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STUDIES ON THE CRITICAL PERIOD FOR APPLYING IRRIGATION WATER TO WHEAT

By D. W. Robertson, Alvin Kezer, John Sjogren and Dwight Koonce

Colorado Agricultural College
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STUDIES ON THE CRITICAL PERIOD FOR APPLYING IRRIGATION WATER TO WHEAT

By D. W. Robertson, Alvin Kezer, John Sjogren[1] and Dwight Koonce

The economic use of irrigation water is a vital problem which confronts the farmer and the scientist in irrigated sections. The problem is becoming more acute since the amount of available water per acre decreases as the area of irrigated land increases. The yield and quality of crops may be affected by irrigating at different growth periods. Therefore, it is important to know the best time to apply water.

The effect on Marquis wheat of irrigating at different growth periods is reported in this paper.

Review of Literature

A rather extensive review of the earlier literature is given in a previous publication by Kezer and Robertson (5)[2]. A brief review of some of the more recent literature is presented. Moliboga (6) reported a study in which Marquis wheat and two-rowed barley were grown in pots under optimum soil-moisture conditions. At different stages the plants were allowed to wilt for several days and the soil again was brought to optimum and kept there until harvest. The following periods were studied: Tillering, shooting, heading and filling. The grain yield suffered most when moisture was withheld at the heading and shooting stages.

Fortier (2) states that "The water requirements of cereals during the stages of growth as determined by tank experiments, agree closely with those of similar crops grown in plots near Twin Falls and near Gooding, Idaho." These seasonal results at the Twin Falls station showed that there should be enough soil moisture at planting time to sprout the seed and maintain a vigorous growth to the jointing stage. "The results also showed that the greatest need for water occurred between the jointing and the soft-dough stages. A heavy irrigation about the time of early jointing produced a large head and supplied sufficient moisture for subsequent growth. When water was withheld during this period and applied after the soft-dough stage, the effect was injurious rather than beneficial. The best yields were obtained by maintaining a fairly constant soil moisture content from the time of seeding until the hard-dough stage was reached."

The results obtained in growing cereals at the Idaho Agricultural Experiment Sub-station at Gooding, likewise showed in-

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[1]Formerly associate in agronomy section of the Colorado Experiment Station.
[2]Numbers in parentheses refer to "Literature Cited."

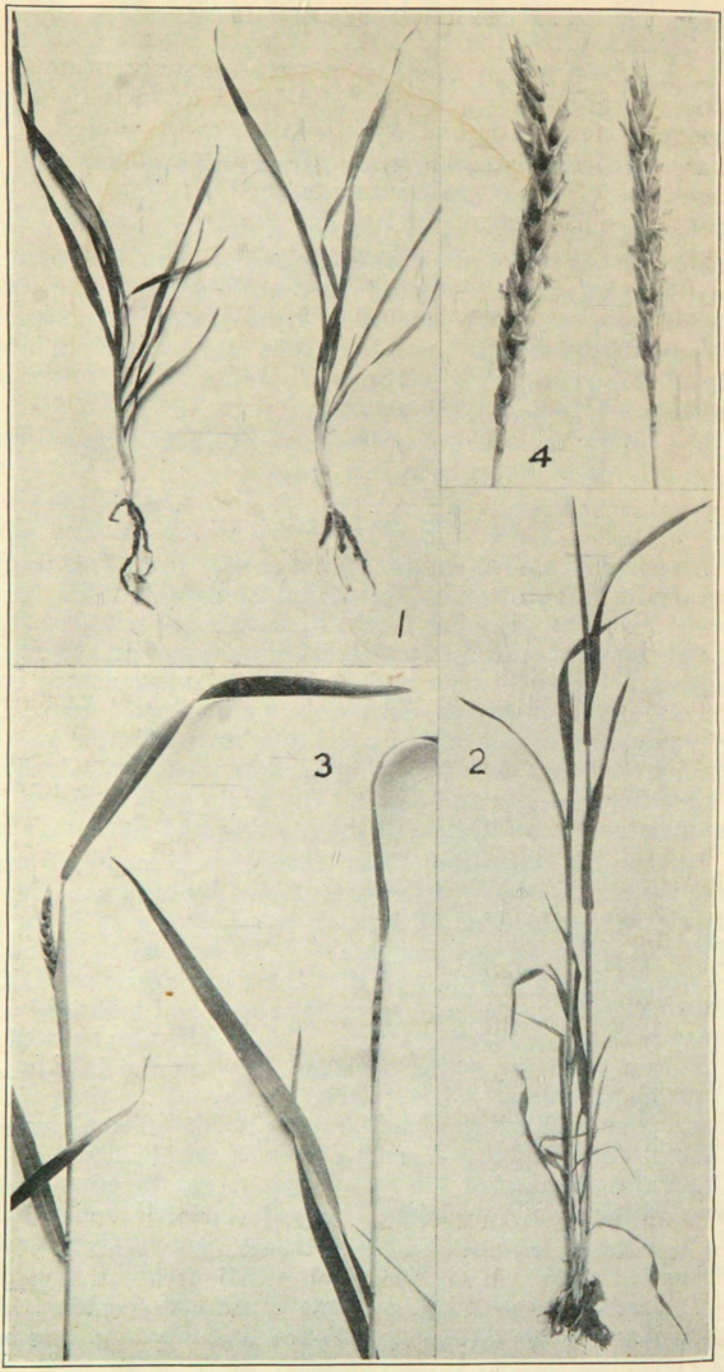

Fig. 1.—The different stages of the wheat growth at which water was applied: 1, Tillering; 2, jointing; 3, heading; and 4, blossoming.

creased yields from an adequate moisture supply prior to the hard-dough stage. Grain yield was reduced when the crop was not irrigated during the critical stages of growth, while the quality was improved. No subsequent waterings could remedy the damage done. In many cases the application of water 3 weeks, or less, before harvest tended to lodge the grain.

Tulaikov (9) found, in field and greenhouse experiments, using Poltavka wheat planted in the spring, that the crop, due to the high soil-moisture loss in the early growth periods, needed abundant soil moisture. The period of greatest moisture demand by grain crops coincided with the period of heading and blooming.

EXPERIMENTAL METHODS

Studies of the critical periods for irrigation in cereal production were started at the Colorado Experiment Station in the spring of 1917. These studies included corn, beans and wheat. The experiment was replanned in 1920 and since that date has been carried in its present form.

SOIL.—The soil of the Colorado Experiment Station, at Fort Collins, is classified as "Fort Collins loam," by the United States Bureau of Chemistry and Soils. The soil of the experimental plats is described by Sweet and Spencer (8), as follows: "The dark-brown or dark, slightly reddish-brown surface layer extends to a depth of 12 to 14 inches, where it gives place abruptly to a lighter-brown material which, when moist, has a slightly pinkish-brown or salmon-colored tint . . . . . . The second layer is slightly heavier in texture and has distributed through it small light-gray spots, from one-eighth to one-half inch in diameter, which effervesce very freely with acid, indicating a high lime content. They are normally most abundant between depths of about 24 and 30 inches. The third layer, beginning at a depth ranging from 30 to 36 inches, is much like the layer above it in the upper part, but is practically free of lime spots. Below this at various depths, but generally within 5 feet of the surface, reddish-brown, purplish-red, and gray very micaceous soil material containing varying amounts of lime, sand, and waterworn gravel is reached."

STAGE IN DEVELOPMENT OF WHEAT WHEN IRRIGATED.—The term, "critical period," as used in this paper, is the stage of plant development at which an irrigation will increase the yield, or when the lack of such an irrigation will decrease the yield. In order to determine which periods are critical, six stages[1] in wheat

[1]In discussing the stages in this publication the above terms will be used to indicate the stages.

development were chosen arbitrarily as follows: Germination, tillering, jointing, heading, blossoming and filling. One irrigation was applied at each stage. Figure 1 shows the development or stages of the plants when water was applied.

The different stages may be defined as follows: Germination is when the seed is sprouted, which is usually not over 6 days after the grain has been planted; tillering is when the seedlings begin to send out shoots, sometimes called the "stooling stage"; jointing is when two joints can be clearly distinguished; heading is when the head is just emerging from the boot; blossoming[1] is when the anthers appear on the head; and filling is when the grain is in the late-dough stage.

Four checks were included in the experiment, as follows: Check 1, distributed irrigation, received the same total amount as put on the critical-period plats, but in 6 irrigations of 1 inch at each critical period. Check 2 received no water. Check 3 received enough water to produce a crop. Check 4 received 1 inch of water at germination.

After 1923, one of the no-irrigation checks was changed and two irrigations of 3 inches each were applied, one at tillering and one at heading. The no-irrigation and keep-growing plats were located at the end of the series after 1923. These acted as guard plats.

PLAN OF EXPERIMENT.—The experiment was carried each year on land which was summer fallowed the previous year. This was found necessary to approach a uniform moisture content in the soil. Summer fallow also was necessary to eliminate volunteer grain and control weeds. Five series of 10 plats were used in 1921, 1922, 1924, 1925, 1926, 1927 and 1929. Four series were used in 1923, and three in 1928. The plats were 1/500 acre in size. These were planted in rows (called series) of 10 plats each. No series had two plats which were treated alike. No two plats receiving the same treatment occupied the same position in any series, except that in 1923, the plats receiving distributed irrigation were adjacent in Series C and D. In 1920 and 1921, two plats receiving the same treatment occurred in Series A and C. In 1924, the two-irrigation plats were opposite in Series A and B and the distributed plats were opposite in Series C and D. The check treatments were alternated in Plats 1 and 10 of all series. The same placing of plats in Series C and D was used from 1925 to 1928, inclusive. In 1927, the first series was C and in 1928, the first series was D. In 1924, the placing of the plats was the same as in Series A, the other series following in rotation. The plan for the 1920 and 1921 experiment is given in

[1]At this stage fertilization is usually complete.

a previous publication by Kezer and Robertson (5), page 87. The 1923 series arrangement is given in Table 1. Table 2 gives the plat arrangement for 1924, 1925, 1926, 1927 and 1928.

