UNITED STATES DEPARTMENT OF AGRICULTURE

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Washington, D. C. PROFESSIONAL PAPER March 31, 1923

USE OF WATER BY SPRING WHEAT ON THE GREAT PLAINS

By

JOHN S. COLE, Agronomist, and
O. R. MATHEWS, Assistant Agronomist in Dry-Land
Agriculture with an introduction by E. C. CHILCOTT, Agriculturist
in Charge of the Office of Dry-Land Agriculture Investigations, Bureau of Plant Industry

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By JOHN S. COLE, *Agronomist*, and O. R. MATHEWS, *Assistant Agronomist in Dry-Land Agriculture*, with an introduction by E. C. CHILCOTT, *Agriculturist in Charge of the Office of Dry-Land Agriculture Investigations, Bureau of Plant Industry.*

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INTRODUCTION.

Since 1906 the Office of Dry-Land Agriculture Investigations has been conducting experiments to determine the possibilities and best methods of crop production on the Great Plains. Coincident with this work and an integral part of it since 1907 has been the determination of soil moisture in cooperation with the Biophysical Laboratory of the Bureau of Plant Industry. The investigations have been continuous, coordinated, and systematic at 24 field stations,[1] carefully located to be most representative of general as well as local conditions.

While the data from a single station or a single year are valuable in themselves, they are still more valuable in their contribution to the mass of facts accumulated. Covering a long series of years, embracing wide ranges of soils, climatic conditions, and crop adaptations found from the northern to the southern Plains and from the lowest to the highest altitudes within them, the mass of comparable data that have been gathered has a value that while foreseen affords possibilities of study that could hardly have been appreciated when

[1] The stations in Montana, North Dakota, Wyoming, Nebraska, and Kansas are conducted cooperatively with the agricultural experiment stations of the respective States. The stations in South Dakota, Colorado, Oklahoma, Texas, and New Mexico are operated independently by the United States Department of Agriculture.

the work was started. The wide range of the curve of every relation that is plotted may reveal a fundamental principle that could not have been suspected from a single group of the data and makes it possible to test severely hypotheses to which its study leads.

The present study is the first that has been presented in which the data are used to develop a general problem other than one dealing primarily with methods of culture and the results as measured in terms of resulting yield. While it develops effectively the problem it undertakes, it is by no means exhaustive and suggests and invites study of more questions than it endeavors to dispose of. It is only suggestive of the possibilities of such data.

While the importance of an adequate supply of water has long been recognized, the dependence of yield upon an uninterrupted supply has perhaps never before been so well established. Determination of the daily rate of the use of water and the dependence of yield upon the maintenance of this rate lays a foundation for more exact prediction of yields than are possible without such knowledge. In the daily rate of the use of water is to be found a reason for the difference in effectiveness of rainfall in different sections of the Great Plains. The writers have done enough checking of results outside the Great Plains to be satisfied that in the same factor is to be found a basis of comparison and explanation of the results in other sections and under other types of rainfall.

E. C. Chilcott,
Agriculturist in Charge.

STATEMENT OF THE PROBLEM.

Dry farming is practiced only in regions where the water available to crops is a factor of prime importance. As the initial water supply stored in the soil and the quantity that may be supplied by rains during the growth period are limited and susceptible of measurement, it is of fundamental importance in any study of the subject to know the daily rate of the use of water by the growing crop and the total consumption by the crop during its life period. In investigational work it has appeared especially important to determine the actual rate of use in the field in order to properly evaluate quantities of water in terms of the length of time they would meet the requirements of the crop.

Other investigators have made exhaustive physiological investigations of the water requirements of crops directed chiefly to the measurement of the water actually transpired by the crop plants alone.

In the field the crop has an initial supply measured by the available water stored in the soil within the zone of depletion by the crop. This is replenished or added to from time to time by the precipitation. The water is used by the crop and by the weeds that accompany it and is lost by direct evaporation and very seldom under dry-farming conditions by leaching. A portion of the precipitation may be lost by run-off.

In the field it is not possible to separate the water actually used by the crop in the sense of passing through the tissues of the plants comprising it from that lost by other means. If it were possible, it does not necessarily follow that it would be desirable. The water lost by weeds, evaporation, run-off, and other factors is as truly a part of the water used by a crop under a given method of cultivation in any region as is the water actually transpired by the vegetative surface of the crop.

To know the requirements of the crop in the field it is consequently necessary to determine the quantity of water that is lost from the soil and the quantity that is supplied by precipitation. The sum of these quantities for any period constitutes the water used by the crop. When this is known for any period the daily rate of use can be calculated directly from the number of days in the period. Many problems arise in addition to or in connnection with the main one. Some of these are considered in the present study.

SOURCE, CHARACTER, AND METHOD OF STUDY OF THE DATA.

In the 14-year period from 1907 to 1920, inclusive, soil moisture determinations have been made at 23 field stations for a total of 205 station years. While data have been obtained from all the principal crops, the present study is confined to the wheat crop. This has been durum wheat and mostly of the Kubanka variety or type.

From the data available, that from two plats has been selected for the present study: Plat A, continuously spring plowed and cropped to wheat, and plats C and D, which are alternately fallowed and cropped to wheat, so that wheat is grown on one of them on fallow each year.

The data for individual years are not all that might be desired, as they were not taken especially for the present study. Greater intensiveness through more frequent sampling would have added to their value and made possible the use of the data of many years that must be rejected because determinations were not made at the necessary stage of growth or condition of soil moisture, but the cases that can be used make up a volume of observations that probably more than offset the intensiveness that might have been obtained had the work been limited to a smaller number.

All determinations here studied have been made on 1-foot sections of soil.

Soil samples are taken with a tube having a diameter at the cutting edge of 20 millimeters. To determine the water content of a plat four cores are taken from it at locations representing its four quarters. The four cores are handled as two samples, the two cores from opposite corners being placed together. Determinations are thus made in duplicate, each one of the samples being made up of two cores and having a weight of dry soil varying from 200 to 300 grams.

Each core of soil when drawn from the ground is discharged from the tube into a can of sufficient size to hold two cores. The cans are provided with tight covers, which prevent any appreciable errors from loss of water before weighing, even though weighing should be considerably delayed. To facilitate weighing, each can is made to balance a weight of 110 grams. The samples are immediately taken to the laboratory and the net weight determined to the nearest one-tenth of a gram.

After the wet weight is determined the cans are opened and placed in an oven, where they are subjected to a temperature ranging from

100° to 110° C. for a sufficient length of time to expel all water, as determined by their coming to a constant weight.

The dry weight of soil is then determined and the percentage of water to the nearest tenth calculated on a water-free basis by means

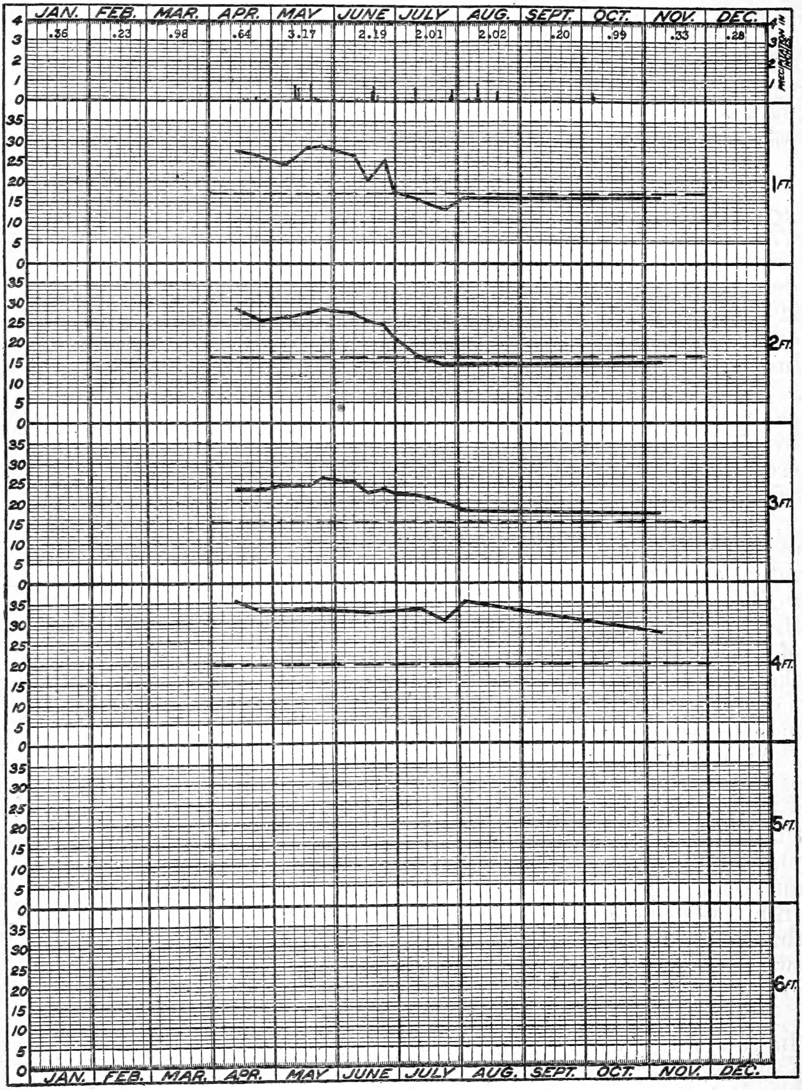

Fig. 1.—Soil-moisture chart of wheat plat C at the Belle Fourche Field Station in 1916. The water content of the upper 4 feet is shown by four curves connecting the points indicating the percentage of water in each foot at each date of sampling.

of a slide rule. The average of the duplicate determinations is the figure used as the percentage of water in the unit at the time of sampling.

For purposes of study the data so obtained are reduced to graphic form by charting on specially designed blanks. Figure 1 is a reproduction of the soil-moisture chart for wheat plat C in the continuous-cropping series at Belle Fourche in 1916. Determinations on that plat were made to the depth of 4 feet that year. Its water content at the several dates of sampling is consequently shown by the points of four separate curves. Immediate reduction of these to a single curve by averaging the four would result in an error of a magnitude dependent upon the differences in the volume weight of the several units of soil. Soils of the several stations also differ in volume weight, and consequently any given percentage of water content may not indicate the same actual quantities of water in different soils or soil units. Further, it is not possible directly to combine percentages of water in the soil with inches of water added to it by rainfall during any period. Consequently it has been necessary to convert the percentage of water in each foot section of soil to terms of inches of water.

Prerequisite to such conversion is the determination of the volume weight of each soil unit under study. This has been determined by calculation from the weight of the cores taken by the soil tube. For this determination periods were selected when the soil tubes were known to be new and in good condition with a sharp cutting edge of a circle of the known diameter of 20 millimeters. As large a number of weights as possible, not less than 50 and preferably more than 100, were averaged for each unit, and the weight per cubic foot was calculated from the weight of a known volume. Weights of obviously defective cores were arbitrarily rejected. It is believed that the volume weights determined by this method are as accurate as those that might be determined by any other method based upon a smaller number of cores of larger volume. The volume weights so determined and used as bases of conversion have been carefully considered in the light of all knowledge and information on the several soils and accepted as fair bases of comparison.

This study is concerned with the amount of change in the water content of the soil during a period rather than with the actual water content. The process, therefore, has been to determine the percentage of change and then to convert this into inches of water, instead of reducing the entire water content to inches and then determining the change by subtraction.

