	40	1,074.5
15	594.0	45	1,148.1
20	822.2	50	1,185.8

An examination of Table III shows that evaporation increased rapidly to about 20 per cent, less rapidly from 20 to 30 per cent, and slowly from 30 to 50 per cent.

LATER EXPERIMENTS

Various later studies were made with loam, sand, clay, and muck. The methods were similar to those used in the preliminary work, but the experiments were much more detailed and thorough. Most of the work was done in small tin plates and copper vessels 8 inches in diameter and 4 inches deep, though some tests were made in Petri dishes, some in long galvanized-iron tanks and some in deep cylindrical galvanized cans.

LOAM

The test with loam was conducted in the manner already described with 100 gm. of dry soil in tin plates. The percentages of moisture ran from hygroscopic water, which was about 1.8 per cent, to 50 per cent. The experiment was conducted for 13 days, from August 29 to September 12, the pans being made up to the original weight each day and shifted on the table to eliminate, in part, the influence of air currents.

A similar test was made during the winter in a steam-heated laboratory. All percentages from 1 to 40 were run in triplicate with 1 per cent intervals. Weighings were made each day and losses were considerably greater than those for the same number of days in the other trial. A possible explanation for this is that the laboratory under artificial heat

was slightly warmer and changed air much more frequently than in summer. The hygrometer showed somewhat lower humidity, but it could not show the influence of thorough ventilation.

The next study was made between June 4 and June 17, 1914. It was conducted in the same fashion, except that weighings were made twice daily, between 6 and 8 o'clock morning and evening. Four pans, instead of three, were used with each percentage from 1 to 50. The pans for 1 per cent gained up to about 1.8 per cent and then neither lost nor gained noticeably.

In addition to the pans containing wet soil, a pan of free water was exposed at each corner of the table on which the test was made. The two pans on the east and nearer the doors lost somewhat more than the two at the west end. All soils that approached saturation lost more than the free water. The losses from the 20 per cent pans were about equal to the average of those from the free-water pans.

An almost identical test was made in July which practically duplicated the former results. As 12 weighings were made, the length of this study was equivalent to 6 days.

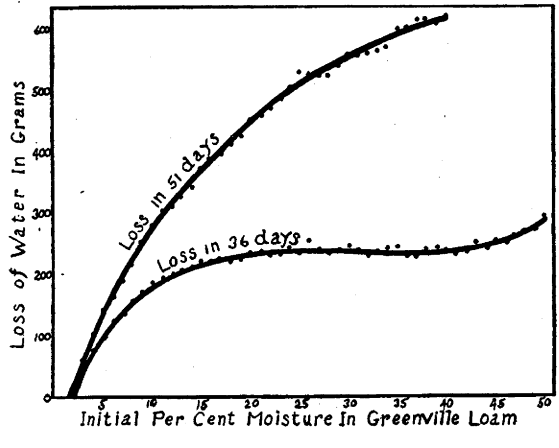

FIG. 1.—Evaporation from Greenville loam containing different initial percentages of moisture.

These various experiments are combined in figure 1, which gives results for a total of 51 days with moisture up to 40 per cent, and 36 days with moisture up to 50 per cent. The curve for the 36-day results shows a rapid increase in evaporation with a higher initial percentage of moisture in the soil up to 7 or 8 per cent; then a less rapid increase up to 18 or 20 per cent, from which point the increase is small. In the tests continued for 51 days, the same general changes in the curve are noted, although the total loss is decidedly more than for the 36-day test.

In some of the trials the free water lost more by evaporation than any of the wet soils, but usually there was a greater loss from soil which was completely saturated than from the free-water surface.

In each of these tests with Greenville loam, there seemed to be a number of more or less definite breaking points in the curves of loss. These indicate critical points where the moisture relations of the soil made rather sudden changes. A great deal of work will need to be done

under favorable conditions before these exact points of change can be determined.

In the summer of 1912 nine large galvanized-iron pans, or tanks, 5½ feet long by 1 foot wide by 3 inches deep were employed to give larger surfaces and deeper soil. The equivalent of 10 kgm. of dry Greenville loam was put into each tank and puddled with excess water to firm the soil and smooth its surface. Enough water in addition to the water already present—5.4 per cent—was added to make a series with 5 per cent intervals from 5.4 to 35.4 per cent. These tanks were set on the floor of the laboratory and were weighed on Monday, Wednesday, and Friday of each week. The losses were made up at the time of weighing. This study ran from June 12 to July 15, a period of 34 days.

The next year seven tanks were set up and run during the 81-day period from June 18 to September 6. This time 7.2 kgm. of Greenville loam, containing 2.6 per cent moisture, were used. Intervals of 5 per cent were again made, bringing the moisture content up to 7.6, 12.6, etc., as high as 37.6 per cent. Weighings were taken three times a week as in the first trial and water added to make up the evaporation loss. Table IV contains the results of the two trials.

