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ROOT BEHAVIOR AND CROP YIELD UNDER IRRIGATION

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ROOT BEHAVIOR AND CROP YIELD UNDER IRRIGATION.

INTRODUCTION.

More than half of the surface of the earth receives insufficient precipitation for the most favorable growth of crops. The best method of making up this deficiency is through the application of water by irrigation. Hence the economical use of irrigation water is one of the chief problems of agriculture in arid regions. Since much more land is available than can be irrigated by the supply of water, even when methods of greatest economy are employed, the welfare of these regions demands that the irrigation water be used as efficiently as possible (cf. Harris, 1916). It has been estimated that in the United States, when all possible economies have been put into operation, the irrigated regions can be enlarged to about four times the present area (Harris, 1920). The magnitude of crop production under irrigation may be recognized from the fact that Colorado alone, which maintains a ranking in irrigation development second to that of California, has an irrigated area of over 3,000,000 acres, yielding an annual revenue at current prices of over $100,000,000 (Hemphill, 1922).

Considerable experimental work has been done to determine the proper use of irrigation water, but notwithstanding the direct relation of roots in furnishing the plant with water and nutrients, the results have been measured only in crop yield and little attention has been given to the fundamental relation of roots to water and air. In this lies the proper understanding of the problem.

Root systems of crop plants are usually if not always very responsive to environmental change. They respond to differences in water-content and aeration, both in amount and direction of growth, and by varying these factors by the application of more or less water, not only the development of the root system but also the above-ground plant parts and yield can be varied, since a close correlation exists between the growth of roots and tops. The application of an excess of water results not only in the waste of the water, loss of labor in applying it, and injury to the soil, but often also in delayed germination and delay in time of maturity with its attending greater liability to rust and attack by other diseases, as well as decrease both in quantity and quality of yield. Time of application is of scarcely less importance. As regards saving of water, Howard (1918) points out that while irrigated wheat in the dry, windy Quetta Valley in Baluchistan is often watered six times, a method of growing the crop on a single irrigation has been worked out under which the yields are often higher and the harvest about a month earlier. He further states that at least a third of the water used on the wheat crop in the Punjab district of India is wasted (cf. Clements, 1921). Widstoe (1914) was probably the first to show that there is a steady decrease in the yield of wheat per acre-inch of water as the irrigation of a field is increased, and that excessive irrigation may produce an actual decrease in total yield. Experiments have further shown that when water is applied at the proper time two or three irrigations give as good results as the use of more water (Harris, 1917). Since crops differ greatly in the amount of water which they can profitably use (Knapp, 1922), as well as in their response to adverse aerial environment, a thorough study of the root systems is not only warranted but imperative for an adequate explanation of their behavior.

Germination is more rapid and complete in a soil containing a moderate amount of water, as has been pointed out by Harris (1918) and others. The formation of a surface crust as a result of irrigation not only forms a mechanical barrier to the tender seedling, but may likewise profoundly affect aeration. For example, in Northern India, following irrigation, a crust bakes on the soil, and this is quite impermeable to air, as may be shown by immersing a portion of the hardened surface in water, when the air escapes sideways and not through the surface skin (Howard, 1918).

The time of ripening is delayed by overirrigation, as has been repeatedly shown for many crops. Indeed, it has been found that soil moisture was capable of influencing the ripening period to such an extent that varietal characteristics were lost (Seelhorst, 1911). Balls (1919), working with the cotton plant in Egypt, has shown that not only was maturity delayed by an excess of irrigation water, but also that when the water-table was again lowered, a new growth of tops took place synchronously with a new growth of roots into the soil area thus provided for root extension.

Rust epidemics often attend the delayed ripening of cereals, while poor aeration resulting from a wet soil gives rise to other diseased conditions. Indigo wilt is caused by a water-logging of the surface soil and consequent defective aeration (Howard and Howard, 1920). While an excess of water may produce yellow, shrunken kernels of wheat, etc., the work of Harlan and Anthony (1921) indicates that cereals are able to utilize water up to the date of full maturity and that a deficiency of water, even after the spikelets are losing their color results in the checking of the deposit of dry matter in the grain, while a deficiency earlier in the development of the kernel probably determines its size, even before the rate of deposit of dry matter is checked. Clearly the necessary water can be applied more intelligently if a knowledge of the extent and position of the root system as modified by the chemical and physical nature of the soil is known. Decreased yields can often be correlated directly with conditions influencing the development of the roots, and this is especially true in irrigated districts where water-supply is the great limiting factor to crop production. In fact, root development often explains the reasons for differences in crop yields that are otherwise obscure.

Roots of plants that mature a crop in fairly dry soil must penetrate deeply and spread widely, a distribution hindered by a very moist surface soil early in the life of the plant. One of the most difficult problems of irrigation is to apply the water in such a way that plants are not made surface feeders and the natural advantages of a deep soil lost in consequence. Raising the water-table even temporarily by irrigation causes death of the deeper roots and usually results in a decreased yield, although the roots of some species succumb more quickly than others (Cannon, 1921). In the case of the cotton plant, Balls (1919) has shown that the amount of shedding of leaves and bolls is proportional to the depth of the root system which was submerged by a rising water-table (and soon died), and that the primary cause of shedding in Egypt is deficient root absorption due to poor aeration. This clearly illustrates the dependence of top development upon a sufficient root-supply. Howard (1916), by comparing the root-range and yield of three varieties of gram, a legume widely grown in India, found that they yielded about the same in a season of good subsoil aeration, but during a wet season the yield was inversely proportional to the depth of the root system, aeration playing the dominant rôle. The importance of a thorough investigation of root development and root activities need not be pointed out in greater detail here (cf. Weaver, Jean, and Crist, 1922 : 3).

The writers wish to acknowledge the faithful assistance of Mrs. F. C. Jean in the execution of the drawings of the root systems. Grateful acknowledgment is made to Professor J. C. Russel, of the Department of Agronomy of the University of Nebraska, for the generous use of his laboratories for the work on soil analyses, and to Dr. John W. Crist for analyzing the soils and making nitrate determinations. To Mr. L. B. Werkheiser we are indebted for many practical suggestions in regard to applying water in irrigation and field management. It is a pleasure to acknowledge the helpful suggestions given by Dr. F. E. Clements throughout the course of the work, and to him and Professor T. J. Fitzpatrick the writers are indebted for the reading of the manuscript.

LOCATION AND DESCRIPTION OF STATIONS.

Greeley, Colorado, 55 miles north of Denver and the center of one of the oldest irrigated districts in the State, was selected as a suitable location for the following experiments. This area has been under irrigation since 1871, water being secured from the mountain stream, Cache La Poudre, a tributary of the Platte. It has an elevation of 4,650 feet and a mean annual precipitation of 12.7 inches. Although about three-fourths of the precipitation occurs during the growing-season, the rainfall is usually so poorly distributed that dry farming is hazardous. Moreover, much moisture is wasted in light showers, which have little effect upon replenishing the holard, and in torrential rains where run-off is very high. The mean annual temperature is about 47° F. It increases gradually from 48° F. for April to 70° F. for August. The average date of the latest killing frost in spring is May 1 and of the first killing frost in autumn, October 1. The sky is usually clear and the per cent of possible sunshine very high (66 per cent, April to September inclusive, for Denver). Clear, hot, dry days are followed by cool nights with marked rise in humidity. The marked changes in day and night temperature and humidity are well illustrated in figure 1.