In 1923, Plats 3 and 7 were interchanged in Series B. The changed arrangement was used in the later years.

Table 3 gives the arrangement of plats in 1929.

Table 1.—Plat Arrangement of Critical-Period Experiments in 1923.

Plat Number	Series B	Series C	Series D	Series E	Series F
1	No irrigation	Keep growing	No irrigation	Keep growing	No irrigation
2	Germination	Blossoming	Filling	Jointing	Tillering-Heading
3	Tillering-Heading	Distributed	Distributed	Heading	Germination
4	Jointing	Heading	Germination	Filling	Filling
5	Blossoming	Tillering-Heading	Tillering	Distributed	Jointing
6	Tillering	Jointing	Heading	Blossoming	Filling
7	Filling	Germination	Blossoming	Tillering	Distributed
8	Heading	Filling	Jointing	Tillering-Heading	Blossoming
9	Distributed	Tillering	Tillering-Heading	Germination	Heading
10	Keep growing	No irrigation	Keep growing	No irrigation	Keep growing

Table 2.—Plat Arrangement of Critical-Period Experiments 1924, 1925, 1926, 1927 and 1928.

Plat Number	TREATMENTS						
1	Keep growing	No irrigation	Keep growing	No irrigation	Keep growing	No irrigation	Keep growing
2	Heading	Germination	Blossoming	Filling	Jointing	Tillering-Heading	Heading
3	Tillering	Filling	Distributed	Distributed	Heading	Germination	Blossoming
4	Blossoming	Jointing	Heading	Germination	Filling	Tillering	Distributed
5	Filling	Blossoming	Tillering-Heading	Tillering	Distributed	Jointing	Germination
6	Distributed	Tillering	Jointing	Heading	Blossoming	Filling	Tillering-Heading
7	Tillering-Heading	Tillering-Heading	Germination	Blossoming	Tillering	Distributed	Jointing
8	Germination	Heading	Filling	Jointing	Tillering-Heading	Blossoming	Tillering
9	Jointing	Distributed	Tillering	Tillering-Heading	Germination	Heading	Filling
10	No irrigation	Keep growing	No irrigation	Keep growing	No irrigation	Keep growing	No irrigation

Table 3.—Plat Arrangement of Critical-Period Experiments in 1929.

Plat Number	Series D	Series E	Series F	Series G	Series H
1	No irrigation	Keep growing	No irrigation	Keep growing	No irrigation
2	Jointing	Distributed	Tillering	Tillering-Heading	Germination
3	Germination	Heading	Filling	Jointing	Tillering-Heading
4	Tillering-Heading	Filling	Germination	Blossoming	Tillering
5	Distributed	Tillering	Jointing	Heading	Blossoming
6	Filling	Blossoming	Tillering-Heading	Tillering	Distributed
7	Blossoming	Jointing	Heading	Germination	Filling
8	Tillering	Tillering-Heading	Distributed	Distributed	Heading
9	Heading	Germination	Blossoming	Filling	Jointing
10	Keep growing	No irrigation	Keep growing	No irrigation	Keep growing

METHOD OF PLANTING.—Marquis wheat was planted at the rate of 90 pounds per acre. One drill width of 16 rows was planted in each series.

TIME OF PLANTING.—Table 4 gives the dates of planting for the years 1920 to 1929, inclusive.

The planting was made between April 6 and April 18 and the covers were placed on the plats between April 11 and April 24. In some years rain fell during the period from planting to covering. In 1926, more than 1 inch fell, but allowances were made for this when the plats were irrigated.

METHOD OF CONTROLLING MOISTURE.—The plats were covered in order to prevent the influence of precipitation. Posts were set in rows on each side of the series, 1 foot from the edge of the grain. This left a distance of 10 feet from the center of the posts on one side to the center of the posts on the other side of the series. A 4-foot alley was left between adjacent series. In the center of the series, posts were set between the ends of plats. This made three rows of posts to each series. The tops of the posts in each row were set level.

Table 4.—Date of Planting and Covering Critical-Period Plats, Colorado Experiment Station, Fort Collins, for the Years 1920 to 1929, Inclusive.

Year	Date planted	Date covered	Rainfall on plats between date planted and date covered
			inches
1920	May 20	June 2	0.30
1921	April 11	April 13	0.00
1922	April 10	April 14	0.17
1923	April 11	April 16	0.00
1924	April 8	April 18	0.03
1925	April 6	April 11	0.00
1926	April 15	April 24	1.27
1927	April 4	April 9	0.00
1928	April 9	April 14	0.00
1929	April 8	April 16	0.08

The center row of posts was 5 feet above the ground and 2 feet in the ground. A No. 9 wire was stretched across the top of each center row of posts, forming the ridge of a temporary roof. The outer rows of posts were 2 feet 6 inches above the ground and 3 feet in the ground. A No. 9 wire also was stretched across the center of the top of each outer row and formed the eaves of the temporary roof.

The posts in the outer rows were 4 feet 4 inches apart. In the middle rows the posts were 13 feet apart. Every third post in the outer rows was firmly anchored to the opposite post in the adjacent series by cross wires. The outer rows of the outside series were anchored by wires to posts buried 3 feet in the ground. This was found necessary to keep the posts upright when subjected to the extra strain of wet canvas covers. The No. 9 wire stretched across the top of each row of posts was drawn tight and anchored to a post buried 5 feet in the ground and at right angles to the line of pull at each end of the series. Over the wires were stretched heavy (12-oz. duck) canvas covers (11 by 14 feet) with snaps on the long sides which enabled them to be quickly thrown back or stretched at will. Each cover protected an entire plat and lapped slightly over the adjacent plat in the series.

Fig. 2.—End view showing the covers in place.

The canvas covers were kept over the plats at night and during rainy weather. (See Fig. 2.) This prevented any moisture except that purposely added, from reaching the plats. In good weather the covers were folded back so that they were above the space between the ends of the plats. (See Fig. 3.)

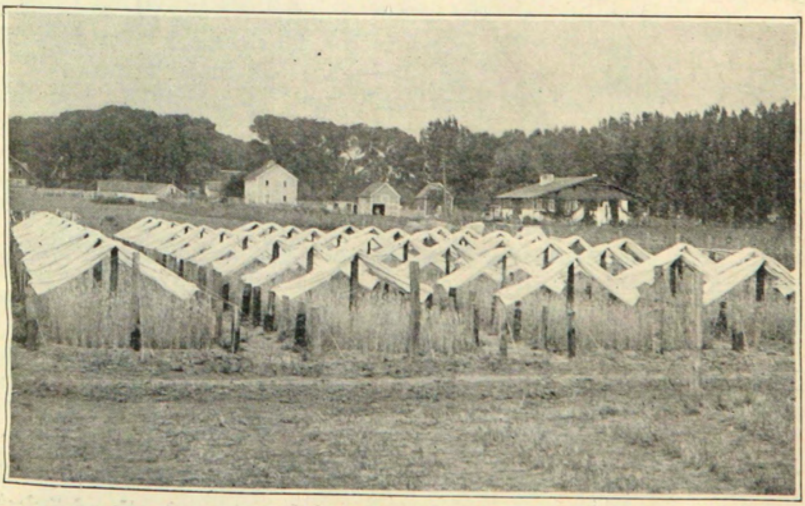

Fig. 3.—End view showing the covers rolled up.

Fig. 4.—End view of series showing the drain which carried the rain from the alleys.

Great care was taken to prevent the loss of water from the plats by other means than evaporation and also to prevent unmeasured water from reaching the covered areas. Each plat was thoroly diked. Banks were set under the edge of the canvas so that any water falling on the canvas-roof covers ran into the alleys between the series. These alleys were 4 feet wide. Ditches having a uniform grade were constructed down the alleys to take care of this water and get it away quickly. (See Fig. 4.) These ditches were connected with a main ditch running across the end of the series which carried the water into a waste ditch. On July 27, 1923, rain in the amount of 2.1 inches fell in 50 minutes. The plats had been covered previously and no moisture from this rainfall penetrated the covered plats. The system of covers and ditches was adequate to take care of this heavy rainfall.

Moisture determinations were made on adjacent summer-fallowed plats in 1922 and 1924 to ascertain whether or not there was sufficient lateral movement of water to modify soil moisture conditions in those plats. In 1922, samples were taken 3 feet from the center of the ditch in which water had been standing 5 hours 50 minutes. Only a slight increase in moisture was found in these samples. Moisture determinations were made 24 hours and 48 hours after the water had receded from the ditch. A similar procedure was followed in 1924, except the water stood 4 hours in the ditch. The samples were taken various distances from the ditch, and the intervals were 48, 72, 120 and 192 hours. These samples were taken to a depth of 5 feet.

No consistent increase was noticed in any of the samples and in many cases there was an actual loss which continued thruout the test. It appears from the data at hand that any difference found was due to a variation in sampling and that lateral movement of water was very slight.

Under soil conditions of the experiment station plats at Fort Collins, water would have to stand over a foot in depth in the alleys for more than 4 hours before any effect on the soil moisture of the plats could be noticed from lateral penetration.

Great care was taken in setting the posts and sinking the anchor posts. All earth removed was returned to the same soil stratum from which it was taken.

SCHEME OF IRRIGATION.—Irrigation water was applied at the rate of 6 acre-inches[1] in the years 1920, 1922 and 1923. In 1921, a slight error was caused by a late snow storm. Sufficient snow drifted onto the plats soon after planting to make a measurable amount of water. Immediately after the snow storm sufficient water was added to each plat to make a 1-inch application on all plats at germination. Each plat, therefore, received 1 inch of water at germination. The later irrigations in 1921 were at the rate of 5 acre-inches, instead of 6, as in the other years. From 1924 to 1929, all plats, except the no-irrigation plats, received 1 inch at germination and 6 inches at the later irrigations. This was found necessary in order to secure a uniform stand. The irrigation plats received a total of 7 inches after

Table 5.—Date of Irrigating Critical-Period Plats from 1921 to 1929, Inclusive.