TABLE IV.—*Effect of initial percentage of soil moisture on evaporation from Greenville loam in galvanized-iron tanks 5½ feet long and 1 foot wide*

1912		1913		Average of 2 tests.	
Moisture.	Loss in 34 days.	Moisture.	Loss in 34 days.	Average moisture.	Loss in 115 days.
Per cent.	*Gm.*	*Per cent.*	*Gm.*	*Per cent.*	*Gm.*
5.4	3,744	7.6	10,710	6.5	14,454
10.4	7,575	12.6	17,530	11.5	25,105
15.4	9,518	17.6	19,275	16.5	28,793
20.4	9,200	22.6	20,395	21.5	29,595
25.4	10,128	27.6	20,300	26.5	30,428
30.4	10,340	32.6	19,870	31.5	30,210
35.4	11,045	37.5	19,990	36.5	31,035

Table IV shows that the loss was rapid to 16.5 per cent and then slow. Of course, the wide intervals prevented locating exact points, but in general this test corroborates rather closely those already reported for loam.

SAND, CLAY, AND MUCK

During the period from December 26, 1913, to January 3, 1914, similar tests were made with sand, clay, and muck. One hundred gm., dry weight, of sand and clay and 50 gm. of dry muck were used in the same kind of tin plates as those used in the other trials. All percentages were run in triplicate, the sand for each percentage from 1 to 33, the clay for each percentage from 1 to 55, and the muck for each 20 per cent interval from

20 to 240 per cent. The muck consisted almost entirely of vegetable mold gathered from accumulated pockets in the brush swales of Logan River. It was known to have high water-holding capacity from previous experiments.

The pans were kept several inches back from the edge of the tables on which they rested. This almost entirely eliminated the effect of air currents which had, in previous tests, caused some variations in the rows of pans set close to the edge. The loss was made up each day after the weighing. The winter losses were much higher in this case than with the loam previously reported.

Figure 2 gives the results for sand and shows an increase in evaporation as the initial moisture is increased, up to 33 per cent. The most rapid increase is up to about 7 per cent. Above this point the increase in loss is not so great.

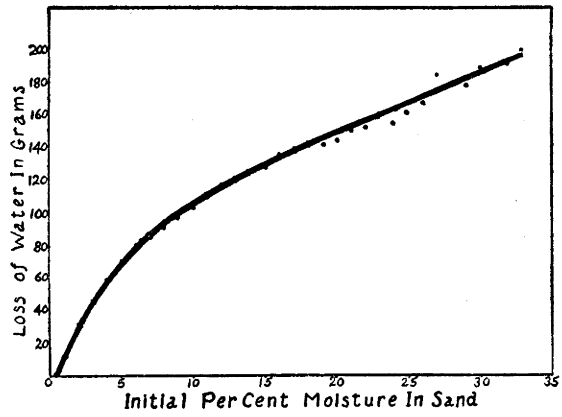

FIG. 2.—Evaporation from sand containing different initial percentages of moisture.

Figures 3 and 4 give the curves for clay and muck. The results for clay show a more gradual ascent in the curve, and a higher point before there is any break, than do the results for sand. This might have been expected from the great water-holding power of the clay. Muck with high percentages and differences at greater intervals produced about the same kind of curve as did loam.

More tests are necessary, however, to establish points as nearly exact as was done in the case of loam.

HUMIDITY OF THE AIR

To study the effect of a saturated atmosphere on evaporation, a set of wet soils in Petri dishes was placed in an air-tight copper germinator. Forty gm. of dry soil were put in each of these dishes, which were about 3 inches in diameter. Duplicate vessels were made up with soil for each 1 per cent from 1 to 35, and for each 2 per cent from 35 to 45 per cent of moisture. They were then set on the shelves of the germinator, which is a hollow box 22 inches wide, 37½ inches deep, and 47½ inches long. The whole was surrounded with a water jacket, except at the doors, which were made of two panes of glass inclosing a dead-air space about half an inch thick. The perforated copper shelves were covered with

cheesecloth and connected by a perpendicular wick to a water container on top. The wick kept all the cheesecloth covers saturated. To make sure no vapor escaped at the door, pieces of cloth kept constantly dripping were hung in front of the door. Tested thermometers showed throughout the experiment an almost constant temperature of 19.5° C., about one degree lower than that of the laboratory. Each day for 10 days the vessels were weighed to 0.01 gm. and made up by adding the water lost. The lower percentages, however, gained and were left at the wetness reached, which was about 7 per cent.

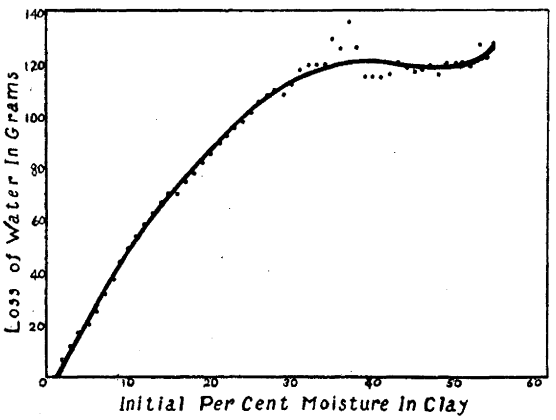

FIG. 3.—Evaporation from clay containing different initial percentages of moisture.

Fairly comparable with this test was another in which the same vessels, made up as before, were surrounded with cheesecloth 24 inches high to prevent drafts and to maintain a uniform temperature. Possible variations were eliminated by shifting the vessels in such a way that each occupied all sections of the cloth box some time during the 20 days of the experiment. The top was left open to permit vapor to escape upward. The relative humidity of the air was almost constantly at 76 per cent, whereas it was about 68 in the open laboratory. The temperature averaged 19° C. during the 20 days. Completely dried soil gained to 4 per cent, then remained constant. Weighings were made each day to the nearest 0.01 gm. and the losses made up as with the test in the germinator.