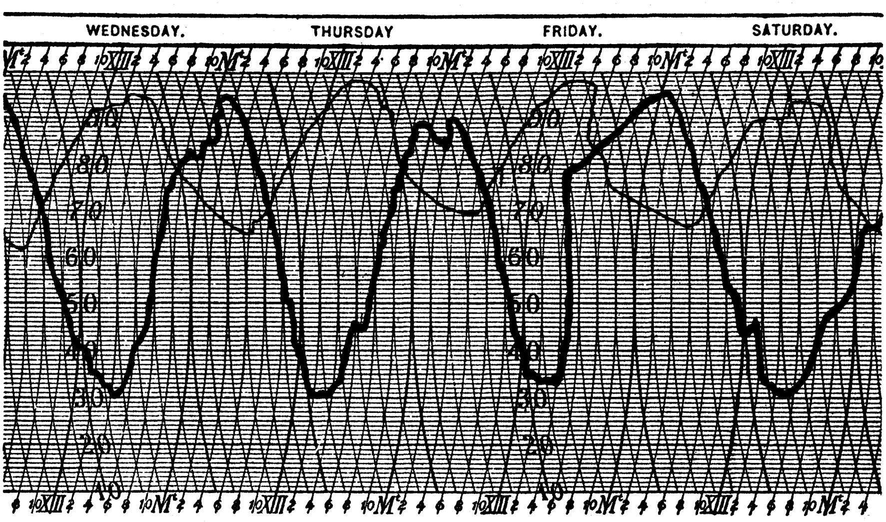


FIG. 1.—Hygrothermograph record for third week in July, 1923, showing usual wide fluctuations between day and night temperature (light line) and humidity (heavy line).

A station for the growth of crops without irrigation was selected on a level tract of land lying within the western edge of the city. That for irrigation was located about a mile eastward and just outside the city limits, being under ditch No. 3 of the Greeley Irrigation Company. It was about 75 feet lower than the dry-land station.

All the soils throughout the region are of alluvial origin and consequently somewhat variable in texture and structure, even within short distances. Hence, great care was exercised in selecting the plats to secure as great a uniformity as possible, and where differences were found in making the root excavations these have been recorded. The soil in both areas consisted of a fine sandy loam. That in the dry land was underlaid at a depth of 18 to 24 inches with a very dry hard layer with a sufficiently high lime-content to rather firmly cement the soil into a hardpan (cf. Weaver and Crist, 1922). This harder layer was usually 10 or 12 inches thick and gave way to a looser soil. At a depth of 5 or 6 feet gravel intermixed with sand often occurred, and small rocks were not uncommon throughout. The soil, where dry, was so compact that a trench could be dug only with the aid of a large pick. In the irrigated plats the sandy loam was also underlaid at a somewhat variable depth (usually 16 to 24 inches) by a harder substratum. Here both the clay and lime content increased rapidly, giving way again below 3 feet to a sandier, less compact subsoil. Below 4 or 5 feet pure sand or gravel and sand occurred.

TABLE 1.—*Mechanical analyses of soils.*

Depth in feet.	Coarse gravel.	Fine gravel.	Coarse sand.	Medium sand.	Fine sand.	Very fine sand.	Silt.	Clay.
Irrigated:	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
0–0.5......	0.0	0.0	9.3	11.4	34.7	21.7	12.5	10.4
0.5–1......	0.0	0.0	7.6	16.7	37.7	20.5	6.1	11.6
1–2........	0.0	0.0	5.0	12.4	25.7	19.7	16.6	20.6
2–3........	0.0	0.0	5.6	11.0	25.4	22.8	17.3	17.9
3–4........	0.0	0.0	8.1	14.5	39.9	21.8	7.1	8.4
Non-irrigated:								
0–0.5......	0.0	0.0	9.3	10.5	29.2	25.0	11.7	14.3
0.5–1......	0.0	0.0	7.2	13.4	36.5	23.9	10.4	8.5
1–2........	0.0	0.0	8.0	10.0	33.6	25.2	10.5	12.7
2–3........	0.0	0.0	7.3	7.0	31.4	26.6	11.8	15.9
3–4........	0.0	0.0	7.8	7.8	32.4	21.6	11.4	19.0

Physical analyses of the soil from large composite samples for each of the several depths to 4 feet in each area are shown in table 1.

TABLE 2.—*Chemical analyses of soils.*[1]

Depth in feet.	Nitrogen.	K_2O.	P_2O_5.	Carbon dioxide.	Volatile matter.	Acidity.
Irrigated:	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	
0–0.5.......	.051	1.41	.109	.24	.88	None.
0.5–1.......	.060	1.29	.109	.33	1.03	None.
1–2.........	.044	1.30	.100	4.39	1.10	None.
2–3.........	.029	1.31	.081	4.38	.70	None.
3–4.........	.018	1.23	.097	1.57	.97	None.
Non-irrigated:						
0–0.5.......	.068	1.38	.045	None	1.48	Slight.
0.5–1.......	.059	1.22	.093	Trace	1.36	Very slight.
1–2.........	.045	1.24	.056	1.94	1.06	None.
2–3.........	.027	1.09	.057	5.40	.65	None.
3–4.........	.017	1.27	.096	4.94	.52	None.

[1] Nitrogen was determined by means of the modified Gunning method, K_2O by fusion with calcium carbonate, P_2O_5 by digestion with aqua regia, volatile matter by ignition, and replacement of inorganic carbonates through the use of $(NH_4)_2CO_3$, and acidity by the Truog method.

There is a distinct increase in both silt and clay content of the irrigated soil in the second and third foot, with a proportional decrease in fine sand. In fact, this layer might well be designated as sandy clay. Less marked differences in the clay-content are found in the non-irrigated land, the hardpan here being due more largely to the chemical soil constituents. Chemical analyses (table 2) show an abundance of carbonates in the second and third foot. Here the lime horizon is clearly indicated, as well as the rise of the soluble salts as a result of irrigation.

An examination of table 2 shows that nitrogen is low, while potash is considerably higher than that of the average arid soil. Phosphorus is also low, especially in the non-irrigated soil. Considering the aridity of the locality, the volatile matter is not low, arid soils usually showing 0.85 to 1 per cent for the surface and 0.65 to 0.90 per cent for the subsoil. Too little acidity occurs at any level to be of any importance. In fact, analyses show considerable alkalinity at certain levels.

CROPS AND METHODS.

The following crops were grown for these experiments: Turkestan alfalfa (*Medicago sativa*), Marquis spring wheat (*Triticum aestivum*), a sugar beet of a variety most commonly grown in the region, Klein-wanzleben (*Beta vulgaris*), Bliss's Triumph potato (*Solanum tuberosum*), widely grown as an early variety, and an acclimated yellow dent corn, Minnesota No. 13 (*Zea mays indentata*), a variety considered best adapted to the region. Thirtieth-acre plats of each crop, exclusive of a discard area surrounding each, were grown on the dry land and in duplicate (except alfalfa) under irrigation. One of the latter plats of each crop was fully irrigated[1] and the other watered less frequently.