Year	Germination	Tillering	Jointing	Heading	Blossoming	Filling
1921	April 20	May 23	June 10	June 21	June 27	July 6
1922	April 21	May 16	June 6	June 19	June 26	July 5
1923	April 17	May 16	June 2	June 20	June 29	July 10
1924	April 19	May 16	June 13	June 24	July 2	July 10
1925	April 14	May 12	June 8	June 17	June 25	July 6
1926	April 26	May 19	June 10	June 22	June 30	July 8
1927	April 12	May 11	June 2	June 17	June 27	July 12
1928	April 16	May 16	June 7	June 25	July 3	July 16
1929	April 17	May 15	June 18	June 24	July 3	July 15

[1]Inches of irrigation water refer to inches in depth over the area.

1924, except where otherwise stated. In 1926, a rain of 1.27 inches fell before the covers were placed. A correction for this was made when the plats were irrigated. Table 5 gives the date of irrigation for the different treatments.

METHOD OF IRRIGATION.—The basin method was used thruout this investigation. The plats were diked and sufficient water was added to give the required depth. (See Fig. 5.) The amount of water required for a given depth on the plat was measured thru a water meter in gallons. The variation in temperature ranged from about 42° F. for the early irrigations to 66° F.

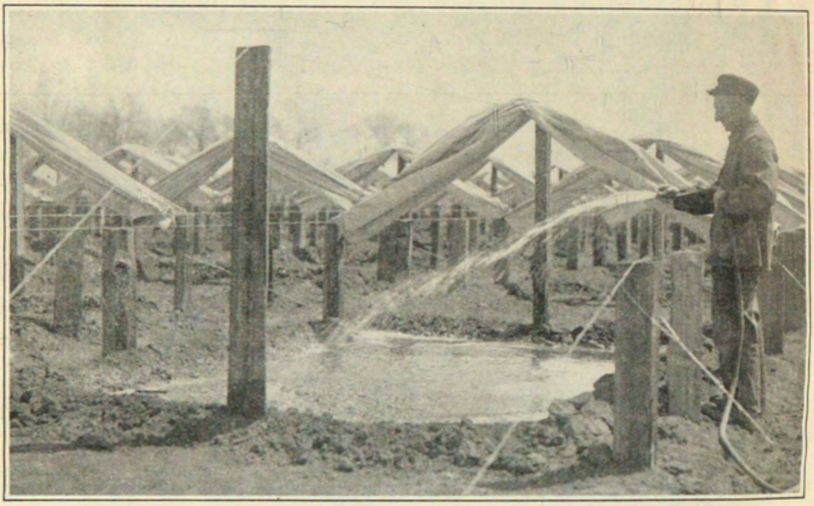

Fig. 5.—Method of irrigating critical-period plats. The water being applied was measured by meters in gallons. The computed numbers of gallons to make the irrigation depth required was used in each case.

Table 6.—Temperature of Irrigation Water.

Year	Germination	Tillering	Jointing	Heading	Blossoming	Filling
	°F.	°F.	°F.	°F.	°F.	°F.
1922	44	50	50	56	60	61
1923	49	48	....	62	60	61
1924	43	50	58	58	60	62
1925	48	54	54	59	59	61
1926	47	51	55	55	59	59
1927	46	50	54	60	60	60
1928	43	52	57	54	60	63
1929	42	50	61	64	66	66

for the late irrigations, as shown in Table 6. The average temperatures for the different treatments were as follows: Germination, 45.2° F.; tillering, 50.6° F.; jointing, 55.6° F.; heading, 58.5° F.; blossoming, 60.5° F.; and filling, 61.6° F.

SOURCE OF IRRIGATION WATER.—The water used for irrigation was the same as that furnished by the city of Fort Collins for domestic use. It was taken from the Cache la Poudre River above the point where the North Fork flows into the main river.

Headden (4) says, "The Cache la Poudre River flows for the first fifty miles of its course over boulders of schist and granite and then over gravel and sand of the same character." The domestic water used in Fort Collins comes from this portion of the river. There is a slight variation in the solids carried in the water. In the early part of the season the total solids carried by the Fort Collins tap water are lower than later in the season when the river is low. The irrigating was done in the early part of the season during the flood-water stage. Consequently, there were less solids than would be found if the plats were irrigated in August and September.

It is conceded that chemical analyses of the irrigation water would have been of value. However, it was not considered of sufficient importance in the present experiment to justify the increased expense.

AMOUNT OF WATER APPLIED.—Water in the amount of 1 acre-inch applied to 1/500 acre of land equals 54 3/10 gallons of water. Larger quantities of water were applied in multiples of this amount.

METHOD OF HARVESTING CROP.—The grain was cut 1 inch above the ground with lawn shears. The area of the plats harvested was 1/871 acre. The 10 center rows were harvested after 3 border rows on each side and 1 foot from each end had been discarded to eliminate possible border effect. The cut grain was tied in a sheaf and carefully wrapped in cloth to protect the heads, leafy material and straw. These sheaves were shocked under cover and allowed to cure for 3 weeks or more. The sheaves were then weighed and the grain threshed. The difference between the cleaned grain weight and the total grain and straw weight was used as the straw yield.

EXPERIMENTAL RESULTS

DATE OF RIPENING.—The data on ripening dates are presented in Table 7. The distributed plat ripened later than the other plats 7 out of 8 years. This plat received a 1-inch irrigation at each stage of growth, except at germination, and had sufficient moisture to develop thru the entire season. The plats receiving 6 inches of water at filling (dough stage) evidently received the water too late to be utilized fully. The plants usually dried rather than ripened normally. However, the data indicate that if water had been applied at the heading and blossoming periods the later applications of irrigation water retarded ripening somewhat.

Table 7.—Date of Ripening of Wheat Irrigated at Different Stages*.

Treatment	1921	1922	1923	1925	1926	1927	1928	1929
Germination	July 28	July 28	Aug. 2	July 23	Aug. 4	July 31	Aug. 8	July 30
Tillering	July 29	July 28	Aug. 2	July 22	Aug. 4	July 31	Aug. 8	Aug. 1
Jointing	July 28	July 29	Aug. 2	July 23	Aug. 4	Aug. 2	Aug. 8	Aug. 1
Heading	July 28	Aug. 1	Aug. 2	July 24	Aug. 4	Aug. 1	Aug. 8	Aug. 1
Blossoming	July 28	Aug. 1	Aug. 2	July 25	Aug. 4	Aug. 2	Aug. 9	Aug. 1
Filling	July 28	July 28	Aug. 2	July 24	Aug. 4	July 31	Aug. 8	July 30
Distributed	July 30	Aug. 1	Few days later	July 26	Aug. 6	Aug. 3	Aug. 9	Aug. 2
Two irrigations	....	....	....	July 26	Aug. 6	Aug. 4	Aug. 9	Aug 1
No irrigations	July 28	July 28	Few days later	July 22	Aug. 4	July 31	Aug. 8	July 29
Keep growing	July 28	July 28	Few days later	July 22	Aug. 4	July 31	Aug. 8	July 29

*In 1924, all plats ripened about the same time. The wheat did not ripen normally, but dry weather dried the grain, causing it to ripen uniformly. No effect of late irrigation was noted. In 1927, the filling, no-irrigation and keep-growing plats dried.

YIELDS OF GRAIN.—The yields of grain are given in Table 8. In comparing the yields, the probable error of a difference[1] was used to determine if the differences were significant. In discussing the yields, the single-application plats will be considered separately from the distributed and two-irrigation plats. The highest-yielding plats receiving a single irrigation of 6 inches are the jointing plats. These yielded 67 pounds more than the heading

[1]Hayes, H. K., and Garber, R. J. Breeding Crop Plants. P.E. of a difference = $\sqrt{a^2 + b^2 - 2 r_{ab} \times a \times b}$ where a and b represent the probable error of the separate values being compared and r is the correlation between separate measurements of the quantities being compared.

Table 8.—Summary of Grain Yields on the Covered Plats for the 9-Year Period, 1921 to 1929, Inclusive.

Years grown	Germination	Tillering	Jointing	Heading	Blossoming	Filling	Distributed	Tillering and heading
	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per.A.
1921	511 ± 37	432 ± 31	526 ± 38	478 ± 35	430 ± 31	321 ± 23	637 ± 46	....
1922	655 ± 21	714 ± 23	780 ± 25	776 ± 25	637 ± 21	518 ± 17	1102 ± 36	....
1923	914 ± 32	952 ± 33	1137 ± 40	1114 ± 39	947 ± 33	753 ± 26	1500 ± 52	....
1924	952 ± 28	1116 ± 33	1217 ± 36	1219 ± 36	1189 ± 35	1125 ± 34	1615 ± 48	1275 ± 38
1925	470 ± 16	493 ± 17	559 ± 19	555 ± 19	524 ± 18	538 ± 18	874 ± 29	726 ± 24
1926	557 ± 29	803 ± 41	950 ± 49	774 ± 40	645 ± 33	601 ± 31	985 ± 50	964 ± 49
1927	783 ± 20	1089 ± 28	1275 ± 32	1043 ± 26	1035 ± 26	812 ± 21	1419 ± 36	1273 ± 32
1928	566 ± 20	657 ± 23	714 ± 25	639 ± 23	614 ± 22	511 ± 18	935 ± 33	773 ± 28
1929	758 ± 65	887 ± 76	945 ± 81	895 ± 76	839 ± 72	733 ± 63	1143 ± 98	933 ± 80
Average	685 ± 11	794 ± 13	900 ± 15	833 ± 13	762 ± 12	657 ± 11	1135 ± 18	992 ± 16

Table 9.—Summary of Straw Yields on the Covered Plats for the 9-Year Period, 1921 to 1929, Inclusive.