In determining the water loss from the soil for any period the first step is to subtract the water content of each foot section at the end of the period from the water content of the same unit at the beginning of the period. At this time the water content is expressed as a percentage of the dry weight of the soil. The next step is to convert these expressions to terms of inches of water by calculation from the determined weights of the soil of each unit. An increase in water content is recorded as a minus loss. The algebraic sum of the losses from all the units (foot sections) involved is the loss from the soil of the plat under determination.

The total water loss or the total water used by the crop in any period is determined by adding the precipitation for the period to the water lost from the soil. It is the algebraic sum of the two quantities. The relative importance of the two quantities will be considered later, and the necessity of combining the two into a single quantity will be shown.

There is, of course, a considerable number of experimental errors in the determinations. Even in the most uniform soils, duplicate determinations of soil moisture are nearly certain to vary at least one-half of 1 per cent, and in less uniform soils variations of much greater magnitude occur. The probable error of the total of any individual sampling or of the difference between the totals of any successive samplings may be relatively large or small, depending upon the dispersion of the errors of the units making up the totals and the extent to which they compensate each other. An error in the same direction of one-half of 1 per cent in each foot in a determination to the depth of 6 feet on a soil weighing 75 pounds per cubic foot would be equivalent to 0.42 inch of water. In soils lacking uniformity the experimental error may be much larger.

In the present study of the use of water the following practices have been followed for the purpose of reducing the experimental error as much as possible:

(1) The depth to which the samples have been included in each determination has been limited to the zone of change of water content. For example, even if samplings have been made to the depth of 6 feet or more but all changes in water content (either reduction by use or addition by rainfall) have been confined to the first 3 feet of soil, the calculations to determine the quantity of water used have been limited to 3 feet. Inclusion of additional depths would only increase the experimental error without contributing anything of value to the results.

(2) Periods of time as long as practicable have been used to determine the rate of use in each instance.

To obtain the rate of use per day, the quantity of water used in any period is divided by the number of days in that period. Any error that may exist in the total quantity of water used is consequently reduced in proportion to the number of days in the period. In a general way, experimental errors of successive samplings tend to compensate each other, and the experimental error for the quantity of water used in a season should be small and is limited to the errors in the first and last samplings.

DAILY RATE OF THE USE OF WATER WHILE THE CROP IS GROWING RAPIDLY.

Under this heading are included the results of attempts made to determine the daily rate of the use of water by the wheat crop under full and uninterrupted growth. This rate was calculated in all years when two soil-moisture determinations at least two weeks apart were made during the period of rapid growth of the crop and while it was not suffering for lack of water. As long a period as possible was selected for each year, in order to make the error in the rate per day due to the experimental error of the determinations as small as possible. In years when no shortage of water occurred the end of the period is determined by harvest. No years were included (1) when the crop had suffered from drought before the period of rapid growth was reached; (2) when the second sampling during the rapid-growth period was delayed until after the crop commenced to suffer from drought; (3) when some condition, such as hail, rust, or insects, destroyed the crop. Years when some factor other than a lack of water was responsible for crop injury were excluded, to avoid the introduction of irrelevant data in a correlation of the rate of the use of water with the yield.

There remained 53 years in which the daily rate of the use of water could be determined under the conditions imposed. These are distributed among 14 stations located in the Great Plains from Huntley, Mont., and Williston, N. Dak., on the north, to Amarillo, Tex., on the south. Two of these stations—Ardmore, S. Dak., and Garden City, Kans.—furnished data for only a single year each, while at Edgeley, N. Dak., a measure of the rate was determined for 10 years.

The rate was determined separately for two cultural methods at each station. The one designated plat A is continuously spring plowed and cropped to wheat. The one designated plat C or D is alternately summer fallow and wheat. This method occupies two plats, so there is available for study each year a crop of wheat growing on land bare summer tilled the previous year.

In the average of conditions this method contains more water in the soil at the time the crop commences rapid growth, supports a heavier growth of vegetation, and produces a larger crop than the plat continuously cropped, but exceptions are to be noted when one or more of these conditions are reversed.

The results of this study are presented in Table 1. This gives the station, the year, the dates of the soil-moisture determinations marking the beginning and end of the period, the average daily precipitation during the period, the average daily evaporation from a free water surface during the period, the daily rate of water use and yield of plat A, and the daily rate of water use and yield of plat C or D.

The daily rate of water use has been charted with calendar dates as abscissa and total use as ordinates. The slope of the curve then indicates the rate of use. This chart is not presented, because a considerable part of its value for study lies in the identification of each line with the year and station it represents. It is impracticable to attempt this on the scale to which it necessarily would be reduced in publication. Such charting shows that the rate of use is not determined by the dates within which or the part of the period of rapid growth during which the rate was determined. This phase of the subject is more fully developed in the study of the rate of the use of water during the season. In this it is shown that after beginning rapid growth, about the time tillering is completed, the rate of use remains fairly constant until harvest if not interrupted by failure of the water supply or by some destructive or inhibiting agency.

These determinations afford opportunity for a study of the relative importance of water from the soil and of precipitation in determining the rate of use and for the examination of the reasons for combining the two to obtain this rate.

The material has been studied in various ways. Charting the two quantities and the total which they make up shows very clearly that they are complementary. Under given conditions a given crop requires a certain quantity of water. If this is supplied by precipitation the quantity of water in the soil will not be reduced, and if more than the required quantity is supplied it will be increased; but if the rainfall is not sufficient to meet the demand the available water in the soil will be reduced by the required difference. This is perhaps best shown by correlations.

TABLE 1.—*Average daily precipitation, evaporation, and rate of use of water by the wheat crop, together with yields per acre, on plats A and C or D during a designated period of rapid growth at the several experiment stations for the years shown.*

Station and year.	Period.		Precipitation.	Evaporation.	Plat A.		Plat C or D.	
	From—	To—			Water use.	Yield.	Water use.	Yield.
			Inches.	*Inches.*	*Inches.*	*Bushels.*	*Inches.*	*Bushels.*
Huntley:								
1913	June 11	June 28	0.11	0.20	0.10	16.0	0.17	22.6
1914	June 13	June 27	.14	.18	.16	18.3	.23	19.5
1915	June 19	Aug. 7	.08	.18	.17	24.5	.20	36.5
Williston:								
1911	June 8	June 24	.04	.25	.10	2.7	.14	7.6
1912	June 12	July 29	.10	.20	.16	25.2	.21	39.7
1914	July 2	July 27	.07	.24	.23	23.8	.30	31.2
1915	May 29	July 12	.07	.21	.12	19.3	.17	27.7
Dickinson:								
1908	June 2	July 22	.09	.22	.19	24.3	.20	33.8
1909	June 3	Aug. 5	.08	.17	.16	26.8	.19	35.7
1910	June 4	July 19	.08	.26	.16	17.4	.21	26.8
1911	June 3	June 16	.05	.22	.13	5.7	.21	23.3
1915	June 11	Aug. 28	.11	.16	.10	25.8	.20	38.7
Mandan:								
1915	June 29	Aug. 23	.12	.18	.11	30.5	.13	39.3
1916	July 7	Aug. 8	.11	.23	.18	19.2	.18	21.8
Edgeley:								
1907	July 1	July 16	.11	.19	.11	4.1	.13	9.9
1908	June 3	July 8	.06	.18	.21	13.3	.18	16.0
1909	June 2	July 19	.06	.14	.16	28.3	.15	27.0
1910	June 2	June 22	.08	.21	.13	4.0	.10	5.7
1911	June 5	June 26	.03	.24	.16	0	.16	0
1912	June 7	July 2	.15	.16	.23	35.0	.20	30.3
1913	June 20	July 29	.11	.19	.15	16.3	.19	16.8
1914	June 23	July 29	.12	.21	.18	11.3	.18	13.0
1915	June 11	Aug. 13	.13	.15	.17	34.8	.16	40.3
1916	June 9	July 29	.10	.16	.18	5.5	.17	6.8
Hettinger:								
1912	May 29	June 26	.04	.20	.18	14.3	.22	17.5
1913	June 21	July 9	.13	.25	.15	13.8	.18	37.0
1915	June 10	July 23	.21	.16	.17	40.7	.22	37.4
1916	May 27	July 5	.08	.16	.10	4.2	.14	4.2
Belle Fourche:								
1909	June 5	Aug. 3	.13	.23	.20	23.8	.21	32.2
1910	June 2	June 16	.04	.25	.18	2.8	.23	5.0
1913	June 18	July 2	.09	.22	.12	6.2	.14	16.8
1914	June 10	June 27	.06	.24	.13	4.0	.18	15.8
1915	June 25	Aug. 5	.16	.18	.17	56.5	.17	57.2
1916	June 10	July 12	.08	.20	.16	10.6	.21	18.7
1917	June 9	July 9	.02	.27	.11	4.4	.11	11.1
1918	June 5	June 24	.01	.23	.13	8.5	.19	35.0
Ardmore:								
1916	June 19	July 29	.06	.27	.21	18.0	.20	15.8
Scottsbluff:								
1913	May 18	June 18	.06	.25	.16	12.0	.19	17.3
1917	June 7	July 6	.04	.30	.19	9.2	.23	18.7
North Platte:								
1908	June 3	Aug. 5	.15	.24	.18	22.7	.22	40.5
1909	June 4	Aug. 2	.17	.24	.25	23.0	.26	18.0
1915	June 4	Aug. 11	.17	.21	.20	22.7	.25	27.8
1916	June 9	July 20	.08	.29	.17	17.2	.20	19.7
Archer:								
1915	June 28	July 28	.04	.21	.17	26.8	.15	25.7
1917	June 4	July 17	.02	.26	.12	15.6	.14	14.9
Akron:								
1908	June 9	June 30	.07	.29	.24	17.3	.23	13.7
1909	June 2	July 28	.12	.27	.18	14.3	.22	18.5
1910	May 25	June 21	.05	.31	.18	11.3	.20	8.5
1912	June 4	July 6	.11	.23	.21	21.3	.21	16.0
1915	June 28	Aug. 12	.10	.21	.17	26.3	.16	33.8
Garden City:								
1909	May 28	June 25	.12	.29	.17	2.1	.22	6.7
Amarillo:								
1911	May 22	June 22	.22	.34	.24	7.3	.33	19.0
1914	May 21	June 13	.05	.30	.23	11.0	.26	13.8
Average			.09	.22	.17	17.0	.19	22.4

The correlation between the total quantity of water used per day and that portion of this quantity that is obtained by reduction of the water content of the soil (designated daily use from soil) is 0.48± 0.07 for plat A and 0.57±0.06 for plat C or D. The correlation between the total quantity used per day and that portion of this quantity that is supplied by precipitation during the period under study is 0.30±0.08 for plat A and 0.29±0.08 for plat C or D. Both these are positive correlations, but the correlation of the total quantity with the precipitation is of a low order. The higher correlation of the total with the portion obtained from reduction of the soil water content indicates that under the conditions specified for this study the stored water is a more dependable source of supply than the precipitation.

The correlation between the two parts that make up the total daily rate of use (the rate of use from the soil and the precipitation) is a negative one of −0.73±0.04 for plat A and −0.67±0.08 for plat C or D. This is a rather high correlation and expresses the high degree to which the two parts that make up the whole are complementary, as previously explained.

Table 1 shows the rates of the use of water per day varying in individual years at individual stations from 0.10 to 0.33 inch per day. That these differences are largely real differences and not experimental error is indicated by the agreement between the two plats. The rate of use may not be the same on the two plats in any year, because they may be supporting different amounts of vegetation, but changes from year to year are in nearly every case in the same direction on the two plats. The rate of water use for any year is undoubtedly not correct to within 0.01 inch and in some cases the error may be several hundredths of an inch, but the use of as long periods as possible for each year and the inclusion of as many years as possible in the data should make the average results for a station reliable.