A record of aerial environmental conditions in the two areas was obtained largely by means of recording instruments, and nearly 2,000 soil samples for holard determinations to depths of 4 or more feet were secured. Also, weekly records of soil temperatures were obtained. To obviate local changes in environment brought about by the growth of the crops (the plats of beets, corn, wheat, etc., each having not only its own partial environment but one which was constantly changing) and hence to more nearly compare conditions in the two areas, a thirtieth-acre plat in the center of the fields where the instruments were placed was kept free from vegetation. Friez's hygrothermographs, placed in appropriate shelters so that the sensitive mechanism was about 5 inches above the soil-surface and frequently checked, recorded air-temperature and humidity. The average day temperatures and humidities were determined from the weekly record-sheets by adding the temperatures or humidities beginning at 8 a. m. and every 2 hours thereafter until 6 p. m. for each day and dividing the sum by the total number of 2-hour intervals. Those for the night intervals were calculated in a similar manner, beginning at 8 p. m. and including the readings until 6 a. m. Evaporation was determined by Livingston's standardized, spherical, radio-atmometer cups, which were run in duplicate and the average daily readings for each week corrected to the standard cup. Wind velocity was not measured. In general, the wind is high in spring until about June 1, after which it consists mostly of gentle breezes. Soil-temperature readings were taken weekly, the thermometers being inserted in the hole left by the Briggs soil-tube for a period of several minutes before each reading. In addition to the weekly water-content detrminations (100- to 150-gram samples dried at 105° C. being used) to a depth of 4 feet in the uncropped areas, similar samples were taken at longer intervals in each of the crop plats from the time of planting until the crops were mature. At times other samples to the limit of root penetration, 5 to 9 feet, were secured. All of these data are expressed in the tables as water-content in excess of the

[1] One of the most important problems of crop production under irrigation where an ever-increasing amount of tillable land is placed under the ditch and the supply of water is limited, is the proper use of the latter. At present the time of application of irrigation water and the amount used are determined entirely empirically, much water often being wasted, yields sometimes actually reduced, and other injurious results ensuing from the use of an oversupply. In these experiments water was supplied at times designated by the owner of the land, a man of many years' experience in irrigation, whose judgment in such matters has been attested by highly successful crop production.

hygroscopic coefficient (i. e., approximately the water available for growth, cf. Weaver, 1920:28).

The amount of water used in surface irrigation (flooding in the case of wheat and alfalfa and ditching in the case of the other crops planted in rows) was not determined by the usual method of measuring the water permitted to flow upon the land in acre-inches. Casual observation shows that much of this is frequently lost in run-off due to variations in the slope of the land (the amount being more or less variable, due to the head of water used), or unequally distributed, depending largely upon the original dryness of the soil, its condition of tilth, etc. Water-content was determined by taking soil samples at 1-foot intervals to depths of 3 feet in the same plat immediately preceding and following irrigation, the water penetrating readily because of the sandy nature of the soil. By this method, owing to the large number of samples taken, the actual increase in water-content was ascertained.

The method used in excavating root systems was the same as that employed during the past 10 years. By the side of the plants to be examined, a trench was dug to a depth of about 4 feet and of convenient width. This affords an open face into which one may dig with a hand-pick and other tools and thus make a careful examination of the entire root system. This apparently simple process, however, requires much practice, not a little patience, and wide experience with soil texture. In every case several plants were examined, often 10 or more at any given stage of development, to insure an adequate idea of the general root habit. Among this number it was possible to secure some root systems in their entirety. In cases where reconstruction was necessary, this was rendered more accurate and less difficult by methods of record in the field. As the work of excavation progressed, the trench was deepened, if necessary, so that finally the soil underlying the deepest roots was undercut for several inches and carefully examined as it was removed to assure certainty as to the maximum depth of the root-ends. Frequently the trenches reached depths of 5 to 9 feet.

The usual practice was followed of writing a working description of the root system after several plants had been examined and then noting any variation from this description as more roots were excavated. This checking of the description in the field leads to a high degree of accuracy, for opportunity is offered for further study if any point regarding the root habit remains indefinite. This is absolutely essential in developmental studies. Drawings of the root systems were made with pencil in the field on a large drawing-sheet and then retraced with India ink. They were made simultaneously with the excavating of the roots and always to exact measurement. In the drawings the root systems are arranged as nearly as possible in the natural position in a vertical plane; that is, each root is placed in its natural position with reference to the surface of the soil and a vertical line from the base of the plant. In the case of potatoes the roots were so abundant that to depict all of them led to confusion, so that in the drawings of these plants only one-half of the root system is shown.

In every case it was sought to illustrate the average condition of root development rather than the extreme. Although the drawings were made on a large scale, the rootlets were often so abundant that it was quite impossible to show the exact number as determined by average root-counts. Such drawings, however, carefully executed, represent the extent, position, and minute branching of the root system even more accurately than a photograph, for under the most favorable conditions, especially with extensive root systems, the photograph is always made at the expense of detail, many of the finer branches and root-ends being obscured.

The dry-land area, which produced no crop the preceding year, but was not entirely free from weeds, was plowed about 8 inches deep and harrowed until a good seed-bed was formed. The irrigated plats, upon which truck crops were grown the preceding year, were fertilized uniformly with 5 tons of barnyard manure per acre, plowed 9 inches deep and well harrowed.

ENVIRONMENTAL CONDITIONS, 1922.

The aerial environment as regards temperature in the two plats was not greatly different, as may be seen in table 3.

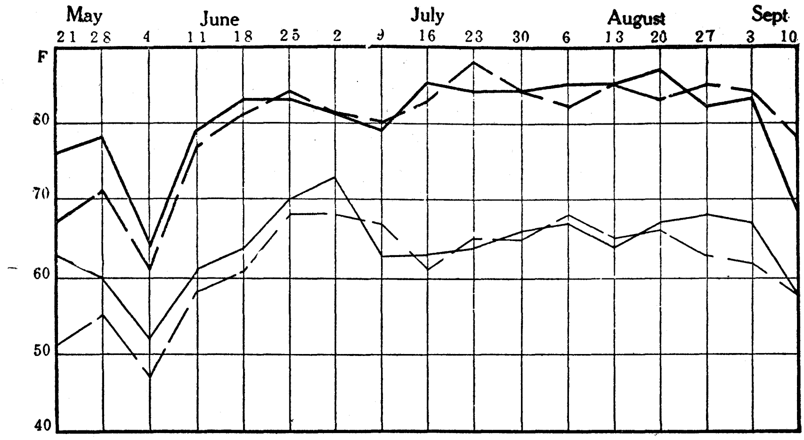


Fig. 2.—Average day temperature (heavy lines) and average night temperature (light lines) in dry land (solid lines) and irrigated plats (broken lines), 1922.

The average day and average night temperatures are shown in figure 2, where it may be seen that, except for May, they are very similar. The lower temperatures on the watered plats early in the season probably resulted in part from the effects of irrigation on May 15, much heat being consumed in drying the surface soil. The somewhat higher night temperatures in the dry land during the early part of the season are due to cold-air

Table 3.—*Average daily air temperatures, 1922.*

Date.	Dry land.	Irrigated plat.
	°*F*	°*F*
May 14	67	54
21	70	59
28	69	63
June 4	58	54
11	70	68
18	74	71
25	77	76
July 2	77	75
9	71	74
16	74	72
23	74	76
30	75	76
Aug. 6	76	75
13	75	75
20	77	75
27	75	74
Sept. 3	75	73
10	63	68
17	62	64

Table 4.—*Average day and average night humidity, dry land, 1922.*

Date.	Average day.	Average night.
	p. ct.	*p. ct.*
May 28	39	66
June 4	57	85
11	49	60
18	43	78
25	49	66
July 2	37	71
9	48	81
16	38	63
23	39	74
30	45	83
Aug. 6	48	84
13	48	83
20	48	90
27	54	78
Sept. 3	45	80
10	42	64
17	48	74

drainage into the irrigated plats, which were about 75 feet lower than the dry land. However, differences in temperature were so slight that they seemed to have little effect upon the growth of the crops, especially after May.

The humidity, which during 1922 was measured in the dry land only, is given in table 4.