Years grown	Germination	Tillering	Jointing	Heading	Blossoming	Filling	Distributed	Tillering and heading
	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per.A.
1921	1592 ± 112	1429 ± 101	1323 ± 93	1175 ± 83	995 ± 70	835 ± 59	1432 ± 101	....
1922	1156 ± 44	1434 ± 55	1452 ± 55	1308 ± 50	1054 ± 40	954 ± 36	1805 ± 69	....
1923	1870 ± 70	2143 ± 80	2358 ± 88	2124 ± 80	1765 ± 66	1528 ± 57	3018 ± 113	....
1924	1805 ± 60	2339 ± 78	2341 ± 78	2195 ± 74	2016 ± 68	1984 ± 66	3042 ± 102	2744 ± 92
1925	1127 ± 35	1262 ± 39	1248 ± 39	1087 ± 34	1093 ± 34	983 ± 31	1644 ± 51	1459 ± 46
1926	1018 ± 34	1536 ± 52	1770 ± 59	1502 ± 50	1294 ± 44	1329 ± 45	1955 ± 66	1807 ± 61
1927	1298 ± 42	2193 ± 70	2341 ± 75	1939 ± 62	1889 ± 61	1567 ± 50	2608 ± 84	2556 ± 82
1928	1413 ± 35	1697 ± 42	1828 ± 46	1623 ± 40	1534 ± 38	1346 ± 34	2181 ± 54	1949 ± 49
1929	1836 ± 82	2035 ± 91	2510 ± 113	2020 ± 91	1734 ± 78	1688 ± 76	2560 ± 115	2458 ± 110
Average	1457 ± 20	1785 ± 24	1908 ± 26	1664 ± 22	1486 ± 20	1357 ± 18	2249 ± 30	2162 ± 29

plats which ranked next in yield. The difference of 67 pounds is 14.3 times the probable error of a difference. The heading plats outyielded the tillering plats by 39 pounds. The difference in yield is 11.3 times greater than the probable error of a difference and may be considered significant.

The next highest in yield are the blossoming plats, which yielded 32 pounds less than the tillering plats. This difference is significant in the light of the probable error of a difference. The blossoming plats outyielded the germination plats by 77 pounds. Again the difference is significant. The germination plats outyielded the plats irrigated at filling by 28 pounds. This difference is 3.99 times greater than the probable error of a difference, indicating that the germination plats outyielded the plats irrigated at heading. The data show that the plats yielded in the following order: Jointing, heading, tillering, blossoming, germination, filling.

The plats which received a distributed irrigation, 1 inch at each of the above stages, outyielded all other treatments. The two-irrigation plats which received 3 inches at tillering and 3 inches at heading gave the next highest yield. The distributed irrigation, while keeping a supply of moisture available during the growing season, is impracticable from the farmer's standpoint.

YIELDS OF STRAW.—The straw yield will be treated similarly to the grain yields, as shown in Table 9. The plats yielded in the following order: Jointing, tillering, heading, blossoming, germination and filling. The difference in yield between the jointing and tillering plats is 123 pounds. The probable error of a difference is 8.37 pounds. The tillering plats outyielded the heading plats by 121 pounds, which is significantly greater than the probable error of a difference. The difference in yield between the heading and blossoming plats is 178 pounds, which is 28.9 times the probable error of a difference, indicating a significant difference in favor of the heading plats. The difference in yield between the blossoming and germination plats is 29 pounds. The difference divided by the probable error is 1.6, indicating that the difference between the blossoming and germination plats is not significant. The germination plats outyielded the filling plats by 100 pounds. The difference is 5.62 times the probable error of a difference and may be considered significant. The distributed and two-irrigation plats again outyielded all other treatments. The late and early irrigations, germination and filling gave low yields of both straw and grain.

The ratio of grain to straw varies slightly. It decreased with the delay in irrigation but increased slightly for the last irrigation. The ratio of grain to straw for Marquis wheat in these studies was about 1:2.

HEIGHT OF STRAW.—The height of the straw is shown in Table 10. For the plats receiving a single irrigation of 6 inches, the ranking of the plats for height was slightly different than for yield of straw in pounds. The following sequence was obtained: Jointing, tillering, heading, germination, blossoming and filling. The length of straw of the germination plats increased to a greater extent than that of the blossoming and filling plats. However, the difference in yield between the germination and blossoming plats was not significant. The data indicate that the later the irrigations after jointing the shorter the straw.

Table 10.—Height of Straw for Wheat Irrigated at Different Stages Under Cover.

Year	Germination	Tillering	Jointing	Heading	Blossoming	Filling	Distributed	Tillering and heading
	in.	in.	in.	in.	in.	in.	in.	in.
1921	33	30	30	29	26	24	30	....
1922	26	29	30	28	24	23	34	....
1923	33	35	37	35	31	31	41	38
1924	32	38	38	36	34	34	40	39
1925	26	27	28	27	24	25	28	31
1926	28	32	33	28	29	27	34	33
1927	33	39	41	35	36	34	42	42
1928	34	36	37	36	32	32	40	40
1929	34	30	34	35	34	36	32	33
Average	31	33	34	32	30	30	36	37

WEIGHT PER 1,000 KERNELS.—The weight per 1,000 kernels was determined on a representative sample from the different treatments. Table 11 gives the data obtained on weight per 1,000 kernels. The heaviest kernels were obtained in the heading plats. The different treatments are ranked as follows: Heading, blossoming, jointing, filling, tillering and germination. The heading and blossoming kernels are well filled. The plats irrigated at jointing have long kernels but they are not as well filled as the heading or blossoming kernels. The kernels from the filling plats are plump and well filled, but small. The kernels from the early irrigated plats are poorly filled, somewhat shrivelled. The kernels from the distributed and two-irrigation plats are plump but

Table 11.—Weight per 1000 Kernels for the Differently Treated Plats.

Year	Germination	Tillering	Jointing	Heading	Blossoming	Filling	Distributed	Tillering and heading
	gms.	gms.	gms.	gms.	gms.	gms.	gms.	gms.
1921	21.28	22.58	21.98	24.82	25.46	24.03	25.43	....
1922	20.64	20.65	21.50	25.54	25.67	21.83	26.89	....
1923	23.59	23.20	25.36	29.53	28.32	24.27	27.32	....
1924	25.16	23.40	25.36	28.95	28.76	27.43	24.88	29.15
1925	18.11	19.28	20.09	23.97	25.04	23.81	23.80	25.59
1926	24.24	26.61	28.31	29.06	24.84	24.68	27.97	30.53
1927	27.63	28.85	30.10	31.42	30.11	25.61	32.53	33.00
1928	18.70	18.40	18.75	19.34	19.82	18.31	20.72	20.18
1929	23.82	23.61	23.13	22.63	22.60	23.44	22.39	22.94
Average	22.57	22.95	23.84	26.14	25.62	23.71	25.77	26.90

Table 12.—Weight per Measured Bushel for the Differently Treated Plats.

Year	Number of plats	Germination	Tillering	Jointing	Heading	Blossoming	Filling	Distributed	Tillering and heading
		lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
1921	5	58.5	58.5	58.3	60.2	61.1	60.7	60.4	......
1922	5	60.6	60.2	59.9	62.5	62.6	61.8	62.0	......
1923	4	59.9	59.3	59.8	61.8	62.1	60.3	61.0	......
1924	5	59.7	59.3	59.2	61.2	61.7	61.0	60.9	59.4
1925	5	55.6	56.8	55.7	59.7	61.1	60.9	59.5	59.7
1926	5	60.2	60.8	61.5	61.3	61.2	60.7	60.9	62.1
1927	5	61.5	61.8	61.8	62.2	62.3	60.6	62.1	62.2
1928	3	56.3	56.6	55.8	56.5	57.0	56.1	57.0	57.2
1929	5	57.5	58.2	57.5	57.0	58.0	57.8	57.9	58.6
Average		58.9	59.1	58.8	60.3	60.8	60.0	60.2	59.9

not as heavy as those from the plats irrigated at heading. The following differences in weight per 1,000 kernels were obtained for the plats receiving single irrigations: Heading, 26.14 grams; blossoming, 25.62 grams; jointing, 23.84 grams; filling, 23.71 grams; tillering, 22.95 grams; and germination, 22.57 grams.

WEIGHT PER MEASURED BUSHEL.—The weight per measured bushel is given in Table 12. The plats receiving a single irrigation may be ranked as follows: Blossoming, 60.8; heading, 60.3; filling, 60.0; tillering, 59.1; germination, 58.9; and jointing, 58.8. The characteristics of the kernels mentioned in the previous paragraph evidently had a similar effect on bushel weight.

SOIL MOISTURE

Soil-moisture samples were taken at planting (April) to determine whether the moisture condition of the plats was uniform. Three sets of samples were taken in each series, one at each end and one in the center between Plats 5 and 6. These samples were taken in 1-foot sections to a depth of 5 feet, except the first foot, which was taken in 6-inch sections. Samples also were taken in the growing season and as soon after harvest as possible. The last samples were taken from each plat in each series.

Table 13 shows the soil moisture at the beginning of the season. When this is compared with the table showing the moisture at the end of the season, it is apparent that very little moisture had been taken from the fifth foot. About 1 percent had been removed from the fourth foot. Varying amounts have been removed from the other depths.

Table 13.—Spring Soil Moisture in Critical-Period Plats from 1921 to 1929, Inclusive.

Year	1-6 in.	6-12 in	12-24 in.	24-36 in.	36-48 in.	48-60 in.
	pct.	pct.	pct.	pct.	pct.	pct.
1921	10.093	13.832	15.165	13.625	12.389	10.933
1922	14.827*		15.698	13.976	12.017	11.665
1923	16.109	17.187	17.367	15.586	13.600	12.907
1924	15.077*		18.705	17.676	15.175	14.962
1925	10.789	15.974	17.060	15.329	13.752	13.755
1926	16.781	18.614	18.516	17.486	15.742	15.201
1927	14.874	18.409	19.440	17.930	14.820	14.550
1928	14.254	17.129	17.576	16.246	14.178	13.210
1929	15.749	18.290	18.514	16.156	13.670	13.662
Average	14.090	17.062	17.560	16.001	13.927	13.427

*Soil moisture in the first 12 inches was not used in determining the averages.