The 53 station years studied show an average rate of use of 0.17 inch per day on plat A with an average yield of 17 bushels per acre, and an average rate of 0.19 inch per day on plat C or D with an average yield of 22.4 bushels per acre. In some cases the rainfall during the period under study has been greater than the quantity of water used, meaning that the quantity of water in the soil increased, and in other cases the rainfall has contributed as little as 0.01 inch per day to the total. The average rate of rainfall was 0.09 inch per day.

Some points may be shown more clearly by assembling the average rates of use per day for each station in a separate table. This is done in Table 2, which gives the average rates of use per day for both plats A and C or D at each station. In this table, as in Table 1, the stations are arranged as nearly as may be with respect to their geographical location, the more northern ones at the top of the table and the more southern ones at the bottom. This table shows immediately for plat A the dependence of the rate upon the geographical location. The northern stations show in general lower rates of use than the southern. Exceptions are to be noted in the case of the record of a single year at Ardmore, which shows a higher rate than its location would indicate, and a single year at Garden City, which has a low rate. This low rate was made by a very light crop and should not therefore be considered as an exception. The average rate of use at Archer agrees with the rate in North Dakota and South Dakota. This station is located at an altitude of more than 6,000 feet and has a summer temperature, evaporation, and other climatic factors more nearly like the Northern States than stations in the same latitude.

TABLE 2.—*Rate of the use of water per day during a period of rapid growth on both plats A and C or D averaged for each station.*

Station.	Use of water.		Station.	Use of water.	
	Plat A.	Plat C or D.		Plat A.	Plat C or D.
	Inch.	*Inch.*		*Inch.*	*Inch.*
Huntley	0.14	0.20	Ardmore	0.21	0.20
Williston	.15	.21	Scottsbluff	.18	.21
Dickinson	.15	.20	North Platte	.20	.23
Mandan	.15	.15	Archer	.15	.15
Edgeley	.17	.16	Akron	.20	.20
Hettinger	.15	.19	Garden City	.17	.22
Belle Fourche	.15	.18	Amarillo	.24	.30

With plat C or D the regional effect is more obscured by the influence of the size of the crop on the rate of use. It is most fully exemplified in the high rate at Amarillo, which averages 0.3 inch per day. This is the average of the rates of 0.33 inch and 0.26 inch, respectively. One of these is the highest yet determined and the other has been equaled only once, which was at North Platte in 1909. The rates of use at North Platte and at Garden City also average high in comparison with those at more northern stations. Archer has a comparatively low rate on this plat, the same as on plat A.

In general terms, the average rate of use on plat A ranges from an average of 0.15 inch per day at the northern stations to 0.24 inch at the most southern station and on plat C or D from nearly 0.2 inch per day at the northern stations to 0.3 inch at the station farthest south. The most southern station therefore shows a daily rate of use from 50 to 60 per cent greater than the northern stations.

The averages of plats A and C or D show a relation between the rate of use and yield. A close correlation between the two should not be expected, because the rate of use of water was determined for a period that covered only part of the life of the crop.

In many cases the crop suffered severely from drought at some time after this rate was determined. Other factors, such as extremely hot weather, may have influenced it after the rate had been determined. It was thought, however, that if any relation between the rate of use of water and yield existed, it would be shown through a positive correlation, even though the correlation might not be strong.

The first correlation was made by using the average yield and the average rate of all stations as bases from which to compute departures. The resulting correlation for plat A was 0.24, with a probable error of ± 0.09. This is a very weak correlation and only indicates that a relation may exist. It was not thought possible that a close correlation can be arrived at in this way. The facts that the northern stations yield heavier than the southern ones and that a rate of use of water that represents a maximum at a northern station is only an average rate at a southern station preclude the possibility of this correlation being close.

To determine whether a closer correlation existed if the difference between the stations could be eliminated, a second study was made. In this second study the average rate of the use of water for each station and the average yield of each station were used as bases for computing departures. Determined in this manner, a correlation of 0.4 with a probable error of ±0.08 was shown for plat A. This is much closer than the previous one and shows clearly that a much closer correlation between water use and yield exists at the individual station than is shown for the Great Plains as a whole. This correlation is marked enough to show that a relation between the rate of water use and yield actually exists, though it does not indicate how close the relationship may be.

It is probable that a closer correlation exists between the potential yields and the rate of the use of water. In other words, if all the crops from which these data were obtained could have been carried through to harvest without suffering from drought, the ones showing the higher rate of water use would have produced the higher yields. This is, of course, a matter of opinion and can not be subjected to any mathematical test. It is worthy of note, however, that years in which heavy straw growth has been noted almost invariably have been above the average in the rate of water use.

An attempt was made to correlate the rate of water use with the evaporation, as controlled water-requirement studies have shown that evaporation is one of the strongest factors in determining the quantity of water needed by the crop.

It was found that while, in general, stations with a higher evaporation showed the greatest rate of use of water, little relation was shown between evaporation and the rate of water use for different years at the same station.

This was accounted for by the fact that the water lost from a plat in a season of low evaporation may exceed that lost in one with a high evaporation. The water lost from the wheat itself is undoubtedly higher in years with high evaporation. This has been conclusively proved by investigations of the water requirements of crops. The water lost from the soil, however, may be much smaller. As a rule, years having a high evaporation are dry, and the quantity of surface moisture or moisture near enough to the surface to be affected by evaporation is small. Low seasonal evaporation is usually accompanied by frequent rains. When these occur there is a great deal of water that is subject to loss by evaporation from the surface. In spite of the fact that the rate of evaporation from a free water surface is low, considerably more moisture may be lost from the soil by evaporation in years of this type than in years having a high rate of evaporation.

RATE OF THE USE OF WATER AS THE SOIL MOISTURE APPROACHES DEPLETION.

This study was made for the purpose of finding whether the rate at which the wheat crop is able to use water from the soil decreases as the water content of the soil nears depletion.

To determine this point the rate of the use of water for the period when the moisture content of the soil neared depletion was compared with the rate of use of water for the two periods preceding. The conditions necessary for obtaining data on this point were as follows: (1) All three periods must have been within the period of rapid growth, (2) the last period must have ended before the soil moisture was depleted, and (3) the samples must have been taken deep enough to include all soil in which a change in water content took place.

The number of years in which data on this point could be obtained was small, and the experimental error due to the short lengths of the periods was large. In order to obtain data for the consecutive periods within the period of rapid growth, the three periods selected were necessarily short. Data were obtained for an average of about two years at each station.

It was found that when the results of all stations were averaged the use of water for each period was nearly the same. It can not be said that anything conclusive was shown by the data, however. The experimental error in the rate of use per day was so large that it obscured any small differences there might have been between the different periods. No consistency in water use in the different periods is shown either between the different stations or the different years at the same station.

The conclusion drawn from this study is that though there may be a slight decrease in the rate of use of water as the soil becomes drier, such decrease is too small to be measured by the means employed. The wheat crop can exhaust nearly all the available water without any serious reduction in its rate of use.

RATE OF THE USE OF WATER DURING THE GROWING SEASON.

Under the second preceding heading the rate of the use of water under certain conditions and for a part of the growing season was considered. The conditions were such as to permit or require the use of water at maximum rates per day. Under the present heading the rate of the use of water for the entire growing season under conditions that obtain for the entire season will be considered.

The use of water was determined, in terms of inches used, for each period between successive samples, beginning with the one nearest seeding time and ending with the one at or near harvest. The same method was used as in the preceding study. While the primary calculation was in terms of use for each period, the material so obtained was prepared for use by successive additions of the water from period to period. The sum at any sampling date represents the total quantity of water used by the crop from the first date of sampling until the date in question. The successive sums from date to date show the cumulative use of water during the growing season from zero at the beginning to the total quantity at harvest time.

The data so assembled were further prepared for study by charting on cross-section paper with calendar dates as abscissa and quantities of water used as ordinates. The first sampling is indicated by a point on the zero line of ordinates at the given date. The second sampling is indicated by a point the abscissa of which is the date and the ordinate of which is the quantity of water used to that date.

In the same manner the water used from the first sampling until each date is indicated. The points are then connected by a line. The slope of the line between successive points shows the rate of use during the period it covers.

The use of water by more than 100 wheat crops has been determined and charted. It is not considered necessary to reproduce all these charts. A sufficient number will be reproduced to show the types of curves representing different seasons and localities. This purpose is adequately served by charts showing the water use at Dickinson, N. Dak., Akron, Colo., and Amarillo, Tex. These stations are representative of the northern, central, and southern sections of the Great Plains.

The use of water at Dickinson, N. Dak., for the years 1909, 1910, and 1911 on plat A, a spring-plowed plat cropped continuously to wheat, is shown in Figure 2. The year 1909 was exceptionally favorable to wheat. There was no time during the season when the crop

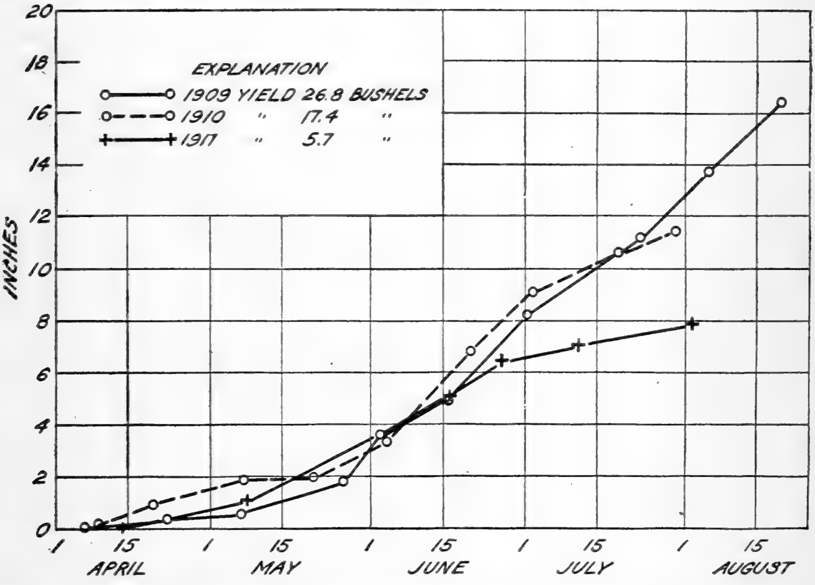

FIG. 2.—Diagram showing the use of water by the wheat crop on plat A at Dickinson, N. Dak., for the years 1909, 1910, and 1911.

suffered for lack of water. As a result, it made a good growth and continued to use water at a rapid rate for a long time. The rate of the use of water from about June 1 to harvest is nearly constant. The year 1910 was not so favorable. The wheat crop commenced to use water rapidly, but the water supply began to run short early in July. The rain in July was sufficient to keep the crop from being badly damaged by lack of water, but there was some suffering that was reflected partly in a slightly lower rate of use near harvest but more particularly in a forced ripening of the crop and an early date of harvest. The year 1911 was one in which the crop suffered for lack of water or lacked sufficient water to make much growth during practically all of its growing season. Except for a short time in the early part of June, there was not enough moisture in the soil to keep the crop growing rapidly. However, the early drought checked the growth of straw, and the crop, by reason of its meager straw growth, was able to maintain life until harvest on the rains that fell and to mature a small yield of grain. This condition is indicated by the curve (Fig. 2), which shows a comparatively low rate of use throughout the season.