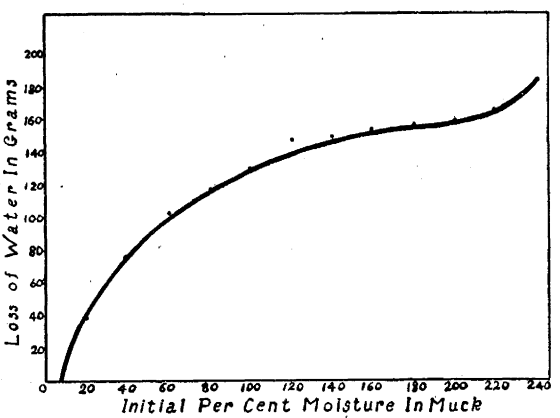

FIG. 4.—Evaporation from muck containing different initial percentages of moisture.

Figure 5 shows the losses for each 1 per cent in the saturated atmosphere of the germinator and for the slightly overmoist air of the cloth boxes.

Since the latter ran 20 days, the total losses have been divided by 2 in order to get the total loss for 10 days to make the figures comparable.

There is a decided difference in the results of the two experiments. The losses in the cloth boxes were nearly 20 times as great as those in the germinator, showing the enormous retarding effect of high humidity. Moreover, the open laboratory was somewhat drier and about one degree warmer than the air in the cloth boxes. No test was made in the open laboratory, but the losses would have been somewhat higher, since both a drier air and a higher temperature prevailed. This would, of course, further accentuate the already enormous differences.

WIND VELOCITY

As was suggested in the literature on wind velocity, King (9) has shown that vessels 20 feet from a windbreak lost 30 per cent less moisture by evaporation than vessels 30 feet distant. This was because the outer vessels were more exposed to air movement. Payne (13) shows nearly similar results, while Bowie (1) reports that with light winds and normal temperature there is an evaporation loss of 0.5 per cent for each mile of wind.

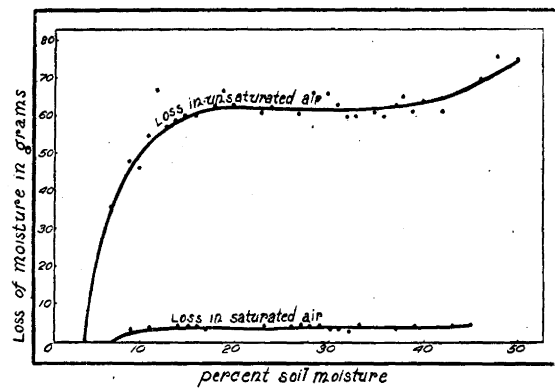

FIG. 5.—Loss of moisture from Petri dishes containing different percentages of soil moisture and kept in a saturated and unsaturated atmosphere.

In order to determine the effect of wind velocity on the rate of evaporation, a series of alleys 8½ inches wide and 70 inches long were arranged in such a way that the air could be made to pass through them at different velocities. The alleys were separated by oilcloth partitions 2 feet high; the air currents were made by electric fans placed in such positions that the desired velocities could be obtained. The velocity of air in each alley was measured with an anemometer placed at the end of the alley away from the fans.

The soils were contained in copper evaporimeters 6 inches in diameter. The loss each day was made up by adding water through a tube entering the evaporimeter at one side of the soil. In each alley there were five evaporimeters—one containing distilled water, one Greenville loam, and one each of quartz sand 0.25 mm., 0.5 mm., and 0.8 mm. in diameter.

Two tests were made in the experiment, one running continuously for 16 days with three wind velocities and another running continuously for

20 days with seven velocities. In each case there was an alley where the air was kept quiet. The combined results of the two tests are shown in figure 6. There is a rapid increase in evaporation with increased wind velocity at first; but after a velocity of about 10 miles per hour is reached, the increase in evaporation is slight. The water loss with the highest velocity was over four times that of the calm for the 16-day trial and nearly six times that of the calm in the 20-day test.

SUNSHINE

The general effect of sunshine in increasing the evaporation of soil moisture has long been known. The work of Seelhorst and Widtsoe on this subject has already been reviewed. In order to get more data an experiment was begun in the summer of 1913 at the Utah Agricultural Experiment Station. A spot on the college lawn just west of the main building was selected, because it was level and exposed to sunshine most of the day.

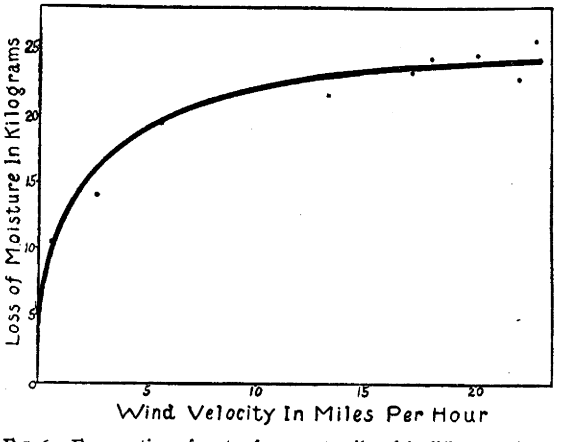

FIG. 6.—Evaporation of water from wet soils with different wind velocities.