MOISTURE USED DURING THE SEASON

In 1926, the weight per cubic foot of soil used in the critical-period studies was determined in the following plats: Series G, Nos. 2, 3, 5, 8 and 10. The series was used for root penetration studies and a trench was made to a depth of 5 feet the entire length of the series. The volume weight of soil was determined by using a thin brass cylinder 3 15/16 inches in diameter and 6 inches deep. The volume of the cylinder was 72.6 cubic inches. The cylinder was driven into the soil and the surrounding soil removed. A thin sharp plate was used in cutting the soil column even with the bottom of the cylinder. The sample then was weighed and the moisture content and the weight per cubic foot of soil determined. Samples were taken to a depth of 5 feet in 6-inch sections. These data are shown in Table 14.

While there is some variability between the plats, the probable errors as determined by the deviation-from-the-mean method are about 1 percent, the greatest variability being found in Plat 8 at the 4-foot depth.

Table 14.—Weight of Soil per Cubic Foot.

Depth	PLATS					Average
	No. 2	No. 3	No. 5	No. 8	No. 10	
in.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
0 to 6	84.68	85.81	88.86	83.46	81.78	84.92 ± 0.78
6 to 12	89.99	87.87	92.03	93.71	91.10	90.94 ± 0.84
12 to 24	87.18	84.47	88.85	88.92	94.43	88.77 ± 0.82
24 to 36	84.02	83.54	84.99	83.83	84.93	84.26 ± 0.78
36 to 48	84.20	84.01	83.66	76.26	86.58	82.94 ± 0.76
48 to 60	84.27	82.58	83.69	85.17	82.29	83.74 ± 0.77

Table 13 was used in calculating the moisture used by the differently treated plats showing the average moisture content at the beginning of the season. The moisture in the 5-foot section of soil was calculated in acre-feet. (Table 15, column 2.) The water added also was calculated in acre-feet, which amounted to 0.5833 acre-feet per plat. The average soil moisture at the end of the season for each treatment was calculated in acre-feet. The amount used or lost during the season was taken as the difference between the total amount and that left in the soil at the end of the season. This amount, calculated as a fraction of an acre-foot, was divided by the total yield per acre, which gave the pounds of water per pound of air-dry matter produced. Figure 6 shows the amount of water per pound of air-dry matter used by the differently treated plats.

Table 15.—The Use of Water Applied to Crops at Different Stages.

Stage of irrigation	Water in 5-foot section soil in spring	Water added by irrigation	Total water	Water in 5-foot section soil in fall	Water used or lost by evaporation	Grain yield	Straw yield	Total yield	Pounds water per pound total dry matter
	acre-feet	acre-feet	acre-feet	acre-feet	acre-feet	lbs. per A.	lbs. per A.	lbs. per A.	
Germination	1.0496	0.5833	1.6329	0.7133	0.9196	685	1457	2142	1169
Tillering	1.0496	0.5833	1.6329	0.7078	0.9251	794	1785	2579	977
Jointing	1.0496	0.5833	1.6329	0.7687	0.8642	900	1908	2808	838
Heading	1.0496	0.5833	1.6329	0.8365	0.7964	833	1664	2497	868
Blossoming	1.0496	0.5833	1.6329	0.8866	0.7463	762	1486	2248	904
Filling	1.0496	0.5833	1.6329	0.9733	0.6596	657	1357	2014	892
Distributed	1.0496	0.5833	1.6329	0.7343	0.8986	1135	2249	3384	723

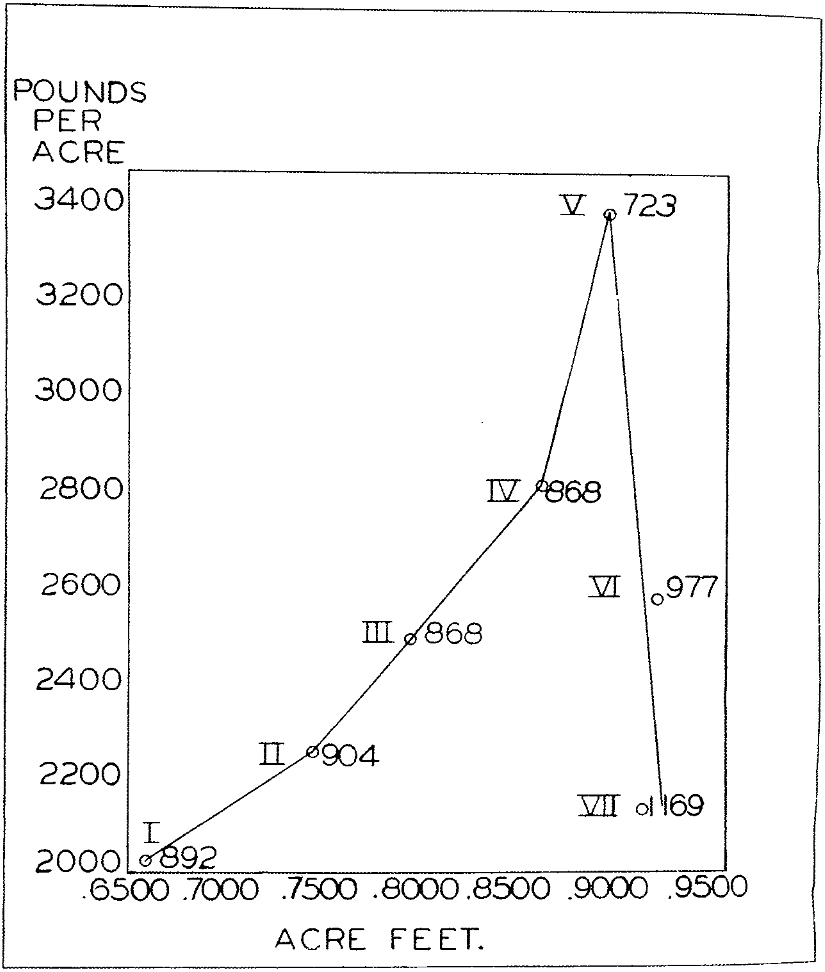

Fig. 6.—Amount of water per pound of air-dry matter used by the differently treated plats: I, Germination; II, jointing; III, tillering; IV, heading; V, distributed; VI, blossoming; VII, filling. Numbers on graph refer to pounds of water per pound of air-dry matter.

The total yield includes the straw and grain weighed on an air-dry basis. The straw was cut 1 inch above the ground. The fact that an inch of the straw was not harvested, will reduce the yield slightly. However, this should be more than counterbalanced by the moisture left in the straw and grain. Under Colorado conditions, this is low.

The last column of Table 13 shows that the plats receiving the earlier irrigations made less efficient use of the water applied than those receiving the later irrigations. The jointing plats made the most efficient use of the water applied in the single-irrigation treatments. The distributed plats receiving small amounts at frequent intervals made the most efficient use of the water applied. The late irrigations leave more moisture in the soil than the earlier applications. Therefore, the crop uses less of the moisture applied but the unused moisture is retained and used by the crop grown the following year. The most efficient use of water from a single irrigation is obtained by applying the water between the jointing and heading stages.

RESIDUAL EFFECT

In an earlier paper (7), the authors discuss the residual effect of previous irrigations on the succeeding crop of Marquis wheat. The data for the period of the study, 1921 to 1925, inclusive, showed a marked carryover on the later-irrigated plats. This was shown by increased grain and straw yields. The ranking of the plats in grain yield from highest to lowest was as follows: Filling, heading, blossoming, jointing, tillering and germination. The ranking of the plats for straw yield was the same as for grain yield.

METHOD OF CONDUCTING EXPERIMENT

The plats which were treated were sown again to Marquis wheat the following year. No irrigation water was applied from the time the previous year's plats were treated until after harvest of the second year's crop. Thus, any moisture used by the second crop was obtained either from moisture left in the soil by the previous crop or from the precipitation falling from the time the covers were removed until after the harvesting of the second crop. A square yard from each plat was harvested and the yields determined from this material.

DISCUSSION OF YIELDS.—The grain yields of the differently treated residual plats are given in Table 16.

The relationship of the plats is practically the same as that reported previously. The difference between the plats receiving an irrigation at filling the previous year and one receiving an irrigation at blossoming is 107 pounds. The difference divided by the probable error of a difference[1] is 7.42, indicating that there is a significant carryover effect from late irrigations. There is very little difference between the heading and blossoming plats. However, there is a difference of 138 pounds between the jointing and heading plats. The difference is in favor of the heading plats. The difference is significant again, being 10.28 times greater than the probable error of a difference.

[1]Probable error of a difference = $\sqrt{a^2 + b^2 - 2r_{ab} \times a \times b}$ where a and b represent the probable error of the separate values being compared and r is the correlation between separate measurements of the quantities being compared.

Table 16.—Yield of Grain on the Residual Plats for the 9-Year Period, 1922 to 1930, Inclusive.

Year	Germination	Tillering	Jointing	Heading	Blossoming	Filling	Distributed	Tillering and heading
	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.
1922	916 ± 38	986 ± 41	1112 ± 46	1417 ± 58	1152 ± 47	1338 ± 55	988 ± 41	....
1923	1603 ± 82	1741 ± 89	1744 ± 89	2158 ± 110	2198 ± 112	2367 ± 121	2042 ± 104	....
1924	1592 ± 43	1586 ± 42	1724 ± 46	1729 ± 46	1586 ± 42	1797 ± 48	1583 ± 42	....
1925	52 ± 16	15 ± 5	87 ± 27	431 ± 133	499 ± 154	949 ± 292	47 ± 14	20 ± 6
1926	2027 ± 58	2123 ± 60	2049 ± 58	1963 ± 56	2006 ± 57	2123 ± 60	1931 ± 55	1963 ± 56
1927	1910 ± 53	1814 ± 50	1995 ± 55	1942 ± 54	2102 ± 58	1995 ± 55	1739 ± 48	1825 ± 51
1928	2860 ± 70	2742 ± 67	3084 ± 76	3030 ± 74	3137 ± 77	3148 ± 77	2860 ± 70	2860 ± 70
1929	1483 ± 59	1323 ± 53	1142 ± 46	1270 ± 51	1483 ± 59	1387 ± 55	1419 ± 57	1408 ± 56
1930	1536 ± 51	1504 ± 50	1686 ± 56	1931 ± 64	1995 ± 66	2017 ± 67	1665 ± 55	1665 ± 55
Average	1553 ± 56	1537 ± 55	1625 ± 59	1763 ± 63	1795 ± 65	1902 ± 68	1586 ± 57	1624 ± 58

Table 17.—Yield of Straw on the Residual Plats for the 9-Year Period, 1922 to 1930, Inclusive.