The use of water by the plat of wheat grown on fallowed ground at Dickinson in the years 1909, 1910, and 1911 is shown in Figure 3. It will be noted that the 1909 curve for this plat is practically the same as the one for plat A shown in Figure 2. The curve follows the same general line and there is the same long-continued use of water and resulting high yield. The actual date of harvest was several days later than for plat A, but the final soil-moisture determination was made on the same date on both plats. In both 1910 and 1911 the water use was continued at a rapid rate practically until

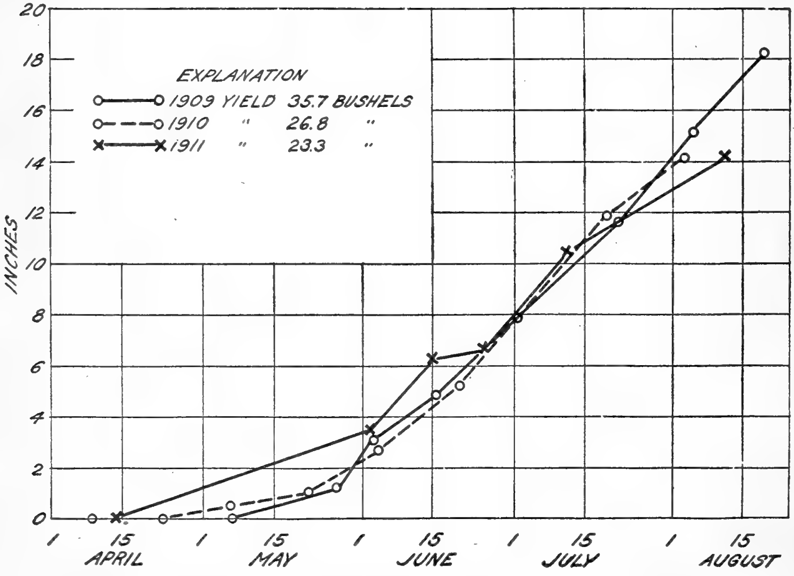

FIG. 3.—Diagram showing the use of water by the wheat crop on plat C or D at Dickinson, N. Dak., for the years 1909, 1910, and 1911.

harvest. This plat ripened a little prematurely in both years on account of drought, and both years show a shorter rapid-growth period and a lower yield than in 1909.

The most noticeable difference between the two charts is in the behavior of plat C or D and plat A in 1911. Plat A suffered for water at nearly all times during the season and was able to mature only a small yield of grain. Plat C or D, by reason of the water stored in the soil through fallowing the previous year, was able to make a good growth and mature a good yield of wheat. It consequently shows a much higher rate of use of water than plat A throughout the season.

Figure 4 shows the use of water on plat A at Akron, Colo., for the years 1909, 1911, 1912, and 1913. Two of these, 1909 and 1912, were good years for wheat. In 1909 the wheat was planted late and did not reach the period of rapid growth as early as in other years. From the time it commenced rapid growth until harvest the crop did not suffer greatly for lack of water, and there was a resulting good yield. While the yield of 14.3 bushels per acre is not high, it is fair for the locality and as high as could be expected from wheat planted as late as April 23. In 1912 the crop commenced to use water rapidly earlier than in 1909 and used it at practically the same rate. The determination on May 16 represents an extreme example of experimental error. In this case it is evident that the rate of water use shown from April 27 to May 16 is too high, and that from May 16 to June 4 too low. It is due to the fact that the soil samples taken on May 16 showed a lower percentage of moisture

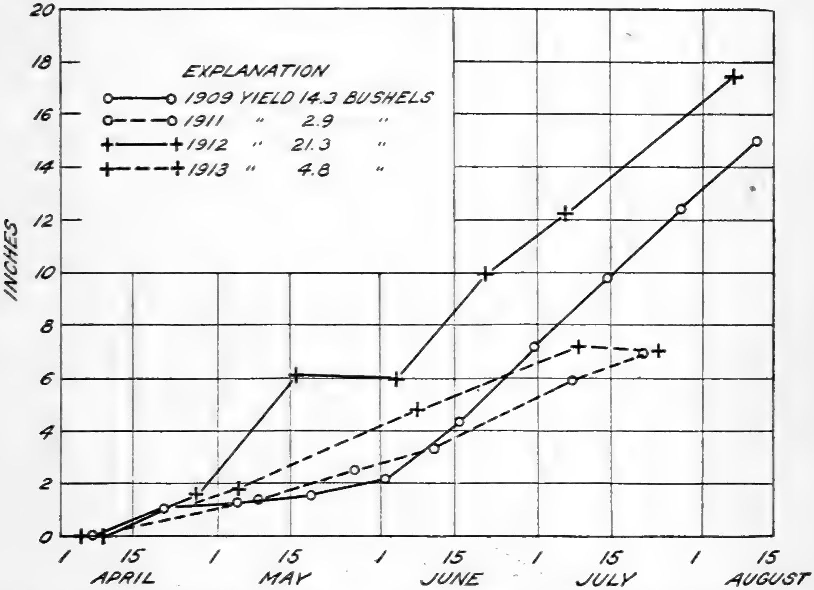

FIG. 4.—Diagram showing the use of water by the wheat crop on plat A at Akron, Colo., for the years 1909, 1911, 1912, and 1913.

than later conditions indicate were warranted. The years 1911 and 1913 both represent seasons when the wheat crop suffered for moisture from the time it began rapid growth until harvest. In both years there is a resulting low rate of water use and low yield shown. Likewise, there is an earlier harvest date than in the two years that were favorable for wheat.

Figure 5 shows the water use on plat C or D at Akron, Colo., for the same years shown in Figure 4 for plat A. The year 1909 was favorable for wheat, and the wheat did not suffer for water at any time during its growing season. That it did not yield more than 18.5 bushels per acre was doubtless due to the late date of seeding. In 1912 the crop actually ran out of water before harvest, and the result is shown in the lower use of water and the slightly lower yield. From the figure it would appear that the date of harvest was later in 1912 than in 1909. The crop in 1912 actually was harvested on August 9, but no soil samples were taken on this plat until August 16. In all other cases soil samples were taken within two days of the harvest date. The years 1911 and 1913 were unfavorable for wheat. In both these years there was enough water in the fallow plat to start the wheat growing rapidly, but in both years the crop soon commenced to suffer from drought, and the resulting lower rate of water use and low yield are shown. Harvest in both of these years was earlier than in the favorable years.

A comparison of the two figures shows one striking fact. The wheat on plat A in 1912 used more water than the wheat on plat A in 1909 and made a considerably higher yield. On plat C or D the quantity of water used in 1909 was greater than in 1912, and the yield was higher. For the quantity used, the crop on both plats in 1909 shows a lower yield than in 1912. This is probably explained by the later seeding.

A comparison of Figures 4 and 5 shows how ineffective in the growth of spring wheat fallowing has been as a means of combating drought at this station. In 1909, 1911, and 1913 there was only a

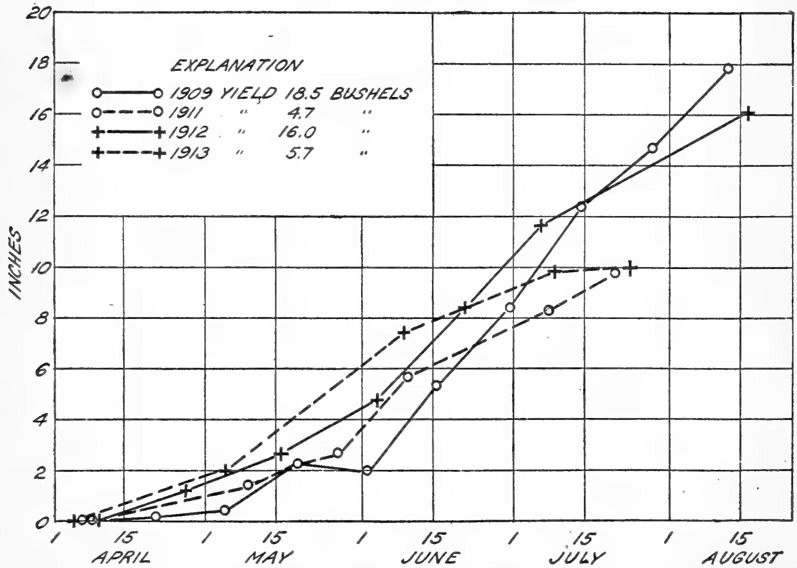

FIG. 5.—Diagram showing the use of water on wheat plat C or D at Akron, Colo., for the years 1909, 1911, 1912, and 1913.

little more water in the fallow plat C or D than in the continuously cropped plat A, and only a slightly higher yield was secured. In 1912 the continuously cropped plat A had more water and made a higher yield than the fallow plat C or D. In no year has there been enough additional water stored in fallow above that in continuously cropped land to carry a crop over any prolonged period of drought.

In general, the Akron curves represent a condition of water use from a soil of medium water-storage capacity. Comparison of the Akron curves with those of Dickinson shows the difference between the two stations in the quantity of water furnished to a crop through fallowing and the resulting increase in yields on fallow over those on continuously cropped land.

Figure 6 shows the water use on plat A at Amarillo, Tex., for the six-year period from 1911 to 1916, inclusive. The curves in this figure show why a high yield of wheat has never been obtained at this station. In three of the six years the wheat crop suffered for water from the time it commenced rapid growth until harvest. These three years all show a low rate of water use and a low yield. In the other three years there was enough moisture to enable the crop to make rapid growth for a time, but in each year the crop was short of water long before harvest and the yield was seriously reduced. In the history of these experiments there has not been a year at Amarillo when severe drought has not injured the crop before harvest, and consequently a high yield has never been produced. The reason for this lies largely in the high rate of water use from the time the crop begins rapid growth. It is evident that for the crop to have used

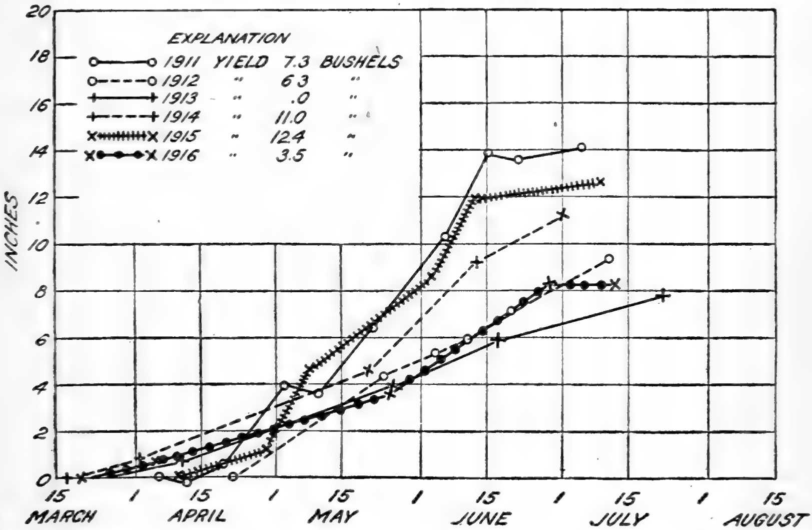

FIG. 6.—Diagram showing the use of water by the wheat crop on plat A at Amarillo, Tex., for the years from 1911 to 1916, inclusive.

water until its harvest date either in 1911 or in 1915 at the rate indicated during its early growth a supply of at least 22 inches would have been required. The average quantity of available water stored in the soil of plat A at the beginning of the crop season is less than 5 inches. In order for the wheat crop to grow to maturity without drought injury, a precipitation of at least 15 or 16 inches during its growth period would be necessary. The fact that such a precipitation is practically unknown gives at least one good reason why spring wheat is not adapted to that section of the Great Plains.