The wide range between day and night humidity is characteristic of the Great Plains region. Not infrequently the daily range is through 80 or 90 per cent, humidities of 10 to 15 per cent not being uncommon in the afternoons, while at night they often rise to 80 or even 100 per cent, owing to the low night temperatures. The humidity was apparently somewhat lower in dry-land than in the irrigated plats, judging by the evaporation from the black porous-cup atmometers (fig. 3), which the following season gave almost identical losses at the two stations, where the humidities were also practically identical. Humidity in the irrigated plats was undoubtedly increased not only by the surface evaporation from the moister soil, but

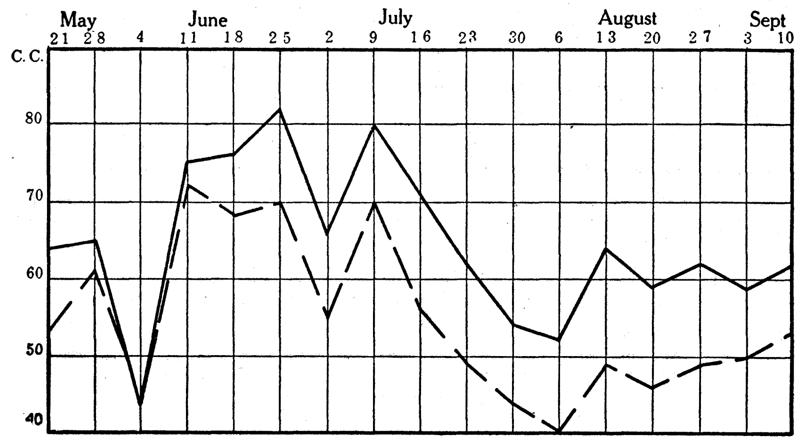


FIG. 3.—Average daily evaporation in dry-land (solid line) and irrigated plats (broken line), 1922.

also by the water transpired from the luxuriantly growing crops. Moreover, in the watered area, the uncultivated plat where the instruments were placed was located in such a manner that they received the shade of some black locust trees at a distance of 80 feet for perhaps an hour each day just before sunset. These trees, which were removed in 1923, did not come into full leaf until about the second week in June. Aside from this, the chief factor in causing these differences in evaporation was greater wind movement in the dry-land plats, which not only lay higher, but also bore shorter crops. In addition, the irrigated plats were sheltered on both the west and north at no great distance by a row of trees.

Soil temperatures in the two areas at various depths were not very different. This may be accounted for by the fact that the irrigation water, although from a mountain stream, had traveled long distances over the broad, shallow bed of the river and through the ditch until it was quite as warm as the soil to which it was applied. Temperature variations were most marked in the surface 3 inches (fig. 4), but no consistent differences occurred in the two plats. Those at 6 inches depth were usually 2° to 5° C.

lower than at 3 inches, but very similar. Differences at a depth of 12 inches were even less, the average temperature being still lower. Table 5 shows

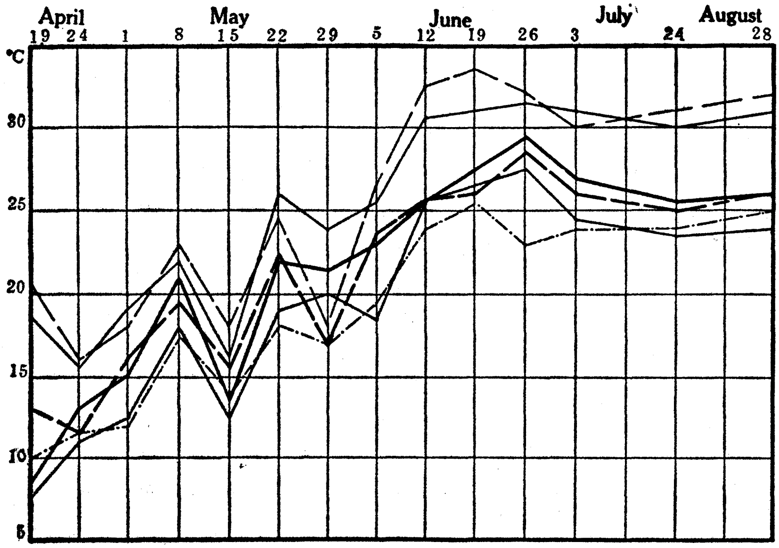


Fig. 4.—Soil temperature in dry-land (solid lines) and irrigated plats (broken lines), at depths of 3 inches (light upper lines), 6 inches (heavy lines), and 12 inches (light lower lines), 1922.

that in the deeper soils (2 to 4 feet) practically no difference occurred. It is interesting to note the rather low temperatures at which deeper root-growth takes place.

Table 5.—*Soil temperatures in the dry-land and irrigated plats, 1922.*

Date.	Depth, 2 feet.		Depth, 3 feet.		Depth, 4 feet.	
	Dry land.	Irrigated.	Dry land.	Irrigated.	Dry land.	Irrigated.
	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*
Apr. 20	8.0	8.5	8.0	8.0	8.0	8.0
24	10.0	10.0	9.0	9.0	8.0	8.0
May 1	10.0	10.0	9.0	9.0	9.0	9.0
8	15.0	13.5	13.0	13.0	10.5	11.5
15	12.5	14.0	11.0	13.0	10.5	11.0
22	17.5	17.0	16.0	16.0	13.0	13.0
29	18.0	17.0	15.5	15.0	15.0	14.0
June 5	17.0	16.5	15.0	15.0	13.0	15.0
12	21.0	22.0	18.0	19.0	16.0	17.5
19	23.0	25.0	20.0	23.5	17.5	20.5
26	24.5	22.0	22.0	20.0	19.0	19.0
July 3	24.0	21.5	22.0	20.0	21.0	18.5
24	22.5	22.0	21.0	21.0	20.0	19.5
Aug. 28	23.0	24.0	22.0	23.0	21.0	22.0

Summarizing, air temperatures on the dry land were very similar to those in the watered area, except in May, when they were 2° to 6° F. higher. Soil temperatures at all depths were almost identical. Humidity was a little lower in the drier area, wind movement somewhat greater, and evaporation higher, all of these not only contributing to greater water-loss directly from the soil, but also accelerating transpiration.

EXPERIMENTS WITH ALFALFA.

Turkestan alfalfa was drilled an inch deep and in rows 20 inches apart in the dry-land plat at the rate of 15 pounds per acre on April 11. Seed was also sown broadcast at a similar rate and at the same time in the irrigated plat, being worked into the soil by the use of a hand rake. A fine moist seed-bed at both stations resulted from a snow which fell on April 16.