Year	Germination	Tillering	Jointing	Heading	Blossoming	Filling	Distributed	Tillering and heading
	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.	lbs. per A.
1922	1268 ± 46	1447 ± 52	1626 ± 59	1989 ± 72	1688 ± 61	2040 ± 73	1362 ± 49	....
1923	1925 ± 121	2469 ± 156	2204 ± 139	2939 ± 185	2928 ± 184	3015 ± 190	2687 ± 169	....
1924	2834 ± 74	2851 ± 74	3094 ± 80	3073 ± 80	2922 ± 76	3216 ± 84	2746 ± 71	....
1925	84 ± 20	54 ± 13	145 ± 35	570 ± 137	670 ± 162	1208* ± 291	68 ± 16	65 ± 16
1926	3532 ± 105	3564 ± 106	3532 ± 105	3329 ± 99	3468 ± 103	3681 ± 110	3244 ± 97	3267 ± 98
1927	3126 ± 108	2881 ± 99	3446 ± 119	3959 ± 137	3872 ± 134	3735 ± 129	2817 ± 97	3041 ± 105
1928	4033 ± 116	4023 ± 115	4524 ± 130	4705 ± 135	4802 ± 138	4494 ± 143	3927 ± 113	3980 ± 114
1929	2241 ± 107	1921 ± 92	1793 ± 86	1953 ± 93	2315 ± 111	2081 ± 99	1782 ± 85	2123 ± 101
1930	2113 ± 84	2027 ± 81	2411 ± 96	2657 ± 106	2902 ± 116	3276 ± 131	2262 ± 90	2145 ± 86
Average	2351 ± 70	2360 ± 70	2531 ± 75	2797 ± 83	2841 ± 84	3027 ± 90	2322 ± 69	2438 ± 72

*Four plats.

The difference between germination and jointing plats is 72 pounds. The difference is slightly significant when compared with the probable error of a difference. The difference between the germination and tillering plats is small and cannot be considered significant. These results indicate again that there is a carryover effect from previous irrigation. The later the application of water the greater the carryover of moisture and the higher the grain yield the next year.

STRAW YIELDS.—Straw yields which are given in Table 17 show the same trend as the grain yields. The plats may be ranked from highest to lowest as follows: Filling, blossoming, heading, jointing, tillering and germination. The difference between the blossoming and heading plats is not great, but may be considered significant when compared with the probable error of a difference. The heading and jointing plats differ significantly as do the jointing and tillering plats. The difference between the tillering and germination plats is too small to be significant.

Table 18.—Rainfall on Residual Plats from Time That the Canvas Covers Were Removed to Harvest the Following Year.

Month	1921 1922	1922 1923	1923 1924	1924 1925	1925 1926	1926 1927	1927 1928	1928 1929	1929 1930
	in.	in.	in.	in.	in.	in.	in.	in.	in.
September	....	....	....	....	1.73	0.02	1.10	0.09	2.13
October	0.53	0.50	3.55	....	3.12	1.00	1.05	1.50	0.99
November	0.24	1.37	0.10	0.09	0.89	0.36	1.00	1.15	0.93
December	0.89	0.26	0.25	0.74	1.50	0.83	0.25	0.06	0.09
January	0.35	0.19	0.51	0.27	0.25	0.04	0.26	0.21	0.45
February	0.53	1.39	0.54	0.08	0.28	0.40	0.52	0.70	0.07
March	0.32	2.74	1.83	0.39	1.54	1.87	1.38	1.78	0.70
April	2.95	2.18	0.93	0.05	2.88	2.77	1.02	2.37	0.58
May	0.46	3.60	3.90	0.97	1.67	0.83	3.01	1.08	3.92
June	1.03	5.72	0.22	1.99	1.66	1.95	2.95	0.64	1.50
July	0.83	5.26	0.16	1.06	0.71	1.96	0.79	0.46	1.04
August	....	0.05	0.05	....	....	....	....	....	....
Total	8.13	23.26	12.04	5.64	16.23	12.03	13.33	10.04	12.40

RAINFALL

The rain falling on the various plats from the time they were uncovered until harvested is given in Table 18. There is quite a variation in the total amount of rainfall. The influence of a very dry season is shown in the 1925 yields. The heavier precipitation in 1922 to 1923 and 1925 to 1926 also increases the yield. The residual effect in 1926 was reduced because of heavy rainfall in October, 1925. The other years, with the exception of 1927, showed the normal trend. The 1926 to 1927 precipitation was high in March, April, June and July and this evidently helped to reduce the carryover effect to some extent. The data seem to indicate that the rainfall during the growing season has less effect than heavy fall rains in reducing the carryover effect.

SOIL MOISTURE LEFT FROM PREVIOUS TREATMENTS

When the soil-moisture content is examined in the fall, after harvest, varying moisture contents are found in the treated plats. Table 19 gives the soil moisture at the end of the season for differently treated plats.

The data show some variation within the years. There is little difference in the fifth foot for any of the treatments with the exception of the two-irrigation plats. The moisture content of the surface 6 inches is reduced in the germination, tillering and jointing plats. Water applied later at the heading to filling periods increases the moisture content of the surface 6 inches. The plat which received a distributed irrigation has a slight reserve. The second 6-inch section has a higher moisture content than the first 6-inch section and shows the same gradual increase in moisture as the irrigations are applied at progressively later dates.

Table 19.—Soil Moisture in Critical-Period Plats in the Fall from 1921 to 1929, Inclusive.

Treatment	Depth	1921	1922	1923	1924	1925	1926	1927	1928	1929	Average
	Inches	pct.	pct.	pct.	pct.	pct.	pct.	pct.	pct.	pct.	pct.
Germination	1 to 6	4.664	4.488	4.173	4.980*	4.033	4.486	4.168	5.190	4.698	4.488
	6 to 12	6.588	7.207	6.437	....	6.438	8.208	7.385	8.138	7.437	7.230
	12 to 24	8.118	8.415	8.253	8.262	8.141	9.811	8.793	9.915	9.284	8.777
	24 to 36	11.628	11.069	12.467	10.907	10.574	12.949	9.840	13.676	11.498	11.623
	36 to 48	11.468	11.879	13.064	13.303	12.070	13.235	11.697	13.719	13.525	12.662
	48 to 60	11.070	12.436	13.122	14.452	13.007	14.210	13.537	14.902	15.370	13.567
Tillering	1 to 6	4.402	4.806	4.654	5.077*	4.366	4.519	4.465	4.916	4.573	4.588
	6 to 12	7.235	7.763	6.276	....	7.267	8.168	7.554	8.190	8.473	7.616
	12 to 24	10.093	9.209	9.154	7.980	9.849	9.238	8.188	9.721	8.806	9.138
	24 to 36	11.666	11.847	11.477	10.157	11.411	11.368	8.521	13.250	9.396	11.010
	36 to 48	10.977	12.467	12.709	11.969	12.836	12.140	10.250	13.375	12.965	12.188
	48 to 60	11.196	11.720	13.113	14.818	13.875	13.840	13.474	14.278	15.460	13.530
Jointing	1 to 6	4.305	5.163	4.635	5.056*	4.497	4.697	4.757	4.841	5.461	4.795
	6 to 12	8.378	7.779	7.166	....	8.173	9.743	8.221	8.406	9.360	8.403
	12 to 24	11.709	10.659	9.811	9.756	11.968	11.463	9.173	10.546	10.509	10.622
	24 to 36	13.223	12.647	13.769	12.581	13.209	13.680	10.922	14.096	12.225	12.928
	36 to 48	11.440	12.359	13.122	13.183	12.892	13.707	11.579	13.818	13.314	12.824
	48 to 60	10.582	12.686	13.589	14.454	13.651	14.090	13.363	13.838	14.360	13.401
Heading	1 to 6	6.253	5.797	5.056	5.884*	4.766	5.679	4.935	5.584	5.987	5.507
	6 to 12	10.200	10.259	7.690	....	9.865	9.766	8.764	10.621	12.276	9.930
	12 to 24	12.319	13.037	11.656	12.627	13.935	13.472	12.080	14.278	13.668	13.108
	24 to 36	12.499	14.173	14.105	13.993	14.131	13.583	13.600	14.830	13.803	13.857
	36 to 48	12.286	13.029	12.942	13.205	13.054	13.743	12.969	13.611	13.383	13.136
	48 to 60	10.720	12.193	13.476	14.529	13.580	13.846	14.043	14.070	14.184	13.405

*Soil moisture in the first foot was not included in the averages.

Table 19.—(Continued.)—Soil Moisture in Critical-Period Plats in the Fall from 1921 to 1929, Inclusive.