Figure 7 shows the water use on plat C or D for the same years shown in Figure 6 for plat A. The water use on the two plats is much the same, though enough stored water was present in plat C or D in most years to keep the crop growing a little longer before drought injury commenced. This resulted nearly every year in a higher yield for plat C or D. The only exception shown is the year 1915. In that year plat A used more water and produced a higher yield than plat C or D.

One fact evident at Amarillo is that the yield is correlated very little with the harvest date in the different years. This is probably because drought injury has been evident in all years. What little correlation exists in these curves is obscured by the fact that the date of the final sampling does not always coincide with that of harvest. For example, the wheat on plat A in 1913 was harvested July 1, but the first soil samples after harvest were taken on July 22.

In general, the soil-moisture results at Amarillo are subject to greater experimental error than those for any other station. In several years the samples were not taken frequently enough to show accurately the water use for the different stages in the growth of the wheat crop. The curves are presented because spring wheat grows better at this station than at any of the other stations so far south. The high rate of water use in good years when water is available

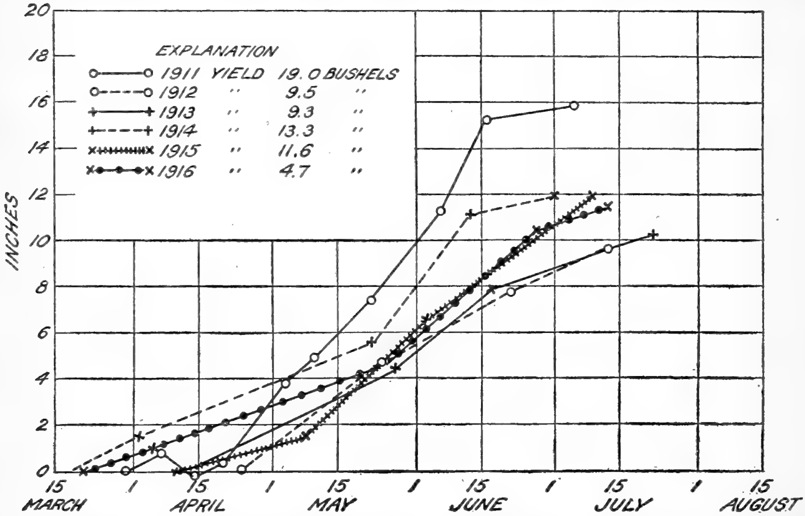

FIG. 7.—Diagram showing the use of water on wheat plat C or D at Amarillo, Tex., for the years from 1911 to 1916, inclusive.

and the evident drought injury in all years are the points most evident in the study of the results for the station.

The results of any one year or any one station are not conclusive in themselves, but those of all the years studied clearly point to certain conclusions in respect to water use.

Four types or general classes of seasons in respect to the use of water by the crop may be distinguished:

Seasons in which there is always sufficient water to meet the needs of the crop. This type of season is comparatively rare.

Seasons when the supply of water in the soil and from rains is great enough to carry a crop almost to maturity, but in which a forced ripening of the wheat takes place because of water depletion just before harvest. This type of season is common.

Seasons when drought conditions begin to affect the crop at or near heading time. In this case a forced ripening takes place, but there is in addition a wilting or firing of the grain for some time before harvest. This is a type of season that occurs frequently on the Great Plains.

Seasons in which the crop at no time has sufficient moisture for optimum growth, but in which by reason of its meager straw growth it may be enabled to come to maturity and make a low yield through timely additions of moisture to the soil through rains. This type of season may occur in any portion of the Plains, but is more frequent in the southern than in the northern part.

To these might be added the very exceptional year of extreme drought in which the crop does not germinate or make any growth.

Each of these several types of seasons can be distinguished in the curves formed by the rate of the use of water during the season. Other conclusions drawn from the study of these data as a whole are as follows:

There is a loss of water from the soil before the crop has made growth enough to make its own demands heavy. This loss is small at the northern stations and increasingly greater farther south. It represents largely evaporation from the soil and is greater at the southern stations because of their higher temperatures and lower humidity.

Rapid growth of the wheat crop accompanied by a higher rate of use of water begins at approximately the same time each year at a given location. This date is earlier at the southern than at the northern stations, owing to the earlier development of the crop.

From the time the crop commences rapid growth until harvest the rate of the use of water continues nearly uniform as long as the crop does not suffer from drought. This is contrary to the general opinion, but this point was evident in all of the cumulative losses charted that were capable of yielding evidence on this point. In nearly every case where there was no suffering for water at any time during the season, the points established by the different dates of sampling between the time the crop commenced rapid growth and harvest lay in an approximately straight line.

The quantity of water used during periods of the same length was nearly the same, no matter whether the use was largely the precipitation for that period or whether it represented water stored in the soil. This indicates that the precipitation falling upon the soil during the growing season is as effective as if it were all added to the soil at a depth great enough to be beyond the reach of evaporation. The conclusion that all precipitation is as effective as if the amount of the precipitation were added to the quantity of water in the soil is open to criticism because of the fact that showers, particularly small ones falling on a dry soil, do not penetrate to a depth great enough to be available to crop roots. This is no doubt true, but, on the other hand, these showers are accompanied by lower temperatures and increased humidity. While none of the water falling in a small shower may be used by crops, the occurrence of the shower and its accompanying phenomena reduces the demand for water by the crop until the net result is somewhere near what it would have been had there been no shower but a quantity of water equivalent to it added directly to the soil.

The rate of the use of water by the crop when in full growth and neither suffering for lack of water nor previously compromised by a lack of water is determined by the environment due to geographical location, the environment due to season, and the extent of vegetative growth that constitutes it. This is the phase of the question that has been considered under the heading "Daily rate of the use of water while the crop is growing rapidly."

Any shortage of available water in the soil is accompanied by one of two phenomena in crop behavior and water use. If the crop is near maturity at the time the shortage occurs, a forced ripening takes place. The rate of water use may not be decreased noticeably during the last period, but ripening takes place at the time the soil moisture is exhausted. If drought begins to affect the crop earlier in the season, there is in addition to a forced ripening a period in which the crop either wilts or fires. During this period very little water is used, because the soil moisture is nearly exhausted. The crop may mature grain, but the yield is always seriously reduced.

The final yield of the wheat crop is determined more by the length of time it uses water rapidly than by the rate of use. In other words, the length of the line from the approximate time the crop commences to use water rapidly to the point where the water is exhausted and the rate of use becomes slower is nearly proportional to the yield. A high yield of wheat usually means not only a great quantity of water used during the season but a late harvest date as well. In general, years in which high yields have been obtained show rates of use of water above the average, but the rate does not seem to be proportional to the size of the crop.

In considering the problem of water use, the ability of the wheat crop to adapt itself to the moisture conditions of the soil must be emphasized. Unless there is a great excess of precipitation over normal the crop will make growth enough or continue to grow long enough to utilize all the available moisture in the soil. In years when the growth is continued a long time the yield is always high unless adverse conditions, such as hail or rust, injure the crop. If at any stage during its growth wheat suffers from drought it seems to spend its last energy in producing seed, and if there is any possibility of doing so it will mature some grain even at the expense of its vegetative growth. In the extensive experiments with wheat in the Great Plains the available soil moisture has been entirely exhausted at harvest in 90 per cent of the cases studied.

QUANTITY OF WATER USED DURING THE GROWING SEASON.

The preceding studies have been concerned with the rate of the use of water. Under the present heading consideration will be given to the total quantity of water used during the growth of the crop under conditions that have actually existed at the points of experimentation during the several years for which data are available.

The total quantity differs in some cases from that reached at the final determination in the immediately preceding study in that the period may be somewhat shorter. That study began with the first determination in the spring, which was usually at seeding time, but may have been earlier. This served a useful purpose in fixing the rate of use, or loss as it might more properly be regarded, from the soil alone before the crop started growth. This period is an uncertain and variable one and likely to be much longer at the southern than at the northern stations. For the present study of the total quantity of water used by the crop it was considered that more comparable data would be obtained by limiting the period to the time the ground was occupied by the crop. The quantity of water used has, therefore, been calculated from a determination of soil moisture made about the time the wheat came up to a determination at harvest. In each case the determination selected as the first was the one made nearest to the time that the wheat came up. Its date varied from about April 15 to May 1 at the southern stations to about May 1 to May 10 at the northern stations.

To obtain the total loss of water during the growth of the crop the loss of water from the soil between the time the crop came up and harvest was determined and to this quantity was added the precipitation for the same period. The loss of water from the soil was determined in the same way as in the previous studies.

This study was made on plat A, which is continuously cropped to wheat.

The quantity of water used from the soil during the growing season, the precipitation for that period, and the total use of water for the growing season are shown in the first three figure columns of Table 3. The next three columns give the yield of grain per acre in bushels, the yield of straw per acre in pounds, and the total yield per acre in pounds.

TABLE 3.—*Quantity of water used by the wheat crop during the growing season, yields of grain and straw, and water ratio on the continuously cropped wheat plat A for the years and stations specified.*

[The column headed "Ratio" shows the number of pounds of water used by the crop per pound of total yield.]

Station and year.	Water used.			Yield.			Ratio.
	From the soil.	Precipitation.	Total.	Grain.	Straw.	Total.	
Assinniboine:	*Inches.*	*Inches.*	*Inches.*	*Bushels.*	*Pounds.*	*Pounds.*	
1917	1.55	2.97	4.52	3.5	590	800	1,279
1919	1.00	3.11	4.11	1.5	200	290	3,208
Huntley:							
1913	4.44	4.12	8.56	16.0	1,740	2,700	718
1914	3.23	6.19	9.42	18.3	1,950	3,050	699
1915	2.00	10.45	12.45	24.5	2,250	3,720	758
Williston:							
1910	1.09	4.22	5.31	1.7	1,040	1,140	1,054
1911	.62	5.09	5.71	2.7	380	540	2,393
1912	2.89	9.08	11.97	25.2	1,860	3,370	804
1913	1.95	7.57	9.52	16.8	2,300	3,310	651
1914	2.19	11.11	13.30	23.8	1,910	3,340	901
1915	2.81	6.57	9.38	19.1	1,150	2,300	923
Dickinson:							
1909	−.97	16.30	15.33	26.8	2,110	3,720	933
1910	4.81	6.06	10.87	17.4	1,410	2,460	1,000
1911	1.32	5.53	6.85	5.7	700	1,040	1,491
1913	4.09	6.69	10.78	13.3	1,310	2,120	1,151
1915	−1.08	12.97	11.89	25.8	1,550	3,100	868
1917	3.12	3.62	6.74	5.5	610	940	1,623
Mandan:							
1915	−1.52	17.70	16.18	30.5	2,120	3,950	927
1916	4.64	7.86	12.50	19.2	2,100	3,250	871
1917	2.12	4.55	6.67	15.3	1,230	2,150	702
1918	3.44	5.97	9.41	12.7	1,390	2,150	991
1919	4.79	2.51	7.30	7.5	700	1,150	1,437
Edgeley:							
1907	2.90	6.60	9.50	4.1	1,950	2,200	977
1908	2.93	7.92	10.85	13.3	2,700	3,500	702
1909	2.51	10.52	13.03	28.3	2,900	4,600	641
1910	3.48	2.93	6.41	4.0	660	900	1,612
1911	4.96	5.54	10.50	.8	900	950	2,502
1912	2.83	12.94	15.77	35.0	3,100	5,200	686
1913	3.33	7.96	11.29	16.3	2,020	3,000	852
1914	2.84	8.20	11.04	11.3	2,970	3,650	685
1915	4.08	11.20	15.28	34.8	3,960	6,050	572
1917	3.58	5.52	9.10	8.3	1,150	1,650	1,248
Hettinger:							
1913	2.23	9.67	11.90	13.8	3,250	4,080	660
1917	2.04	4.67	6.71	5.2	....	....	....
1919	1.30	3.02	4.32	0	0	0	....
Belle Fourche:							
1909	2.53	11.74	14.27	23.8	3,050	4,480	721
1910	3.23	3.03	6.26	2.8	660	830	1,707
1912	2.09	4.31	6.40	0	1,300	1,300	1,114
1913	3.25	5.25	8.50	6.2	1,320	1,690	1,138
1914	1.40	5.25	6.65	4.0	1,180	1,420	1,060
1915	2.35	12.26	14.61	56.5	5,260	8,650	382
1916	2.66	7.34	10.00	10.6	1,360	2,000	1,132
1917	1.86	5.17	7.03	4.4	980	1,250	1,273
Ardmore:							
1915	3.43	15.16	18.59	49.2	3,450	6,400	657
1917	7.17	6.80	13.97	7.5	600	1,050	3,012
1918	2.51	11.11	13.62	27.7	2,090	3,750	822
1919	3.45	6.32	9.77	3.3	950	1,150	1,923
Archer:							
1914	3.71	3.32	7.03	6.8	940	1,350	1,179
1915	3.98	7.57	11.55	26.8	1,930	3,540	739
1916	1.70	7.34	9.04	2.3	680	820	2,495
1917	2.69	8.38	11.07	15.6	1,310	2,250	1,114
Scottsbluff:							
1911	3.57	3.85	7.42	.5	670	700	2,399
1912	3.26	4.81	8.07	8.7	980	1,500	1,218
1913	2.17	6.35	8.52	12.0	1,520	2,240	861
1917	2.81	8.14	10.95	9.2	970	1,520	1,631
1918	1.83	6.31	8.14	3.7	600	820	2,247