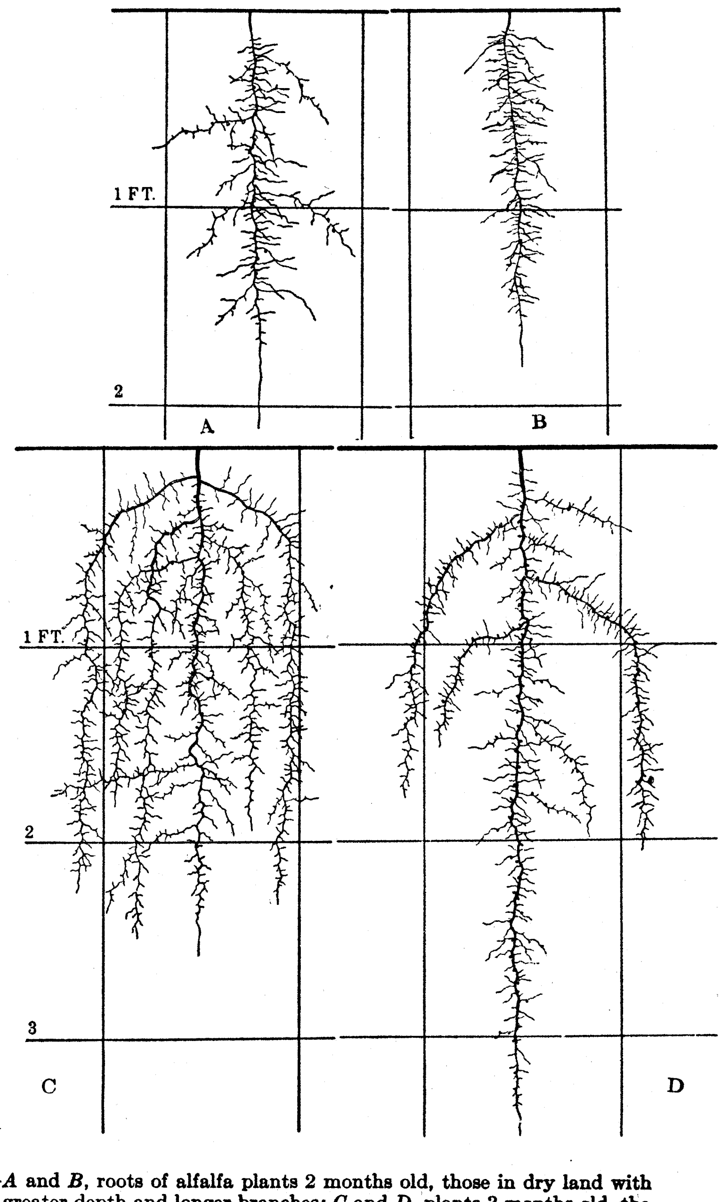


Fig. 5.—*A* and *B*, roots of alfalfa plants 2 months old, those in dry land with greater depth and longer branches; *C* and *D*, plants 3 months old, the one from the dry land having the greater number of branches.

The drilled dry-land plat was hoed at frequent intervals throughout the season to conserve the moisture, but the irrigated plat was not tilled, the weeds merely being pulled from time to time.

Owing to favorable temperatures, the crop grew well, and on June 10, 60 days after the seed was sown, it had reached a height of about 3 inches in the dry land and 6 inches in the irrigated field, the plants in both plats being furnished with 6 to 8 leaves. Root excavations at this time showed rather marked differences in the branching habit, as well as depth of penetration (fig. 5, A, B).

Alfalfa is characterized by a strong tap-root which penetrates rather vertically downward, its course in dry, hard soil often being somewhat tortuous. Plants in the dry land had reached depths of 18 to 27 inches, which was 4 to 5 inches deeper than in the irrigated plats. The number of laterals (about 6 per inch) was less in the drier soils, but they were longer. In the irrigated plats they were mostly less than 2 inches long, but in the dry land many were 3 inches and some as much as 7 inches in length.

TABLE 6.—*Holard in excess of the hygroscopic coefficient in uncropped areas at the two stations, 1922.*[1]

Date.	Dry-land plat, depth in feet.					Irrigated plat, depth in feet.				
	0 to 0.5	0.5 to 1	1 to 2	2 to 3	3 to 4	0 to 0.5	0.5 to 1	1 to 2	2 to 3	3 to 4
	p. ct.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
Apr. 19	6.7	3.5	1.1	4.5	4.9	6.4	10.2	12.8	12.2	10.5
24	4.6	3.4	0.0	0.4	3.5	6.1	4.6	10.5	10.3	6.2
May 1	9.1	7.3	5.6	2.3	2.8	6.3	8.5	5.8	12.1	5.6
8	3.9	3.6	3.8	−1.4	3.9	5.3	8.9	13.1	10.0	6.0
15	5.9	5.0	3.1	−0.3	4.6	4.9	8.4	13.2	9.0	8.0
15	.....	.....	.....	.....	.....	(9.0)	(9.0)	(0.8)	(3.3)	.....
22	3.2	3.9	2.6	−1.4	4.8	6.7	8.8	10.9	12.0	7.0
29	2.7	3.4	2.6	−1.5	−1.3	6.6	8.8	11.7	12.8	5.6
June 5	3.0	2.9	3.1	−0.5	−0.7	6.4	8.5	9.5	11.4	3.1
12	2.4	3.2	3.4	−1.1	−2.1	3.9	9.0	12.8	12.2	6.1
19	1.8	1.6	2.8	−1.4	−1.7	−0.6	2.7	15.2	14.5	4.8
19	.....	.....	.....	.....	.....	(13.3)	(13.3)	(4.7)	(0.0)	.....
26	0.7	1.5	2.7	−1.7	−2.2	5.9	11.8	11.7	10.5	4.9
July 24	−0.2	1.9	−0.2	−1.2	−0.8	2.4	10.8	11.1	11.4	3.8
31	1.5	1.1	1.9	−0.8	−1.3	4.4	9.7	12.4	11.0	3.5
Aug. 7	3.2	2.1	2.6	−0.1	−0.8	4.0	6.9	11.3	11.7	12.3
28	0.4	−0.8	1.5	−1.1	0.0	5.4	8.9	12.7	11.0	8.2
Hygroscopic coefficient	4.2	5.4	4.4	4.3	5.6	4.6	4.9	8.0	6.8	4.0

[1] Figures in parentheses in all of the tables indicate the increase in water-content due to irrigation.

Secondary branches were more abundant in the dry land, as were root tubercles also. These differences may be largely if not entirely attributed to differences in soil moisture. In the dry land the first foot of soil had about 5 per cent chresard on April 19, but this was rather gradually depleted (table 6) until, at the time of the root examinations, none occurred in the first 6 inches and only 3 or 4 per cent to the depth of root penetration (table 7).

Available water in the irrigated plats was about 8 per cent on April 19 and the crop was furnished with an abundant supply on May 12 (table 7) and at the time of root examinations 3 to 13 per cent was available.

TABLE 7.—*Holard of alfalfa plats in excess of hygroscopic coefficient, 1922.*

Date.	Dry land, depth in feet.					Fully irrigated, depth in feet.				
	0 to 0.5	0.5 to 1	1 to 2	2 to 3	3 to 4	0 to 0.5	0.5 to 1	1 to 2	2 to 3	3 to 4
	p. ct.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
Apr. 19..........	6.7	3.5	1.1	4.5	4.9	6.4	10.2	12.8	12.2	10.5
May 12..........	......	......	......	......	......	−0.7	0.0	8.9	12.5	......
12..........	......	......	......	......	......	(6.4)	(6.4)	(3.9)	(2.8)	......
June 10..........	0.0	3.0	4.5	......	......	2.5	3.7	12.5	9.4	......
10..........	......	......	......	......	......	(7.0)	(7.0)	(2.8)	(5.2)	......
June 28..........	......	......	......	......	......	2.4	4.4	8.2	7.2	......
28..........	......	......	......	......	......	(7.8)	(8.0)	(1.6)	(6.5)	......
July 8..........	0.0	1.5	2.4	3.5	......	1.9	4.8	7.1	9.4	......
Sept. 12..........	0.0	0.6	0.1	0.9	2.4	0.0	0.0	5.3	7.6	5.4
Hygroscopic coefficient...........	4.2	5.4	4.4	4.3	5.6	5.5	8.1	8.0	4.5	2.3

Practically no efficient rainfall occurred to July 8, when the root development was again examined. A glance at table 6 shows that the soil moisture, even in the uncropped area, had gradually been depleted, while in the alfalfa plat there was practically none available in the surface foot, and only 2 or 3 per cent remained in the deeper layers (table 7). Good moisture conditions had been maintained in the irrigated plat by flooding on June 28. The plants were now nearly 3 months old. Those in the watered plat were 18 inches in average height and many were in blossom. In the dry land they were only half as tall and, while some were in blossom and a few in fruit, most of them had not bloomed.