Treatment	Depth	1921	1922	1923	1924	1925	1926	1927	1928	1929	Average
	Inches	pct.	pct.	pct.	pct.	pct.	pct.	pct.	pct.	pct.	pct.
Blossoming	1 to 6	5.950	6.852	6.067	6.367*	5.593	5.987	5.872	7.836	7.121	6.410
	6 to 12	11.498	12.310	13.168	....	11.685	12.813	10.228	13.507	14.303	12.439
	12 to 24	13.767	13.754	14.487	13.863	14.577	14.975	14.049	15.926	15.279	14.520
	24 to 36	13.705	13.860	14.367	14.071	14.375	15.190	13.578	15.701	13.985	14.315
	36 to 48	12.246	12.221	13.646	12.750	13.400	13.990	12.455	14.082	13.651	13.160
	48 to 60	11.357	12.137	13.099	14.023	13.832	13.786	13.146	14.048	14.677	13.345
Filling	1 to 6	8.743	9.576	10.386	8.219*	8.291	7.431	11.732	10.426	11.625	9.776
	6 to 12	13.615	13.934	14.659	....	14.286	13.932	15.610	16.257	17.570	14.983
	12 to 24	14.648	15.275	17.132	14.972	15.629	16.007	17.002	17.123	17.008	16.088
	24 to 36	13.219	14.438	16.746	14.111	15.463	14.906	15.448	16.231	14.603	15.018
	36 to 48	11.877	13.279	14.526	13.090	14.049	14.124	13.701	14.631	14.032	13.701
	48 to 60	11.027	13.007	13.759	14.371	13.637	14.409	14.164	14.662	15.259	13.811
Distributed	1 to 6	5.204	5.569	6.330	5.237*	5.093	5.559	5.548	6.555	6.185	5.718
	6 to 12	8.012	7.881	7.996	....	8.473	9.553	8.985	9.956	10.264	8.890
	12 to 24	9.787	8.639	9.328	8.423	10.571	10.686	9.296	11.365	10.521	9.846
	24 to 36	11.689	11.882	12.029	9.038	12.235	12.375	10.320	13.851	11.512	11.659
	36 to 48	10.961	11.342	12.269	12.232	11.955	12.450	11.927	14.130	12.650	12.213
	48 to 60	9.894	12.025	12.120	14.061	12.103	13.230	13.000	14.237	14.675	12.816

Probable error† in percentage for different depths: 1 to 6 inches = 2.57; 6 to 12 inches = 1.82; 12 to 24 inches = 1.35; 24 to 36 inches = 1.30; 36 to 48 inches = 0.78; 48 to 60 inches = 0.62

*Soil moisture in the first foot was not included in the averages.
†Variance method used to determine probable error.

The second foot shows the same moisture trend as the second 6-inch section. The third foot varies less. The third foot is lowest in moisture content in the tillering plats, followed closely by the germination plats. There is a slight increase in the jointing plats, which continues with the advance in seasonal treatments. The fourth foot remains very stable in the first three stages, but increases slightly at heading and holds uniform in the two later stages. This indicates that some moisture had been taken from the fourth foot by plats irrigated earlier than the heading stage. The relation of soil moistures at the end of the season to the yields the following year is very noticeable and is depicted graphically in Fig. 7. The highest-yielding plat had the

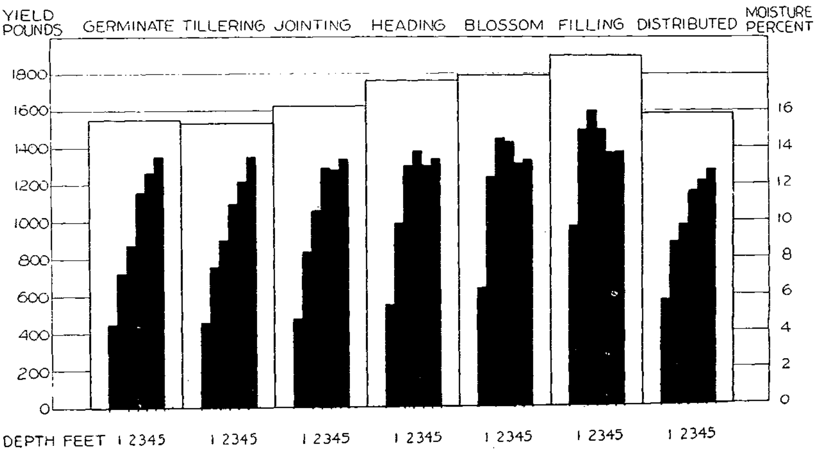

Fig. 7.

most soil moisture. The yield decreased with a lower soil-moisture supply. The tillering and germination plats had the lowest soil moisture and produced the lowest yields. The soil moisture in the distributed plats was very low.

Root Penetration Studies

Root penetration studies were made on one series in 1926, 1927 and 1928. A trench was dug the entire length of the series. A section of the soil was removed carefully from the side of the trench. The removal was accomplished by using an ice pick and a fine stream of water from a hose having a special nozzle. This section was 1 foot wide and 6 inches deep. A row of grain was in the center of the 6-inch section. Root maps were made on cross-section paper as the soil was removed.

The root penetration in the germination and tillering plats was about the same. In the first and second feet the roots were intermingled rather abundantly in the soil. They were more nu-

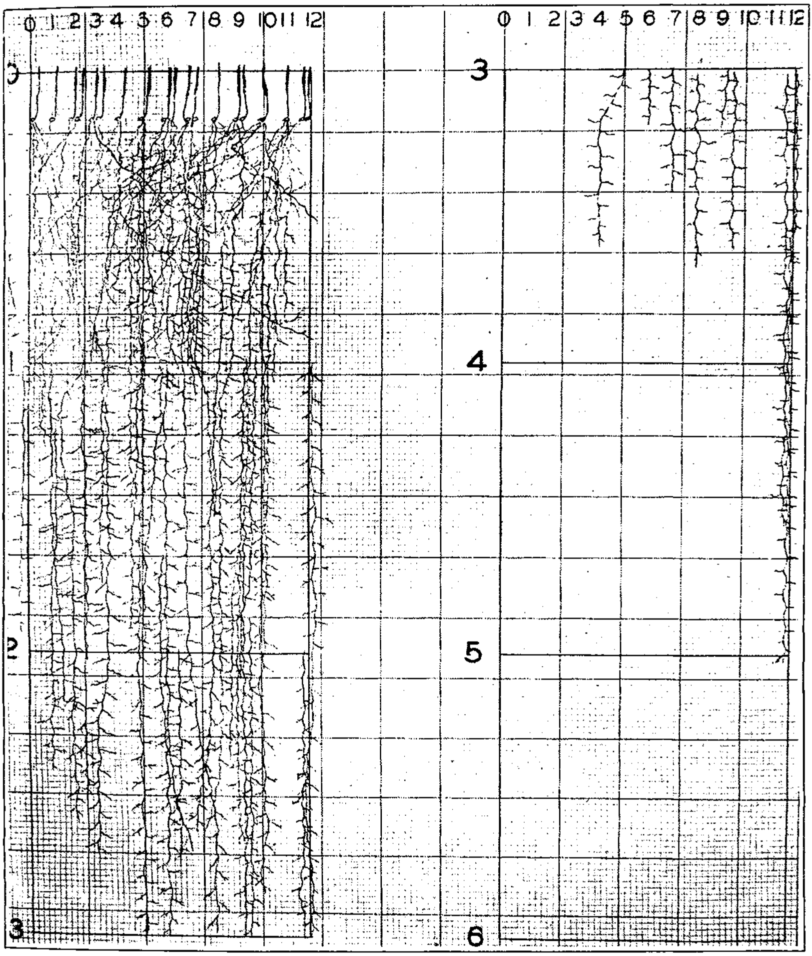

Fig. 8.—Root penetration at end of season in a section of soil 1 foot by 6 inches by 5 feet. The plats were irrigated at tillering.

merous in the first foot than in the second foot. About one-half of the roots penetrated from the second foot to the third foot and a few penetrated the fourth foot. An occasional one penetrated the fifth-foot section. (See Fig. 8.)

In the jointing plats the roots were numerous in the first foot and were fairly numerous in the second foot. There were fewer roots in the third-foot section of this treatment. An occasional root penetrated into the fourth foot.

In the heading plats the roots were less numerous in the first foot, but were as numerous in the second foot. However, there are more roots in the third foot of the heading plats than in the jointing plats. A few roots entered the fourth foot. (See Fig. 9.)

The plats irrigated at blossoming showed about the same root distribution as those irrigated at heading. The roots in the third foot were less numerous than in any of the treatments already discussed.

In the filling plats the roots were fairly numerous in the first foot. The roots were more numerous in the filling than in the blossoming plats in the second foot and third foot. A few penetrated the fourth foot. (See Fig. 10.)

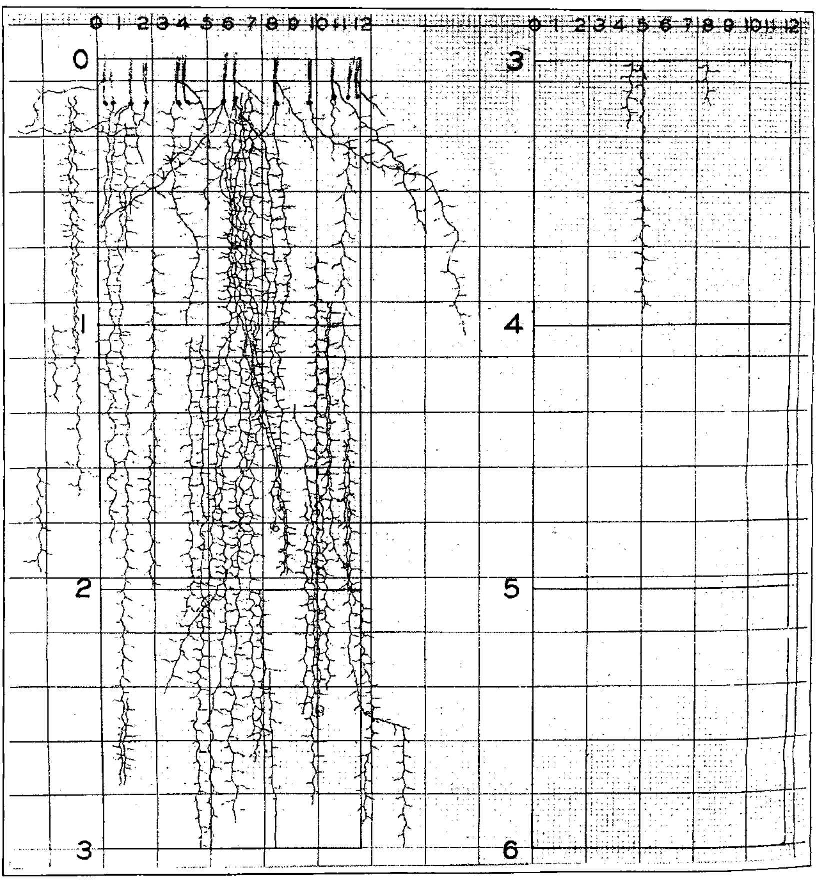

Fig. 9.—Root penetration at end of season in a section of soil 1 foot by 6 inches by 5 feet. The plats were irrigated at heading.