Small tin plates containing 100 gm. dry weight of Greenville loam were prepared by puddling the soil and then drying, in order to get uniformity. They were then made up to the desired degree of wetness—5, 10, 15, 20, and 25 per cent, respectively. Each treatment was run in triplicate, making 15 pans to the set. One set was exposed to open sunshine, another was placed under a shade of cheesecloth 8 inches above the soil, and a third was shaded by a tight board cover also 8 inches above the soil. In each case the pans of soil were placed on a floor of boards and air was allowed to circulate freely over the soil beneath the cover.

The pans were each morning made up in the laboratory to the proper wetness and carried outside. Temperature readings were taken in the morning when the pans were carried out by laying a tested thermometer for a few minutes between the pans. A reading was taken at noon and another in the afternoon just before the pans were carried back into the laboratory. Another weighing of the pans showed the recorded loss due to evaporation. The pans were then left over night to be made up in the morning before placing outside.

Table V shows the average temperature for morning, noon, and afternoon. It is worth noting that the shade caused a reduction in temperature, complete shade causing a greater reduction than part shade.

TABLE V.—*Effect of shading on temperature and evaporation; temperature (° C.) average for 13 days*

Treatment.	Time.			Average.	Evaporation loss.
	Morning.	Noon.	Evening.		
					Gm.
Sunshine	30.2	41.3	34.2	35.2	554.8
Half shade (cheesecloth)	25.6	32.2	28.7	28.8	513.4
Shade (wood)	19.7	23.2	24.6	22.5	407.8

Table V shows the total loss in grams for each treatment. Figure 7 shows by graph the average temperature and the total loss with sunshine for part and for complete shade. It is noticeable that the evaporation losses decrease as shade increases.

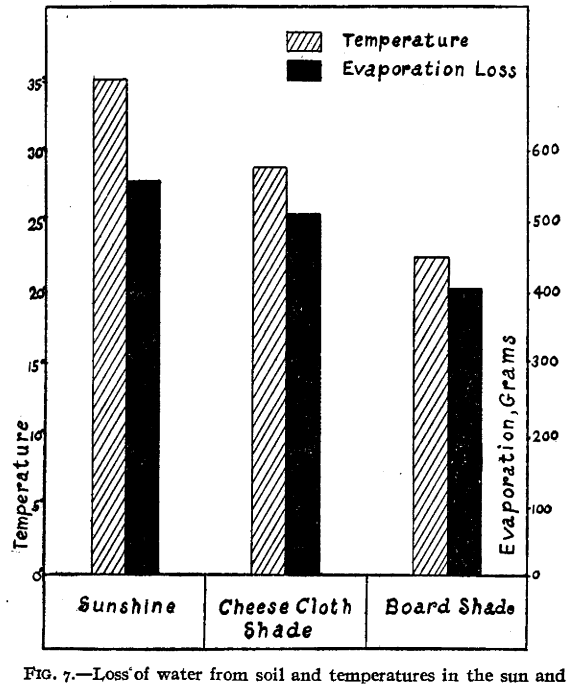

FIG. 7.—Loss of water from soil and temperatures in the sun and under cheesecloth and board shade.

TEMPERATURE

Temperature, relative humidity, and initial quantity of moisture are usually considered to be the most important factors in determining the intensity of evaporation. Perhaps temperature is most active. Fortier (5) shows that a reduction from 88° to 53° F. causes a corresponding reduction in evaporation loss of 85 per cent. These figures suggest the close relationship of evaporation to temperature. This important effect of temperature was made clear in a number of experiments where other factors were being studied.

To get some specific effects of temperature on the rate of evaporation of moisture from the soil, a number of large water baths were so arranged

that they could be kept uniform in temperature to within about one degree. Twenty-five gm. of soil were moistened and then put in flat-bottomed aluminum cans 7 cm. in diameter and 3 cm. deep, the cans being about one-fourth full. In order to bring the temperature of the soil quickly to the temperature of the water, these cans were allowed to float on water in the water baths. The baths were maintained at 20, 30, 40, 50, 60, 70, 80, and 90° C. It was almost impossible to maintain a uniform temperature when the bath was hotter than 90°; and when it was colder than 20° the evaporation was too slow to give noticeable results.

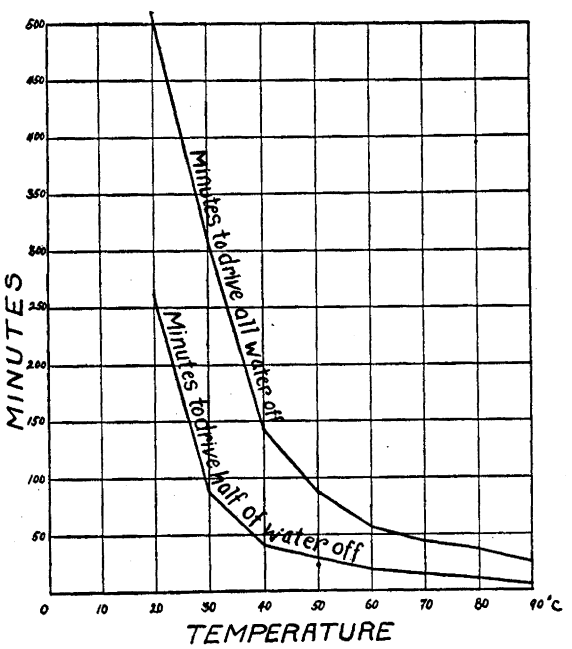

FIG. 8.—Time required at different temperatures to drive off half and all the water from Greenville loam containing 12 per cent moisture.