Even a glance at figure 5, C, D, shows marked differences in the root habit. The prominence of the tap-root, its greater depth of penetration, and the relative scarcity of large branches characterized the plants in the moist soil. This is the rooting habit characteristic of alfalfa (cf. Weaver, Jean, and Crist, 1922: 52). This contrasted sharply with the shallower, more profusely branched tap-root found in the dry land, where several of the major branches frequently reached depths nearly or quite as great as the main root. A similar root habit has been determined in the dry land at Burlington, Colorado, where the available soil moisture was also largely confined to the surface 2 feet (l. c., p. 69). While most of the dry-land plants gave off from 3 to 6 large branches in the first foot of soil, about half of the plants in moist soil had none, and many had only one, although some, especially isolated individuals, frequently had 2 or more. Moreover, there was a greater tendency for the branches in dry land to turn downward with less lateral spread than in moist soil. The number of small laterals (6 to 10 per inch) was about the same in both cases, although they extended much closer to the root-tips in the dry soil, undoubtedly because of the slower elongation of the main roots. In the irrigated plats the tap-roots had grown at an average rate of about 0.5 inch per day, some reaching depths of over

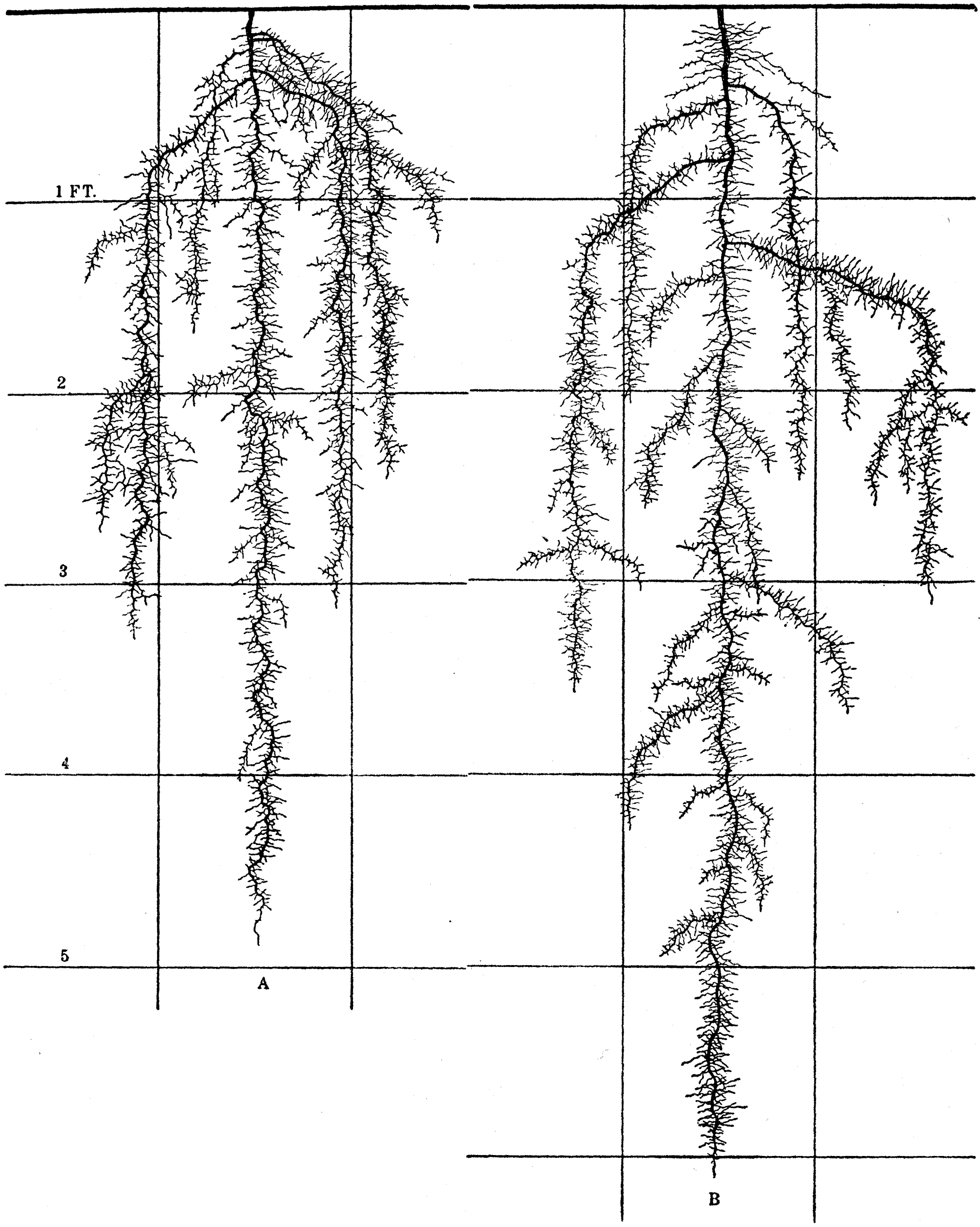


Fig. 6.—Alfalfa near the end of the first season's growth: *A*, dry land; *B*, irrigated soil.

3 feet. Nodules 1 to 2 mm. in diameter occurred abundantly over the entire root system of irrigated plants, but in the dry land they were smaller, not

abundant, and fairly well distributed only in the first 18 inches of soil. Thus it seems clear that the unfavorable environment not only affects crop

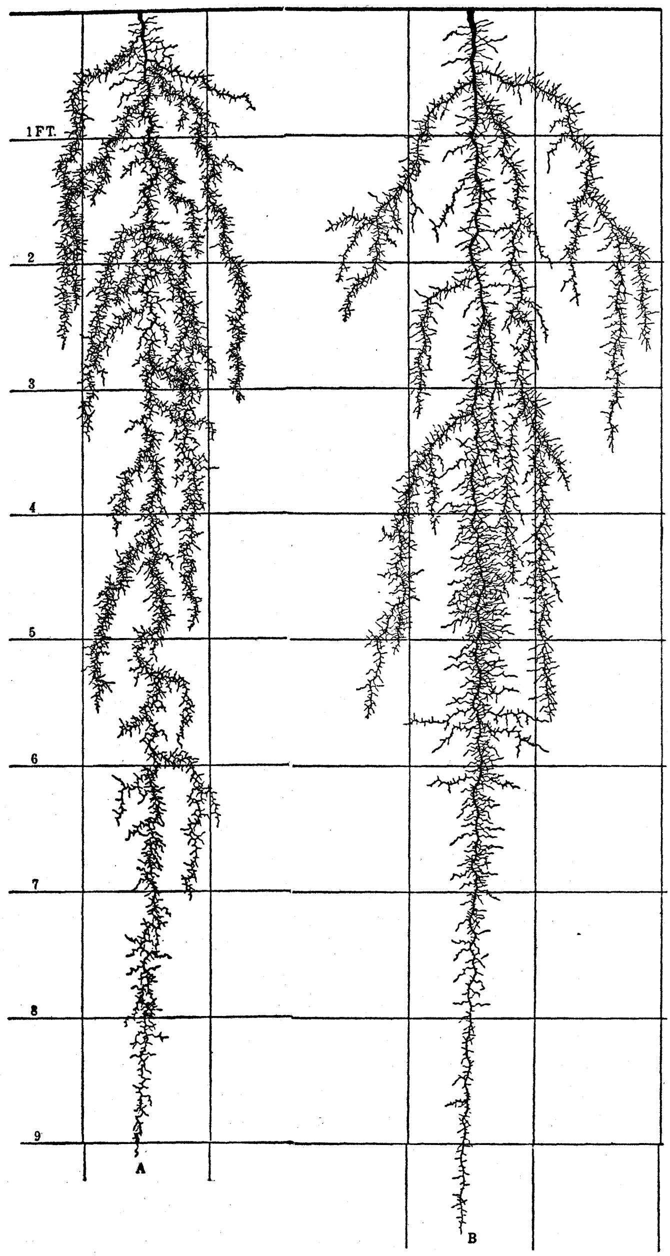


FIG. 7.—Root system of alfalfa on July 2 of second year of growth: *A*, dry land; *B*, irrigated soil.

growth directly, but also indirectly through its influence upon the nodule-forming as well perhaps as other types of nitrogen-fixing bacteria.