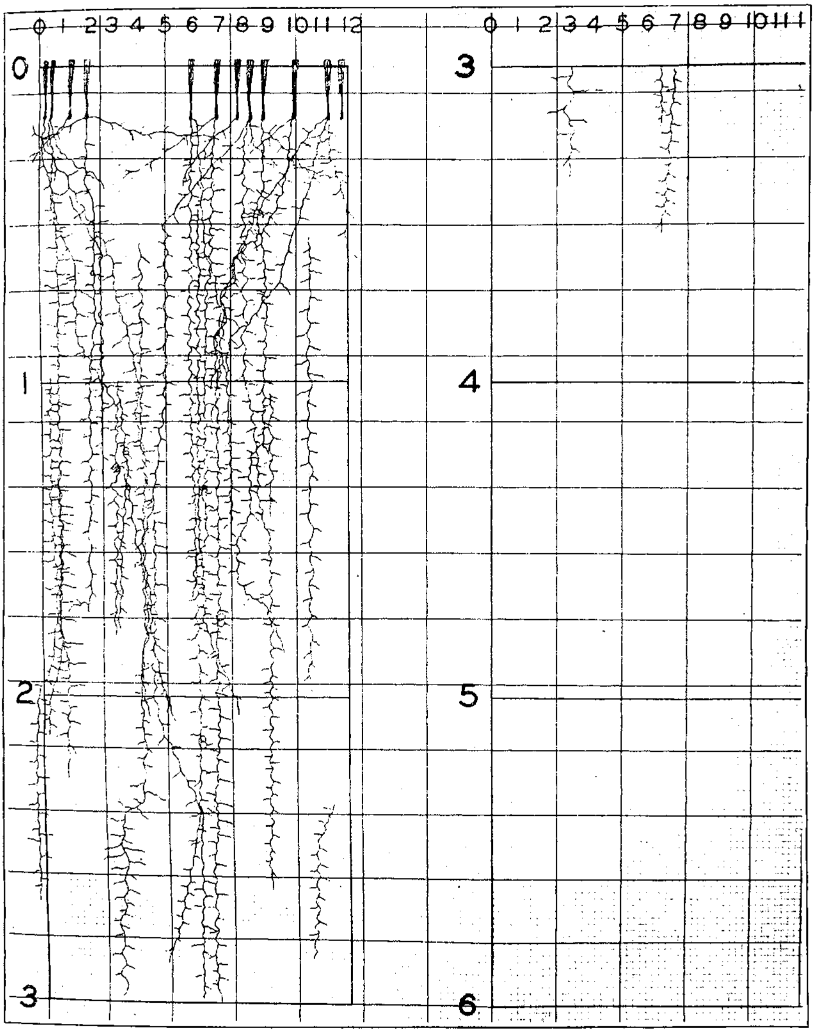

Fig. 10.—Root penetration at end of season in a soil profile 1 foot by 6 inches by 5 feet. Plats irrigated at filling.

The roots in the distributed plat were very numerous in the first and second feet. In the lower half of the second foot they became less numerous. A few penetrated the third foot. (See Fig. 11.)

In making the root studies it was noticed that many of the roots followed earth-worm holes or other openings in the soil. In all of the plats studied a great profusion of roots was noticed

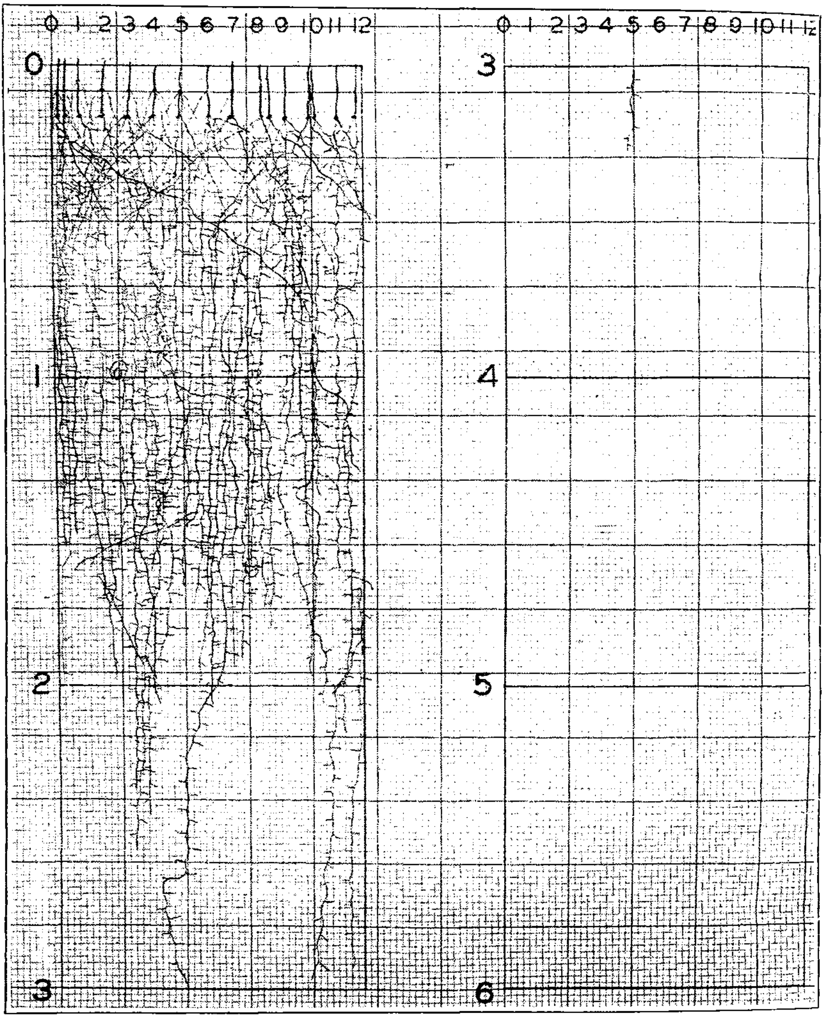

Fig. 11.—Root penetration at the end of the growing season in a profile 1 foot by 6 inches by 5 feet. Plats received distributed irrigation.

in the cultivated part of the soil. They accumulated in great numbers just above the plow sole. There were fewer fine roots below this area. The penetration of the roots was associated closely with the amount of soil moisture in the fall. A similar condition was found by Conrad, J. P., and Veihmeyer, F. J., with grain sorghum in California.

There was very little root penetration into the fifth foot and the moisture content at this depth was very uniform for all treatments. The third-foot section for the early irrigations was reduced in moisture content and the root penetration was extensive in the early treatments. The third foot had numerous roots in all treatments, but the carryover was greater in the late-irrigated plats. The roots in the third foot were fewer, but the moisture content was higher. It seems from these studies that the roots are most numerous in the upper sections and tend to stay where the moisture is plentiful. The late-irrigated plats had less roots in the lower depths, indicating that little root growth occurred at this late stage of plant development.

DISCUSSION

The yield data in the critical-period studies are similar to those previously published by Kezer and Robertson (5). They emphasize the necessity of a sufficient amount of water at the jointing and heading stages. This agrees with studies reported previously and with some recent studies cited in the literature review. Sufficient moisture is required to bring the plants to the critical stages and an abundance is required at that time to obtain the highest yield. However, Moliboga (6) showed that a deficiency at the critical stage was detrimental to yield, even tho sufficient moisture was applied previous to, and following, the critical stage.

The residual studies emphasize several important points relative to soil-moisture content and yield of grain. When the moisture reserve is high in the fall, the chances of obtaining a good yield are better than when the moisture reserve is low. These findings, while referring to spring wheat under irrigation, should have some relation to dryland production. The soil-moisture reserve in the spring might be a good indication of the grain yield that year. However, water applied early in the season to a crop which is still vigorous and healthy is not an economical use of water. A more efficient use is to store the water and irrigate nearer the critical period.

The pounds of water required to produce a pound of dry matter is a measure of the efficient use of water.

The root-penetration studies show the relation between moisture and root development. The results indicate that the roots of wheat under competition do not penetrate the soil beyond the available moisture supply. This is shown most clearly in the plat receiving a distributed irrigation. The soil moisture in the first 2 feet of all treatments was lower than the wilting coefficient as calculated from moisture-equivalent determinations. A similar condition is discussed by Conrad and Veihmeyer

(1). In such cases the plants evidently drew some of their moisture from lower depths. The moisture-content and root-penetration studies of the germination and tillering plats showed an abundance of roots in the third foot with a lower moisture content than in plats irrigated later. The later-irrigated plats have less roots in the third foot, but a higher moisture content.

SUMMARY

Marquis wheat required sufficient moisture thruout the season to produce normal growth. The highest yield and most efficient use of water was obtained by irrigating at the jointing or heading stage when only a 6-inch irrigation was used. A higher yield and more efficient use of water was obtained when a small amount of water was applied at frequent intervals, or distributed. However, application of water at frequent intervals is not feasible in field practice.

Irrigations made one year have a carryover effect on the crop the following year.

When no irrigation was applied the second year, the highest yield was obtained from Marquis-wheat plats upon which irrigation had been made at the filling stage the first year; the second highest yield was obtained from irrigation at heading; the third highest at jointing; and the lowest at germination.

The residual yield was correlated with the soil moisture of the preceding fall.

Root-penetration studies indicated that the root development varied with the treatments. There were fewer roots in the third- and fourth-foot sections of the heading, blossoming and filling plats than in the germination, tillering and jointing plats.

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