Two soils were investigated. The first was Greenville loam with an initial moisture content of 12 per cent of the dry weight of the soil and the second was a coarse sand with 20 per cent of initial moisture on the dry basis.

Hundreds of weighings were made to determine the rate of loss with each temperature. These weighings gave the results contained in figures 8 and 9.

The loam containing 12 per cent of moisture required 265 minutes at 20° C. to lose half of its moisture and 510 minutes to become practically dry. At 30°, 89 and 312 minutes were required to make it half and completely dry, respectively; at 40°, 46 and 143; at 50°, 23 and 88; at 60°, 17 and 56; at 70°, 12½ and 45; at 80°, 9½ and 38; and at 90°, 7 and 27.

In sand containing 20 per cent of moisture, the number of minutes required to become half and completely dry respectively at the various temperatures was as follows: At 20°, 315 and 819; at 30°, 90 and 240; at 40°, 45 and 100; at 50°, 30 and 72; at 60°, 13 and 35; at 70°, 9 and 24; at 80°, 6 and 18; and at 90°, 4½ and 13 minutes.

In the loam containing 12 per cent of water as an average, it required nearly three times as long to drive off the last 6 per cent of water as it did for the first 6. In the sand containing 20 per cent, it required more than

twice as long to evaporate the last 10 per cent as it did the first. In each case the last water that was driven off was the hygroscopic moisture. This probably accounts for the greater time required.

SIZE OF SOIL PARTICLES

Since evaporation takes place almost entirely at the surface, the rate of capillary movement directly affects this form of water loss. Because the size of soil particles and the porosity of the soil influence capillary movement, they indirectly affect evaporation. Principi (14) says that materials having the greatest pore space permit greatest evaporation. Wollny (21) reports no capillarity with particles more than 2 mm. in diameter, and also an increase as the particles get finer, though in clay the movement is slow. Losses from below the surface take place, according to Buckingham (2) by diffusion and vary with the square of the porosity of the soil.

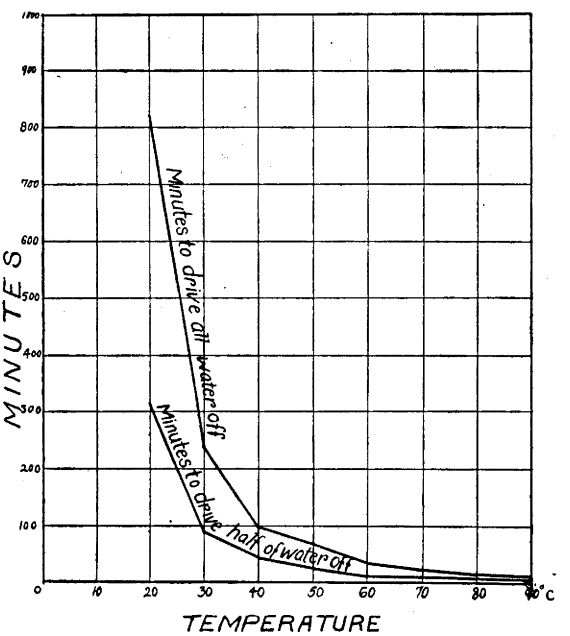

FIG. 9.—Time required at different temperatures to drive off half and all the water from sand containing 20 per cent moisture.

On account of the great difficulty in interpreting the results connected with this phase of the evaporation problem when ordinary soils are used, most of our work has been done with sands having grains of different diameters. The early experiments were conducted with river sands and gravels; but because of greater ease in obtaining uniform size of particles and because of lesser influence due to the composition of the materials, most of the later work was done with graded quartz sand.

In all trials except those in saturated atmosphere beneath the soil, these tests were made in the copper evaporimeters with free water maintained from about 1 to 3 cm. below the surface of the soil, the distance varying in different experiments. At weighings, which occurred about a week apart, the vessels were made up to their original weight.

The results of these tests are presented in figures 10, 11, and 12.

An examination of figure 10 shows a gradual increase in evaporation as the size of particles decrease. There are a number of irregularities probably caused by the difficulty in getting a uniform surface on all the evaporimeters. It will be noted that in some cases the evaporation was greater from the wet sand than from water.

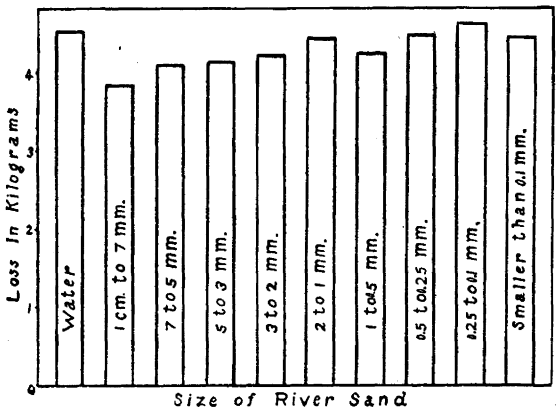

FIG. 10.—Evaporation of water in 66 days from sand of different sizes with a water table maintained 1 cm. below the surface.

In figure 11 results for three grades of pure quartz sand, for Greenville loam, and for water are shown. Here, as in figure 10, the finer grades lose more than the coarser.