TABLE 3.—*Quantity of water used by the wheat crop, etc.*—Continued.

[The column headed "Ratio" shows the number of pounds of water used by the crop per pound of total yield.]

Station and year.	Water used.			Yield.			Ratio.
	From the soil.	Precipitation.	Total.	Grain.	Straw.	Total.	
North Platte:	*Inches.*	*Inches.*	*Inches.*	*Bushels.*	*Pounds.*	*Pounds.*	
1908	1.74	12.96	14.70	22.7	1,920	3,280	1,014
1909	3.24	13.56	16.80	23.0	3,060	4,440	856
1910	3.16	4.59	7.75	6.8	1,000	1,410	1,244
1911	−.08	1.55	1.47	0	0	0	....
1912	5.74	3.32	9.06	12.8	1,790	2,560	801
1914	3.57	5.60	9.17	6.0	1,600	1,960	1,059
1915	−1.66	18.12	16.46	22.7	2,310	3,670	1,015
1916	3.26	6.72	9.98	17.2	2,440	3,470	651
1917	3.35	6.35	9.70	4.2	1,290	1,540	1,426
1919	3.56	10.66	14.22	15.5	3,370	4,300	749
Akron:							
1909	2.21	11.24	13.45	14.3	1,590	2,540	1,199
1911	1.26	3.94	5.20	2.9	480	660	1,783
1912	4.69	11.32	16.01	21.3	2,760	4,040	897
1913	.86	4.51	5.37	4.8	660	950	1,279
1914	4.71	5.50	10.21	22.2	2,530	3,860	599
1915	3.79	11.18	14.97	26.3	1,740	3,320	1,021
1916	2.76	5.04	7.80	9.3	1,140	1,700	1,039
Garden City:							
1909	.45	9.26	9.71	2.1	560	690	3,185
1911	.90	5.35	6.25	0	0	0	....
1912	3.25	6.98	10.23	3.5	1,010	1,220	1,898
1914	5.15	4.12	9.27	1.5	1,290	1,380	1,520
1915	4.20	8.79	12.99	17.5	1,950	3,000	980
1916	2.44	2.24	4.68	0	0	0	....
Dalhart:							
1909	−.36	5.61	5.25	0	0	0	....
1910	2.41	7.05	9.46	0	0	0	....
1911	.86	3.60	4.46	0	0	0	....
1913	.83	4.03	4.86	0	0	0	....
1914	6.23	10.41	16.64	7.8	1,280	1,750	2,152
Dalhart, new field:							
1914	4.23	10.41	14.64	8.4	690	1,200	2,761
1915	2.61	8.08	10.69	4.0	760	1,000	2,420
Amarillo:							
1909	−.97	8.68	7.71	0	0	0	....
1911	2.39	11.01	13.40	7.3	1,070	1,510	2,009
1912	5.79	4.25	10.04	6.3	630	1,010	2,250
1915	7.66	4.17	11.83	12.4	1,800	2,550	1,050
1917	1.81	4.21	6.02	1.7	480	580	2,349
1918	1.11	3.73	4.84	0	0	0	....
Tucumcari:							
1913	1.28	3.91	5.19	0	0	0	....
1914	1.88	9.53	11.41	13.5	1,010	1,820	1,419
1915	6.95	4.80	11.75	5.6	685	1,020	2,607
1916	2.14	1.98	4.12	0	0	0	....

Study of Table 3 shows that, at least so far as the individual stations are concerned, a definite relation exists between the total quantity of water used and the yield of grain, straw, and total weight per acre. This relation is not always consistent, but it must be borne in mind that when crops are subjected to the varying conditions that occur in the field a very close correlation is impossible, and any strong correlation, either positive or negative, is highly significant.

It will be noted from the study of all the stations that high yields are always associated with high water use. A high water use does not necessarily mean a high yield, because the crop may suffer either through poor distribution of rain or through some extreme climatic condition that limits the yield. On the other hand, a high yield necessitates a high use of water. Table 3 contains data on the use of water by 96 wheat crops. Twenty of these crops yielded more than 20 bushels of grain per acre. Only one of these consumed less than 11.5 inches of water. At Akron, Colo., in 1914, a yield of 22.2 bushels was produced with a total water use of 10.21 inches. Plats on all sides of the one studied yielded much less, although their water content at the time of the determinations was nearly the same. An uneven drifting of snow was noted in the spring of this year, and it is possible that portions of this plat, which was in stubble, contained more water at the beginning of the season than the average shown by the soil samples taken.

The larger quantity of water needed at southern stations to produce a crop is clearly shown in this study of the total use of water at the different stations. For example, at Assinniboine, the northernmost station reported, small yields of grain and straw have been obtained from the use of 4.52 and 4.11 inches of water, respectively. At Hettinger, a little farther south, the use of 4.32 inches resulted in a total failure of both grain and straw. At Belle Fourche the use of between 6 and 7 inches of water has resulted in yields of grain ranging from nothing to 4 bushels per acre, and in yields of straw a little higher than those produced by the lesser quantities of water at Assinniboine. At Scottsbluff, Nebr., there has been no total failure, but yields approximating those at Assinniboine have required from 7 to 8 inches of water. At the four stations farthest south, Garden City, Dalhart, Amarillo, and Tucumcari, respectively, total failures of both grain and straw have resulted from the use of quantities of water varying from 4.12 to 9.46 inches. At none of these stations has a yield of grain or straw been secured when less than 6 inches of water has been used. Dalhart shows the poorest adaptation for wheat of any station under study. A yield of grain or straw has not yet been obtained there when less than 10 inches of water has been used.

In a few cases stations have matured a crop on less water than stations north of them, but the figures presented certainly justify the general statement that the quantity of water required to produce a crop of wheat depends upon geographical location and on the Great Plains increases with the distance south except as this is modified by altitude.

In order to obtain a mathematical expression for the relation that exists between the total use of water and the yield of wheat, a series of studies was made in which the total use of water was correlated with the yield of grain, yield of straw, and total weight of crop produced. All of these correlations have been determined by the product-moment method.

In these correlations the average yields for each station and the average water use for each station were used as bases for computing departures. As the quantity of water required to produce a crop is influenced by the location, this method of procedure was necessary in order to eliminate station differences. While this method may not be mathematically correct, it at least gives a result that can not be far wrong. It is the only method practicable, since there are only a few stations where there have been enough years to make individual-station correlations between yield and water use.

The results of the studies are as follows:

The correlation between the total quantity of water used and the yield of grain in bushels is 0.76, with a probable error of ±0.03; the correlation between the total quantity of water used and the yield of straw per acre is 0.69, with a probable error of ±0.03; and the correlation between the total quantity of water used and the total weight of grain and straw is 0.78, with a probable error of ±0.03.

These figures represent a high degree of correlation and point out that the quantity of water used by the crop certainly exerts a preponderant influence on the yield. The fact that the quantity of water used correlates more closely with the total weight of crop produced than it does with the yield of either grain or straw is one that would be expected. It was not anticipated, however, that so close an agreement would exist between the two correlations of the yield of grain and water use and the yield of straw and water use as was shown by this study. It is, of course, necessary that there should be a yield of straw before a yield of grain can be produced, and it was thought probable that the total water use would correlate much more closely with the yield of straw than with the yield of grain or with the total weight. The fact that the three correlations agree very closely strikingly illustrates a statement previously made. This statement was that when affected by drought the wheat crop seems to spend its last energy in producing grain and that if there is any chance at all it will produce some yield of grain. This study indicates that a high yield of straw means a high yield of grain and that a low yield of straw means a low yield of grain. There have been a few cases when exceptionally favorable weather enabled wheat to fill so well that the yield of grain was out of proportion to the yield of straw. These years are very infrequent, and as a whole the yields of grain and of straw are nearly proportional.

It will be noted in Table 3 that in most years the precipitation has greatly exceeded the stored water used from the soil. In nearly every case a high precipitation means a high yield and a low precipitation a low yield. Very little relation is shown between the quantity of stored water used and the yield. There are two reasons why this is the case. In the first place the quantity of water stored in the soil is never enough to produce a good crop. Rainfall is necessary to supplement the soil moisture stored and a large quantity of stored moisture may be associated with a low rainfall, or vice versa. Another reason why the water used from the soil has little relation to the yield lies in the fact that the reduction of the soil water content is dependent upon the sufficiency or insufficiency of the rainfall. In years of heavy precipitation there may be an actual increase in the quantity of stored water in the soil at harvest over the quantity present at seeding time, and in these years a negative correlation between the water used from the soil and the yield is shown. This condition has been observed, but is very infrequent in dry farming.

That the stored water used from the soil actually plays an important part in the yield of the crop was shown by correlating precipitation with yield.

The correlation between the precipitation and the yield of grain was 0.74 ± 0.03, that between the precipitation and the yield of straw was 0.60 ± 0.04, and that between the precipitation and the total yield of grain and straw was 0.73 ± 0.03. These correlations are distinctly lower than those obtained in correlating the total water used and the yield. This makes it certain that though precipitation is the deciding factor in the yield of wheat the quantity of water stored in the soil in many cases is of great value in determining yields.