A final examination of the growth of the plants was made on September 12. Rainfall since July 8 had been very light (table 8), much of the moisture having been dissipated in light showers. Water, even in the

TABLE 8.—*Mean monthly precipitation and precipitation in 1922 and 1923, in inches.*

Month.	Average, 33 years.	1922.	1923.	Month.	Average, 33 years.	1922.	1923.
Jan.	0.29	0.29	0.07	July	1.87	1.46	.69
Feb.	.42	.36	1.39	Aug.	1.06	1.72	1.80
Mar.	.76	.15	2.12	Sept.	1.02	.05	....
Apr.	1.72	1.73	.82	Oct.	.96	.02	....
May	2.50	1.25	2.14	Nov.	.33	.61	....
June	1.40	.25	4.58	Dec.	.41	.43	....
				Annual	12.76	8.32	....

uncropped dry-land area, was very scarce, while in the alfalfa field practically none was available above the 3-foot level, and only 3 per cent in the fourth and fifth foot. A deficiency also occurred in the surface foot of the other plat, which had not been watered since June 28, but the deeper soils at least to 5 feet had 5 to 8 per cent of chresard.

In the irrigated plats the crop was 26 inches high and blooming profusely; this was a second growth, a first cutting having been made on July 26, when the plants were in bloom and 20 inches tall. In the dry land, where it had also been cut on July 26 when 9 inches tall, it was only 8 inches in average height. The working-depth of the roots (i. e., depths to which many of the roots penetrated and to which level much absorption took place) was 4.6 and 3.2 feet in the irrigated and dry-land plats respectively (fig. 6). In the irrigated field the strong tap-roots, now 3 to 10 mm. in diameter, with their characteristic vertical penetration, had reached a maximum depth of 6.1 feet where the soil was filled with seepage water. Those in the dry land, while similar in this general habit, were much more kinked and curved, probably owing to the difficulty in penetrating the hard, dry soil, and none extended deeper than 5.5 feet, since below this the soil was dry. The strong lateral branches, from 2 to 9 in number, arose almost invariably in the first foot of soil, in some cases branching being so profuse that the tap-root diminished in size so rapidly as to be scarcely distinguishable from the branches. They seldom spread over 6 to 8 inches laterally before they turned downward and penetrated deeply. But on the irrigated plants rarely more than 4 or 5 large branches occurred, and although they usually originated in the shallower soils, they not infrequently arose at greater depths. Their spread was much more pronounced, sometimes reaching 2 feet. As before, little difference was noted in the number, length, or branching of smaller laterals, which were now well furnished with branches of a lower order. While no nodules were found in the dry-land plants, they were abundant to a depth of over 4 feet on roots in the irrigated soil. The yield of the crop in tons per acre for the first cutting on July 26 was 0.12 on the dry land and 0.52 on irrigated soil (cf. plate 1, A).

EXPERIMENTS WITH WHEAT.

Marquis spring wheat was drilled at a depth of 2 inches in rows 8 inches apart at the rate of 90 pounds per acre in both dry and irrigated land on April 1. No efficient moisture fell until April 16, and hence the crop germinated and grew slowly. The chresard in the dry land was practically nil in the second foot of soil during April (table 6), but in the irrigated plats a good water-content prevailed to May 10, the time of the first examination.

The crops in both areas were now 4.5 inches high, the parent plants having about 4 leaves each and 2 tillers. The number of roots varied from 4 to 7 in both plats. Their characteristic spreading habit is shown in figure 8, A, B, together with the branching and depth of penetration. The roots had grown more rapidly in the soil of the irrigated plats (about 0.5 inch per day), where they showed the usual penetration and branching (cf. Weaver, Jean, and Crist, 1922 : 49), reaching maximum depths of 23 inches as compared with 18 inches in the dry land; 3 to 6 inches of the tips in the first case, but only 1 or 2 in the latter, were devoid of branches. Although the number of branches was about the same in both cases, they averaged considerably longer in the dry-land plat.

TABLE 9.—*Holard of wheat plats in excess of the hygroscopic coefficient, 1922.*

Date, etc.	0 to 0.5 foot.	0.5 to 1 foot.	1 to 2 feet.	2 to 3 feet.	3 to 4 feet.
Dry land:	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
Apr. 19	6.7	3.5	1.1	4.5	4.9
May 22	1.9	3.4	4.7	3.8	5.1
June 9	0.2	2.0	5.7	2.7	...
July 7	1.0	0.3	2.7	3.5	...
Hyg. coef	4.2	5.4	4.4	4.3	5.6
Lightly irrigated:					
Apr. 19	6.4	10.2	12.8	12.2	10.5
May 17	0.0	−0.1	7.1	12.6	...
May 22	0.2	2.1	7.0	10.8	5.1
June 9	0.2	1.7	8.4	10.3	4.4
June 9	(18.7)	(18.9)	(10.1)	(5.0)	...
June 28	−0.1	−0.2	9.4	11.5	...
June 28	(16.8)	(16.0)	(5.0)	(1.1)	...
July 7	3.1	5.1	12.7	11.5	5.9
Hyg. coef	5.5	8.1	8.0	4.5	2.3
Fully irrigated:					
Apr. 19	5.9	11.1	12.0	11.9	10.8
May 17	0.2	0.2	2.6	3.4	...
May 17	(20.0)	(20.0)	(11.4)	(11.1)	...
May 22	4.2	4.3	3.9	6.2	7.2
June 9	0.4	0.6	0.4	3.5	5.1
June 9	(14.1)	(14.1)	(12.6)	(5.7)	...
June 21	0.0	0.1	1.9	3.6	4.9
June 21	(18.8)	(18.8)	(14.2)	(14.0)	...
June 28	1.2	1.0	3.7	4.0	6.4
June 28	(12.5)	(12.4)	(11.7)	(3.0)	...
July 7	0.0	1.7	2.8	4.4	7.9
Hyg. coef	3.5	3.7	3.5	3.2	2.8

A second study of root-growth was made a month later on June 7–9. Only 1.25 inches of rain fell during this interval and the dry-land soil was constantly at a low water-content, although since May some moisture was available in the second as well as the first foot (table 9). No water had yet been added to the lightly irrigated plat, but its water-content had been constantly higher than on the dry land. The third plat had been irrigated on May 17 (table 9). The crops in the dry-land, lightly irrigated, and fully irrigated plats respectively were 13, 19, and 21 inches in average height, the average length of leaves being 4, 5, and 6.5 inches. While only 1 to 2 tillers per plant occurred in the dry land, 2 or 3 were usual in the other plats. The dry-land crop showed distinct signs of suffering from drought.