Figure 12 includes five sizes of quartz sand, three sizes of river sand, and water. The differences are not marked, but are sufficient to bear out previous results in showing the greater evaporation from the surface of the smaller particles.

MULCHES

Wherever water storage in field soils is important, mulches are used to decrease the evaporation loss. Ridgaway (15) and Fortier (5) both indicate the great saving due to mulches made by stirring the topsoil or by adding covers of dry soil.

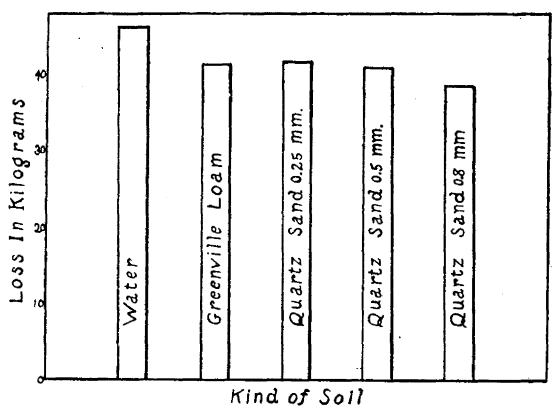

FIG. 11.—Evaporation of water in 36 days from loam and sand of different sizes with a water table maintained 3 cm. below the surface.

A number of laboratory experiments to study the effectiveness of different mulches when the effect of capillarity has been eliminated were conducted. In these experiments the different mulches were suspended above the water. The mulch was placed on wire gauze covered with cheesecloth or on perforated sheet metal to keep it about 1 cm. from the surface of the water in the lower part of the vessels. No water could evaporate except through the mulches.

A study of two sand mulches ½ inch and 1 inch deep, respectively, when placed where the sun would shine on them for half the day for 32 days shows a loss of 57 gm. for a mulch 1 inch deep, 60 gm. for a mulch ½ inch deep, and 155 gm. for the cheesecloth with no dry soil over it. Thus the shallower mulch lost but little more than 5 per cent more than the deeper. The check in which the water evaporated through the cloth and gauze lost nearly three times as much water as that from the mulches. This bears out Fortier's findings in regard to the effectiveness of mulches, but not in regard to the relative value of deep and shallow mulches.

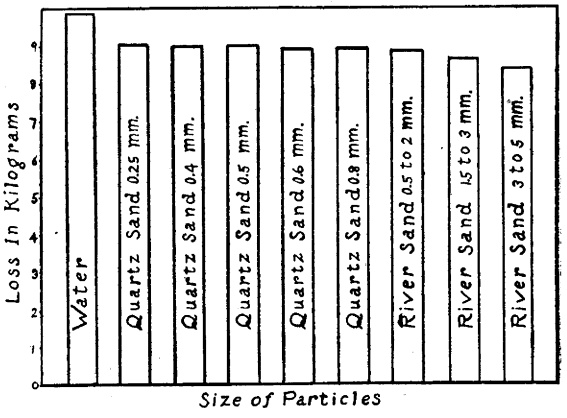

FIG. 12.—Evaporation of water in 115 days from quartz and river sand of different sizes with a water table maintained 3 cm. below the surface.

Figure 13 gives the results of the evaporation from 1-cm. mulches of river sands varying in size from 0.1 mm. to 7 mm. for 40 days. The loss is somewhat greater through the smaller sands. When, however, the sizes are larger than 1 mm., the variations in loss are irregular and inconclusive. The mulches prevented over half the evaporation that occurred from free water.

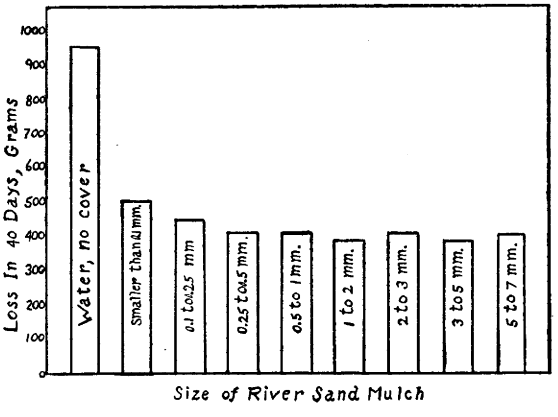

FIG. 13.—Loss of water from glasses having dry mulches of sand of various sizes suspended above free water.

With perforated aluminum lids 6 cm. in diameter and with a mulch nearly 2 cm. thick, a more exhaustive experiment was conducted. It was similar to the above, except that quartz sands were used for the smaller sizes and that tests with muck, clay, loam, and straw were also run. This experiment continued for a period equivalent to 180 days, the weighings being made at about 10-day intervals. Results of this experiment are shown in figure 14. Of the mulches the greatest loss was through the muck, followed by loam, clay, and straw in order, with the sand mulches

having the least evaporation. The sands show somewhat the same results as were found in the experiments mentioned above, except that there is a tendency for the losses to increase with increasing size of soil particles when the particles are more than 2 mm. in diameter.

COMPACTING THE SOIL

A set of six galvanized-iron cans 13 inches deep and 11 inches in diameter with an opening at the bottom through which water could be added from below to maintain the soil at a constant moisture content were filled with soil. Two sections of the soil at various depths were compacted in order to determine the effect of compacting on evaporation. The cans contained 12 inches of Greenville loam made up to about 15 per cent moisture. In can 1 the surface 2 inches were compacted; in can 2 the second 2 inches; and so on, until in can 6 the bottom 2 inches were compacted. The packed layers contained 20 per cent more soil in a 2-inch layer than a similar volume of the loose soil. These cans were weighed weekly for seven weeks and the loss made up through the side tubes at the bottom, which were kept closely stoppered except while water was being added.