That the quantity of stored water is of importance in determining yields was shown by another study. Comparison of two plats each year showed that the plat having the greater moisture content about May 1 gave the highest yield in 73 out of 93 cases. Very little correlation existed between the quantity of moisture stored and the yield in different years of the same plat. In other words, it was not possible to prove that 6 inches of stored water in the soil of a plat in one year was any more effectual in producing a good yield than 4 inches of water might be in another year. The precipitation was the deciding factor. However, when two plats were compared for the same year the plat having the greater quantity of stored water present was fairly certain to produce the higher yield. A plat with 6 inches of stored water available was almost certain to produce a higher yield of grain than one having 4 inches of water. While the

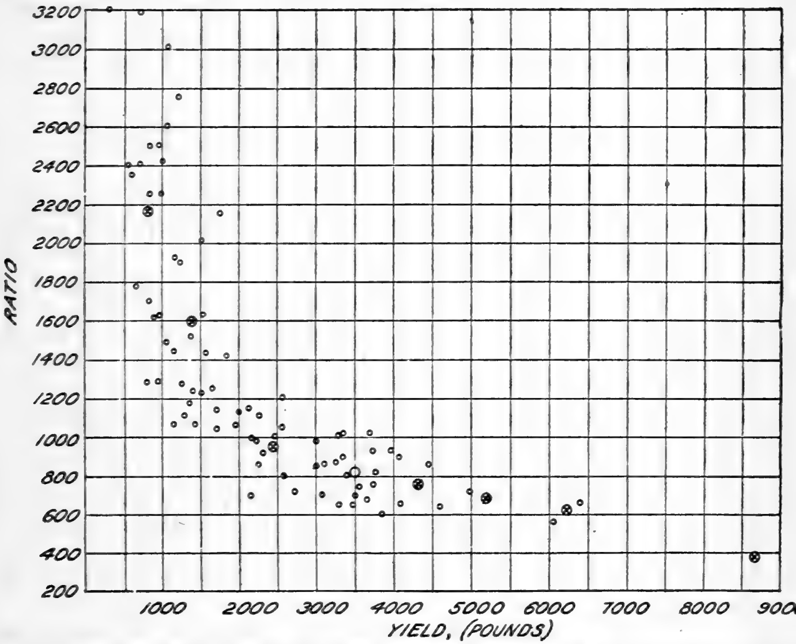

FIG. 8.—Diagram showing the total yield and ratio of pounds of water used to pounds of yield of wheat. The small circles are from data in Table 3. The crosses within circles show the averages by 1,000-pound yield groups, as given in Table 4.

precipitation for the growing season is the deciding factor in wheat production, the quantity of stored water supplementing the rainfall has a decided bearing upon the yield of the crop.

To facilitate comparison of these results with those obtained in controlled studies of water requirement, the ratio of the total water use to the total weight of crop harvested has been calculated and is given in the last column of Table 3. The correlation of the yield with these ratios is shown by dots in Figure 8. The yields of grain and straw in pounds per acre are charted as abscissa and the pounds of water per pound of crop as ordinates. The dots tend to arrange themselves in a curve showing increasing efficiency in the use of water with increasing yield. A reason for this is brought out under the succeeding heading, where it is shown that the consumption of a certain quantity of water is necessary before any yield is produced and that yields increase in proportion to the quantity of water consumed above this. For those yields under 2,000 pounds per acre there is a wide variation in the ratio of water used to yield. This is not unexpected, as such yields do not represent normal growth throughout the season or in many cases for any part of the season. A further cause of divergence is the wide range of conditions from the northern to the southern Plains covered by the data. There is a much closer grouping for the yields above 2,000 pounds per acre, as these are more nearly expressive of the requirements of normal growth.

The yields have been averaged in groups of 1,000 pounds and the corresponding averages of the respective ratios determined. These averages are given in Table 4 and shown in Figure 8 by crosses within circles. No attempt has been made to determine a mathematical expression of the relation evidenced in the data comprising Figure 8.

TABLE 4.—*Ratios and total yields of wheat shown in Table 3 arranged in yield groups of 1,000 pounds and expressed as averages of such groups.*

Yield group.	Number in group.	Yield average.	Ratio average.	Yield group.	Number in group.	Yield average.	Ratio average.
		Pounds.				*Pounds.*	
1 to 1,000 pounds....	15	793	2,165	5,001 to 6,000 pounds	1	5,200	686
1,001 to 2,000 pounds.	26	1,413	1,588	6,001 to 7,000 pounds	2	6,225	615
2,001 to 3,000 pounds.	14	2,444	951	7,001 to 8,000 pounds	0	....	....
3,001 to 4,000 pounds.	18	3,492	814	8,001 to 9,000 pounds	1	8,650	382
4,001 to 5,000 pounds.	6	4,323	754				

While the ratios of water to yield obtained in this work range higher than those obtained in controlled water-requirement studies, such as those reported by Briggs and Shantz,[2] there are sufficient reasons why this should be the case. These field studies include all loss from the soil itself which was excluded in physiological studies. Our yields are relatively lighter, because they do not include an undetermined residue that remains as stubble in the field plats from which the crop is harvested with the self-binder but which was included with the crop by clipping close to the ground in pot cultures. This difference, however, is partly offset by the difference between dry and air-dry material. Maximum efficiency was obtained in pot cultures by constantly maintaining an optimum water content, a condition which is the exception rather than the rule in the field. The results all show that the efficiency of water is increased (the water requirement reduced) by the maintenance of conditions that favor maximum production.

CORRELATION BETWEEN THE USE OF WATER AND THE YIELD AT INDIVIDUAL STATIONS.

A study was made of the correlation between water use and yield at two stations—Edgeley, N. Dak., and North Platte, Nebr. These stations were not selected because of their location but because results for more years were available at these stations than at any of

[2] Briggs, L. J., and Shantz, H. L. The water requirement of plants. U. S. Dept. Agr., Bureau of Plant Industry Bul. 284, 49 pp., 2 fig., 11 pl. 1913.

the others. Even at these stations the number of years was far too small for a reliable correlation to be made, but it was thought that any close relation that existed would be shown.

At Edgeley the results for 10 years on plat A were used. The correlation between the total water used and the yield of grain was 0.90±0.04. Since the other studies made showed little difference in relations between the yield of grain and the total weight, only the one correlation was made. Figure 9 shows the use of water and the yield of the plat each year. In this figure the axis of ordinates represents the water used in inches and the axis of abscissas the yield in bushels.

It can be easily seen that the points established in the different years group themselves along a line that does not have its origin at zero. The use of several inches of water seems to be necessary before

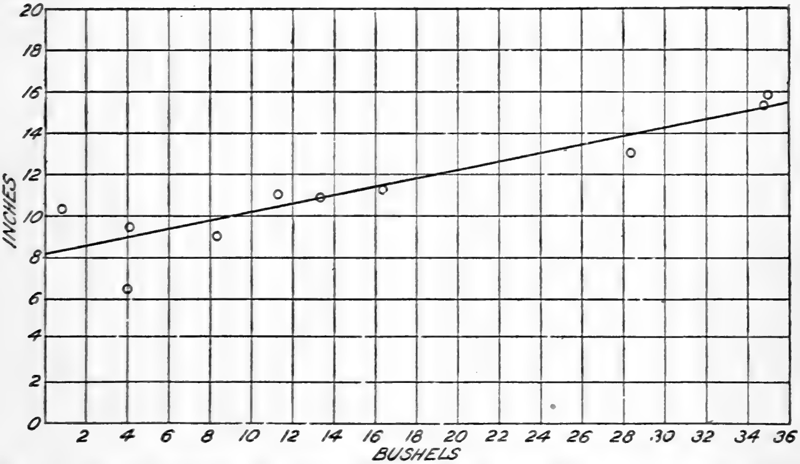

FIG. 9.—Diagram showing the yield of wheat and use of water on plat A at Edgeley, N. Dak., for 10 years. The line is drawn from the linear-regression equation M= 8.16 + 0.20 *e*.

any yield is produced. After enough water to produce a yield has been used there appears to be a linear relation between the water and the yield. The starting point and slope of a line representing the relation of water use and yield were determined by the linear-regression formula:

$$M=\overline{y}-(\sqrt{xy}\ \sigma x \div \sigma y\ \overline{x})+\sqrt{xy}\ \sigma x \div \sigma y\ e.$$

Determined in this way, the resulting linear-regression equation was M equals 8.16 plus 0.20 *e*.

The application of this equation is made as follows: Eight and sixteen one-hundredths inches represents the quantity of water necessary before a yield of grain is secured. Starting from that point, each succeeding increase of 0.20 inch of water should result in an increase of 1 bushel in yield. The line in Figure 9 is the line established by this equation.

It is not contended that 8.16 inches represents the quantity of water necessary before a yield is secured. It is simply a point determined by 10 years' results that indicate the average zero point for these years. It may be either above or below the point that might be established if the results of a larger number of years were available.

The accuracy of the linear-regression equation in expressing the relation between water use and yield at this station is shown in Table 5. This table gives the total water used in inches, the actual yield in bushels per acre, and the yield in bushels per acre as calculated from the water use by the linear-regression equation.

TABLE 5.—*Actual and computed yields of wheat per acre on plat A at Edgeley, N. Dak., in the 10 years stated.*

[The quantity of water used during the growing season as stated in the table forms the basis of the computed yield as calculated by the linear-regression equation $M=8.16+0.20\,e$.]

Year.	Water used.	Yield.		Year.	Water used.	Yield.	
		Actual.	Computed.			Actual.	Computed.
	Inches.	*Bushels.*	*Bushels.*		*Inches.*	*Bushels.*	*Bushels.*
1907	9.50	4.1	6.7	1912	15.77	35.0	38.1
1908	10.85	13.3	13.5	1913	11.29	16.3	15.7
1909	13.03	28.3	24.4	1914	11.04	11.3	14.4
1910	6.41	4.0	0	1915	15.28	34.8	35.6
1911	10.50	.8	11.7	1917	9.10	8.3	4.7

Table 5 shows how accurately in this case the yield of wheat can be determined from the quantity of water used. In only two years, 1910 and 1911, did the computed yield differ greatly from the actual yield. In 1910 a yield of 4 bushels per acre resulted from a use of water considerably below the 8.16 inches theoretically supposed to show a zero yield, and in 1911 a yield of only 0.8 bushel per acre was secured with a total use of 10.5 inches of water. In 1911 hot winds badly damaged the crop and seriously reduced the yield. This represents a year in which climatic conditions overbalanced the quantity of water used in determining the yield. The closeness of the computed yield to the actual yield at this station is probably due in part to the fact that at Edgeley crops feed to a depth of only about 2 feet. The inclusion of only 2 feet of soil no doubt makes the size of the experimental error in the determination of water used at the station small.

At North Platte the data of nine years are available. The correlation between the total water use and yield is 0.85 ± 0.06. The year 1911 is eliminated because of the zero yield. This failure was the result of a use of only 1.47 inches of water. Since there might still have been a failure had more water been used, this year does not establish any definite point, and consequently is not included in making the correlation or in determining the linear-regression equation.

The linear-regression equation determined is $M=6.22+0.40\,e$. Figure 10 shows the points established by water use and yield in the several years, together with the line established by the linear-regression equation.

At North Platte the points established by the water use and yield each year do not lie as close to the line established by the linear-regression equation as those at Edgeley. They do, however, group themselves near enough to the line to indicate that it is not far wrong.

Comparison of Figure 10 with Figure 9 shows some interesting facts. In the first place, the quantity of water calculated as necessary before a yield above zero would be produced is lower at North Platte than at Edgeley in spite of the fact that it is located much farther south. The reason for this is not known, unless it is because of the shallowness of the Edgeley soil, which makes even a short drought seriously reduce the yield.

The point most in evidence is this: Each bushel of yield at Edgeley requires 0.2 inch of water above the minimum, and each bushel yield at North Platte requires 0.4 inch of water above the minimum. A greater mass of data to work from would undoubtedly change the

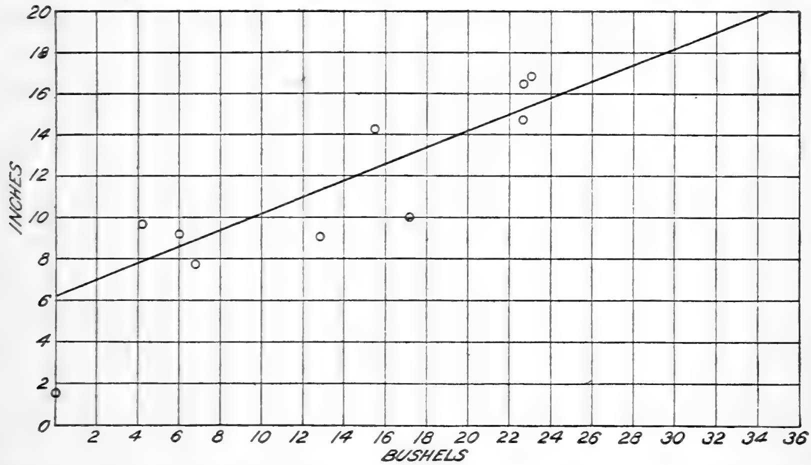

FIG. 10.—Diagram showing the yield of wheat and use of water on plat A at North Platte, Nebr., for 10 years. The line is drawn from the linear-regression equation $M=6.22+0.40\ e$.

slope of these lines somewhat, but it is apparent that the quantity of water necessary to produce each successive bushel of yield is much higher at North Platte than at Edgeley.

The linear-regression formula has been used in computing yields at North Platte. Table 6 gives for plat A at North Platte the water use in inches, the actual yield, and the yield computed by the linear-regression equation.

TABLE 6.—*Actual and computed yields of wheat per acre on plat A at North Platte, Nebr., in the nine years stated.*

[The quantity of water used during the growing season as stated in the table forms the basis of the computed yield as calculated by the linear-regression equation $M=6.22+0.40\ e$.]

Year.	Water used.	Yield.		Year.	Water used.	Yield.	
		Actual.	Computed.			Actual.	Computed.
	Inches.	*Bushels.*	*Bushels.*		*Inches.*	*Bushels.*	*Bushels.*
1908	14.70	22.7	21.2	1915	16.46	22.7	25.6
1909	16.80	23.0	26.5	1916	9.98	17.2	9.4
1910	7.75	6.8	3.8	1917	9.70	4.2	8.7
1912	9.06	12.8	7.1	1919	14.22	15.5	20.0
1914	9.17	6.0	7.4				

It has not been possible to compute yields by the linear-regression formula as closely at North Platte as at Edgeley. This may be because there is a greater experimental error at North Platte than at Edgeley, for it is necessary to include the soil to a depth of 6 feet in the samplings. It is probable, however, that the real reason lies in the fact that North Platte lies in a section not so well adapted to spring wheat as Edgeley. Extreme conditions of temperature that affect wheat adversely are much more common. The lack of the same correlation at North Platte as at Edgeley may and probably does indicate the greater proportional effect that conditions other than the quantity of water used have upon the yield.

GENERAL DISCUSSION OF THE RESULTS.

Physiological studies of the use of soil water by crop plants have determined the use of water by the plants alone. Such studies have been of utmost importance in their contribution to knowledge of the relation between the plant and its environment and between different groups of plants. As such studies are made under conditions that permit the escape of no water except through the plant they measure the maximum possibilities of growth or production from a given quantity of water.

The present study attempts to measure the rate of use and the quantities of water used under the complex of conditions that environ the crop in the field. The data available for study are of such a character that only approximations for given conditions and averages can be arrived at. Indeed, the problem itself is not of a nature to permit exact determinations. If the methods were so refined and the work so replicated as to approach exactness in the results for any given condition, the complex of this condition might never be duplicated. To furnish usable information marking a distinct advance in the knowledge of the subject it is not necessary that determinations of the rate of use or the quantity of water used be exact. It is not of primary importance to know whether a crop uses water at the rate of 0.15 or 0.16 inch per day, but it is important to know whether the rate be 0.15, 0.30, 0.60 inch, or even more per day. The wider variations and greater ranges are of primary agricultural importance, and within such ranges the approximations of rates and quantities arrived at meet the requirements made of them.

Many writers draw erroneous conclusions of the possibilities of a given rainfall by not recognizing the fact that yield is not directly proportional to the quantity of water used. A common presentation is that if a given number of inches of water produces a certain size of crop then double the quantity of water will produce twice that much. The data here presented show that such calculations may be very misleading. An analogy may be drawn from the animal world to illustrate the source of error in such calculations. In feeding live stock it is well recognized that a certain quantity of feed is consumed as a living ration. This quantity alone results in zero growth, and some quantity in addition to this must be supplied if there is to be an increment of growth. The results of the present study show that in the field the consumption of a certain quantity of water is necessary before any yield of grain is produced. Or, stated in another way, the consumption of a certain quantity of water only results in a zero yield. This quantity may vary in the Great Plains from perhaps 4 to 10 inches for wheat, depending upon the season and the locality. Yields have a direct relation to the quantity of water consumed above this minimum. In general, the quantity required as a minimum to any production as well as the quantity above this minimum required for each unit increment of yield increases with change of location from north to south.

The study now made shows the incessant and heavy demand of the crop for water from the time it commences growth until it matures. The yield depends upon this demand being met uninterruptedly. When the water to meet this demand is not available in the soil, the rate of use is necessarily decreased. Such decrease always compromises the yield. Fortunately for the success of agriculture, death of the plant from a shortage of water is a very indefinite and long-delayed occurrence. When field crops suffer distress, they sacrifice vegetative growth to seed production and only cease their efforts after they have exhausted all available water and produced more or less seed. Under conditions where the water supply is normally insufficient or very seldom more than sufficient to meet the possible maximum demands of the crop under full possible development, it is consequently the normal condition for the available soil water to be exhausted when the crop matures. If death of the crop were as sudden a phenomenon as the exhaustion of soil water, the percentage of crop failures would be much higher than it is.

Abbreviated column headings used in the tables and repeated in the text have distinguished between water used from the soil and watter supplied by precipitation. Actually, of course, the entire use is from the soil, and the division is between the quantity already in the soil at the beginning of the period studied and the precipitation by which this quantity is replenished from time to time. The available water in the soil is the reservoir from which the crop draws. Its quantity may fluctuate from time to time as the precipitation is greater or less than the current needs of the crop. So long as it is not depleted to the point of exhaustion the crop appears able to maintain its normal rate of use indicated by an uninterrupted curve. When depletion reaches the critical point marking the division between available and nonavailable water, the rate of use is interrupted and the crop suffers. Precipitation replenishes the supply, and the use of water is resumed. A sufficiently detailed study of this condition would show intermittently low and high rates of use. In the present study these are averaged together for considerable periods of time. The result of this is to show a low rate of use for the period. When such a condition exists early in the season the vegetative growth is either reduced or not developed, and the rate of use when water is available is thus reduced. This is the condition reflected in the curves that show a low rate of use and a small quantity of water used. This is the condition referred to by such statements in the text as "The crop suffered from drought throughout the season."

Maximum possibilities can be realized only when the water supply is at all times adequate to permit use at an uninterrupted rate. The present determinations of this rate show that at the northern stations the wheat crop in the field requires an inch of water every five or six days. At the southern stations the demand rises to an inch of water every four or even every three days.

This rapid consumption of water, considered in connection with the normal rainfall, shows why it is so unusual for water to accumulate during this period and why the water in storage at its beginning is so generally exhausted. To furnish a surplus in addition to meeting the needs of the crop, a rainfall much greater than the normal would be required. Of all the years and stations studied there has been only one year at one station when the water content of the soil at harvest time was higher than at the commencement of rapid growth.

Knowledge of the rate of use and of the quantity of water used is of fundamental importance in forecasting at any time during the period of growth the probable production from the rainfall that is to be expected, or the quantity of water that must be received to realize a given production, or the quantity that will result in very small yields or complete failure.

After certain preliminary investigations and determinations on a soil it is possible to determine quickly, within 24 to 48 hours, the quantity of available water that it contains. Knowing the approximate daily rate of use, it is a simple calculation to determine how long a period of drought can be endured without damage. It is equally easy to calculate the rate at which water must be supplied in order to bring the crop to maturity without damage or to calculate the probable results of any given rate or quantity of rainfall. The probabilities of a given rainfall and the probable range of rainfall for most points are known or may be easily calculated. Precipitation, of course, can not be foretold except as to its probabilities and the limits that are likely to encompass it.

Practical application of such forecasting has been made at a number of the field stations of the Office of Dry-Land Agriculture Investigations by members of the office staff for several years with very gratifying results. Such predictions may even be advanced to the preceding fall, but the longer the period involved the greater is the chance of unfavorable conditions being corrected.

CONCLUSIONS.

The crop has a supply of water measured by the available water in the soil at the time growth begins plus the precipitation during the period of growth. Under dry-farming conditions the two combined are seldom more than sufficient to meet the needs of the crop.

For any period during the growth of the crop the rate at which water is used is practically independent of whether it is obtained by reducing the water content of the soil or is supplied by precipitation during the period.

Water is lost from the soil before seeding or before the crop commences growth, and at an increasingly rapid rate as vegetation develops until, at about the time tillering is completed or just before the crop begins to shoot, it reaches a rate that is maintained practically constant until maturity, provided there is always water available to maintain this rate.

Maximum yields are dependent upon the uninterrupted maintenance of this rate throughout the period of growth. Yields are compromised to the extent that the normal rate is interrupted or reduced. If the water supply is short in the early season, vegetative growth may be reduced and the rate continue low. Interruption and insufficiency of water supply later may result in firing and forced maturity. Failure of the water supply near the end of the growth period may result in forced maturity without marked reduction in the rate of use before maturity. Type curves showing the rate of use for the entire season are presented for representative years and localities.

The daily rate of use of water by a wheat crop is dependent upon climatic environment and the quantity of vegetation that composes it. As climatic environment is determined by geographical location, the rate of use of water by a unit quantity of crop is consequently primarily dependent upon geographical location and secondarily upon seasonal conditions. Within the limits that these overlap, either one or the other may dominate.

The normal rate of the use of water by the wheat crop during its period of rapid growth has been determined to average from about 0.15 to about 0.20 inch per day at stations in the northern Great Plains, the rate depending upon the quantity of crop as influenced by cultural practices. This rate is increased from 50 to 60 per cent at stations in the southern Great Plains.

The total consumption of water by the crop shows a high degree of correlation with the yield produced by it. A high yield necessitates a high use of water. Of 93 crops studied in this connection only one yield of more than 20 bushels per acre was produced from the use of less than 11.5 inches of water. On the other hand, a high use of water may not necessarily result in a high yield, because of failure of the water supply toward the end of the growing season, or because unfavorable conditions other than water supply may intervene to prevent the potential yield from being realized. This lowers the correlation.

The data studied indicate that for any locality within the Great Plains the relation between the yield and the water consumed during the growth of the crop is a linear one, but the origin of the line is not zero. The consumption of a certain minimum quantity of water is necessary before any yield above zero is realized. Each unit increase of water consumed above this minimum appears to result in a unit increment of yield. Both the minimum quantity required and the quantity required for each unit increment of yield depend upon the climatic environment of the season and in the average upon the geographical location. The minimum quantity of water necessary to the harvest of any grain has varied from about 4 inches at the northern stations to as high as 10 inches at the southern stations. Tentative formulas are presented for Edgeley, N. Dak., and North Platte, Nebr., by which to calculate the yield from the water consumption.

The quantity of available water that may be stored in the soil is not sufficient of itself to meet the needs of the crop. The quantity of available water in the soil can be quickly determined at any time. Knowing the daily rate of use and the time necessary to mature the crop or the total quantity of water required for a given production, the probable yield from a given precipitation during the remainder of the growing season or the precipitation necessary to produce a given yield can be calculated. This method of forecasting yields has obvious limitations, but it affords a better basis of approximation than has heretofore been available.

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