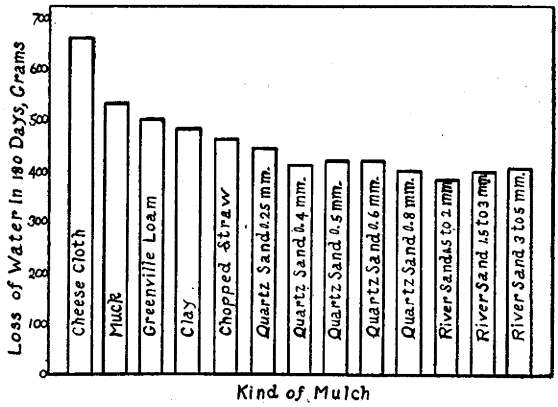

FIG. 14.—Loss of water in 180 days from glasses having dry mulches of various kinds suspended above free water.

Table VI shows that cans 1 and 2, compacted in the first and second 2-inch layers, respectively, lost much more heavily than the cans in which the packed layers were farther from the surface.

TABLE VI.—*Loss of moisture from cans of soil containing a 2-inch section compacted at various depths*

Can No.	2-inch section compacted.	Total loss.
		Gm.
1	Top	1,205
2	Second	1,045
3	Third	885
4	Fourth	870
5	Fifth	880
6	Bottom	805

Compacting the surface caused a marked increase in the loss; packing the second 2-inch section also increased the loss, but only about half as much. Compacting below 4 inches affected evaporation little if any.

METHOD OF APPLYING WATER

An important thing to know where irrigation is practiced is the effect on evaporation of applying water in different ways. Fortier (5) and Widtsoe (19) indicate that a great saving results from applying water in deep furrows or by subirrigation in which the water is added some distance below the surface.

In the summer of 1912 a study with soils 12 inches deep was conducted. Cylindrical vessels 11 inches in diameter and 13 inches deep were filled to within an inch of the top with Greenville loam. An equivalent of 10 kgm. of dry soil was used and made up with moisture ranging from 5.4 to 35.4 per cent in 5 per cent intervals. Weighings were made on three days weekly—usually Monday, Wednesday, and Friday. The losses were made up by adding water through spouts which entered the bottom of the cans and which were kept closed except while water was being added. Thus, the water had to move through 12 inches of soil, rather compact and unstirred, and evaporated from a small surface. Parallel to this test and used as a companion were the large galvanized-iron pans already described under the initial-quantity study. Here the soil was only about 1½ inches deep. To these shallow tanks the water was applied at the surface. The two trials were parallel throughout. The same percentages of moisture were used, weighings were made at the same time, they were run the same period, and the same kind of soil was used. A comparison of the two sets of results may be interesting, as they show the effect of different methods of applying water.

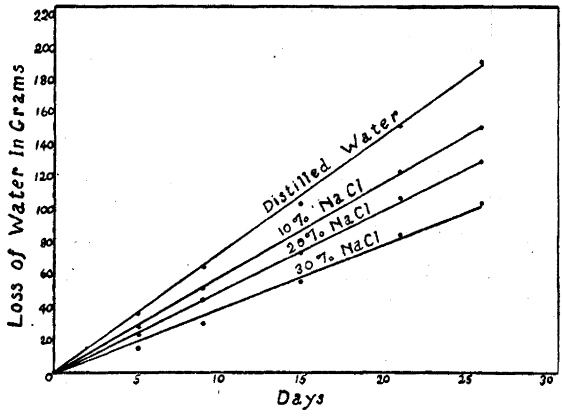

FIG. 15.—Evaporation from distilled water and from sodium-chlorid solutions of different concentrations.

Table VII gives the comparative data. In this table it may be noted that the losses at low percentages were somewhat more rapid from the shallow tanks, but that the deeper cans tended to lose more at the higher percentages. These had no free water exposed on top, while the wetter soils in shallow pans did. As already pointed out, the wet soils often

lost more than the free-water surfaces. The deeper soils were also more uniformly wet. Capillarity doubtless played a part in this experiment.

TABLE VII.—*Comparison of evaporation from large areas and shallow soil with small areas and deep soil, 10 kgm. of Greenville loam being used in each case*

Soil moisture.	Shallow tanks.			Deep cans.		
	Surface area.	Total evaporation.	Evaporation for each square foot of surface.	Surface area.	Total evaporation.	Evaporation for each square foot of surface.
Per cent.	*Sq. feet.*	*Gm.*	*Gm.*	*Sq. feet.*	*Gm.*	*Gm.*
5.4	5.42	2,935	542	0.66	270	409
10.4	5.42	6,100	1,125	.66	440	666
15.4	5.42	7,770	1,434	.66	700	1,066
20.4	5.42	7,405	1,366	.66	920	1,395
25.4	5.42	8,299	1,531	.66	1,010	1,530
30.4	5.42	8,415	1,553	.66	995	1,500
35.4	5.42	8,985	1,658	.66	1,270	1,939

SOLUBLE SALTS

The effect of dissolved salts in reducing the vapor tension, and consequently the evaporation of solutions, is well known. The action of these salts in the soil on evaporation, however, is not so clear, since secondary factors may be introduced. In the ordinary agricultural soil the concentration of soluble salts is not sufficient to have any marked effect on evaporation, but in the alkali soils of arid regions salts may be present in sufficiently high concentrations to affect the loss of moisture materially.

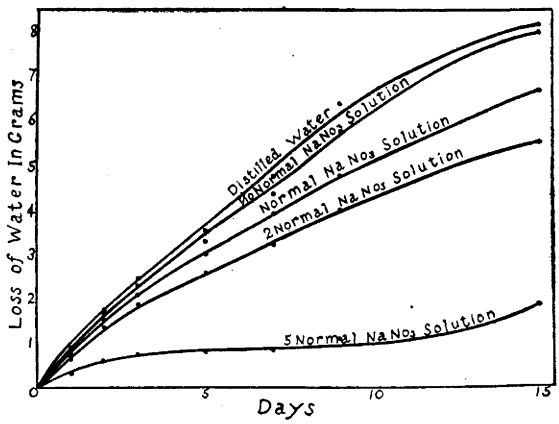

FIG. 16.—Evaporation from sand wet with distilled water and with sodium-nitrate solutions of differ ent concentrations.

With a view to determining some of the effects of salts on evaporation, a number of experiments were conducted. In the first, solutions of sodium chlorid of various concentrations without soil were investigated. The solutions were placed in glass tumblers, two tumblers being used for each treatment, and set in the open laboratory where evaporation could go on freely. The tumblers were weighted every few days and the loss made up with distilled water.

The results of this test are shown in figure 15, which brings out clearly the fact that as the concentration of the solution increases the evaporation decreases.

The second test was conducted in porcelain crucibles, each containing 10 gm. of quartz sand which had been wet with 4 c. c. of solutions of sodium nitrate ranging in concentration from a check solution containing no salt up to 5 times a normal solution. There were two crucibles for each concentration. The crucibles were placed under a bell jar in order to avoid air currents and to keep the humidity as uniform as possible over all the crucibles.

Weighings were made each day at first, and every two or three days later. The experiment was begun January 12 and continued till January 27, making a period of 15 days.

The results are given in figure 16, which shows a decrease of evaporation from the sand the same as when the solution of sodium nitrate is added. A third test was conducted in galvanized-iron cans, 11 inches in diameter and 13 inches deep, partly filled with Greenville loam to which sodium chlorid was added in different quantities, ranging from the control containing nothing to 7 per cent of the dry soil. The quantity of moisture that evaporated was added every three or four days through a tube near the bottom of the cans. In this way the surface of the soil was never disturbed, but there was a gradual accumulation of salts at the surface. The experiment ran from August 19 to September 25.

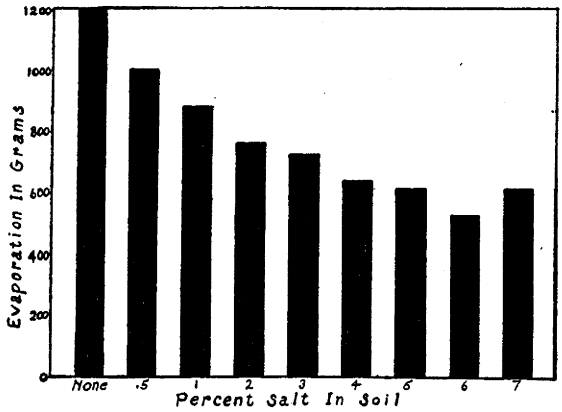

FIG. 17.—Evaporation of water from Greenville loam containing different quantities of sodium chlorid.

The results of the experiment are given in figure 17. There is a gradual decrease in the evaporation as the salt content of the soil is increased. The can with 7 per cent of salt lost slightly more than that with 6 per cent. This irregularity was doubtless due to the fact that considerable salt was crystallized at the surface of the soil in this can, consequently the real concentration of the solution was decreased; and it is the salt actually in solution that affects vapor tension.

From these experiments it seems clear that soluble salts in the soil decidedly decrease the evaporation of moisture if the concentrations are high, but the reduction is only slight for the solutions found in ordinary soils.

SUMMARY

(1) The conservation of soil moisture is one of the most important problems of agriculture, particularly in arid regions.

(2) One of the important factors involved in water conservation is evaporation.

(3) In this paper a study has been made of a number of the factors having to do with evaporation.

(4) Evaporation of moisture increases with the initial quantity in the soil. The increase is not so great with the higher percentages as with the lower, and there seems to be a number of critical points where the rate of loss changes rapidly.

(5) The rate of evaporation from a moist soil is very rapidly decreased as the humidity of the air is increased.

(6) Air currents greatly increase evaporation; but after about a certain wind velocity is reached, the rate of evaporation is only slightly increased by increasing the wind velocity.

(7) For the sizes investigated, evaporation was higher from the finer soil particles than from the coarser when both are completely saturated.

(8) Reducing the intensity of sunshine greatly reduces the rate of evaporation.

(9) Slight changes in temperature have a marked effect on evaporation.

(10) A thin mulch, if kept dry, is effective in reducing evaporation. Dry mulches, composed of fine particles, seem to be less effective than if composed of coarser particles.

(11) Compacting the surface of the soil increases evaporation.

(12) Dissolved salts in high concentrations reduce the evaporation of moisture from soils.

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