FIG. 8.—Roots of wheat: *A* and *B*, 6 weeks old, the former in soil where little water occurred in the second foot: *C*, *D*, and *E*, 2.5 months old in dry land, lightly irrigated (more clayey) and fully irrigated (sandier) soils respectively.

The root habit in the three plats was very different, as may be seen in figure 8, C, D, and E. The larger roots, which were 4 to 8 in number in the drier soils, were slightly fewer in the fully irrigated plat, where they also spread less widely (according to normal habit), but penetrated much deeper in the sandy soil. The maximum depth of penetration in the several plats, beginning with dry land, was 31, 41, and 65 inches respectively. In dry land the roots often spread horizontally a few inches below the soil surface for distances of 6 to 10 inches, others reached a similar lateral spread at depths of only 6 or 8 inches, thus securing the water furnished by showers, and some grew rather vertically downward. All showed by their meandering course the difficulty of penetrating the compact soil. In irrigated soil the lateral spread was much less pronounced. However, except for a greater length of unbranched root-ends in moist soil, the rate of branching (8 to 12 per inch) was not greatly different. But the branches became longer as the soil became drier and the supply of tertiary branches, which was practically nil in the moist soil, became pronounced. In all the plats the plants had put forth fine roots which ran almost horizontally in the surface soil. In many instances, more especially in the drier plats, some of these had grown but a few inches and died. It seems that this root-growth had been stimulated by rains (or irrigation), some of the roots which had failed to penetrate deeper dying as the holard was lost by evaporation. Great mats of these roots, especially long and branched in the dry land, filled the furrow slice. The presence of a clayey subsoil below the surface 10 inches of sandy loam in the lightly irrigated plat may have accounted in part for the reduced penetration of the root system here, as compared with the fully irrigated plat where the soil was sandy throughout.

The third examination was made a month later, on July 5 to 7, when the crops, now 96 days old, were nearly ripe. The very meager rainfall during this interval was entirely dissipated in several light showers, and the soil in the dry land had become progressively drier (table 6). The water-content in the several wheat plats is given in table 9. The lightly irrigated plat had been watered on June 9 and 28 and the fully irrigated one in addition on June 21. The crop in the dry land was only 15 inches high, perhaps half of the plants only being furnished with a tiller, very few of which headed (plate 2A). In the lightly irrigated plat the crop was 41 inches tall, mostly 1, but very frequently 2, tillers per plant with heads occurring, while in the heavily irrigated field 2 tillers with heads predominated, although many plants had but 1. The average height was 43 inches (plate 2B).

Differences in root habit were quite as marked as at the preceding examination (fig. 9). A comparison of figures 8 and 9 shows that the roots in the dry land had grown relatively little during the month, the chief difference being a more thorough occupation of the second and, to a slight extent, the third foot of soil. The working depth was 24 inches as compared with 36 and 52 inches in the lightly and fully watered plats respectively. In the same sequence the maximum depths of penetration were 37, 55, and 75 inches. As before, the lateral spread was greatest in dry land. The plants in all the plats were similar in having a large number of superficial roots arising from the nodes above the hypocotyl and spreading widely in a rather horizontal position so as to thoroughly occupy the furrow slice. Probably owing to the death by drought of many of these roots in the drier plats, they were more abundant and also longer in the fully irrigated one. Here they extended outward to distances of 10 to 14 inches. These, with the profusely branched older roots, formed a wonderfully efficient absorbing system. Although little or no difference in the number of primary branches on the larger roots was determined, the smaller growth of these in length as the soils grew wetter was very marked, those in the best watered soils being

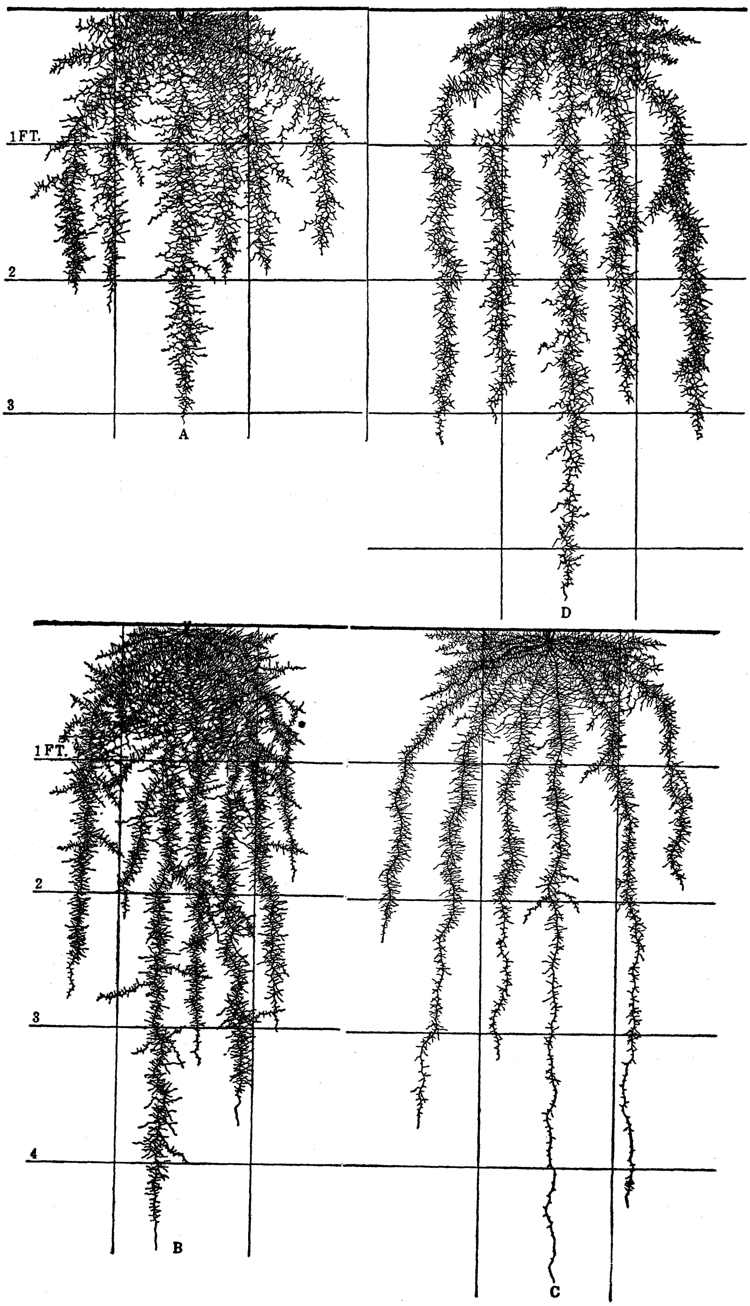


FIG. 9.—Roots of wheat at maturity: *A*, dry land; *B*, lightly irrigated; and *C*, fully irrigated soil, 1922; *D*, dry land, 1923.

usually only about an inch long. Moreover, they had relatively few secondary and tertiary branches compared with the densely rebranched roots in the dry land. These differences in number and length of branches were clearly marked, even among the plants of the fully and lightly watered soil. Owing to the sandier soil in the fully irrigated plat (nearly pure sand below the furrow slice) the yield, which was at the rate of 29 bushels per acre, was 3 bushels less than in the lightly watered but more clayey soil, but that in the dry land was only 3 bushels per acre. The total dry weight in tons per acre in the above sequence was 2.9, 3.4, and 0.4 respectively (plate 1, B).

EXPERIMENTS WITH SUGAR BEETS.

Klein-wanzleben sugar beet was drilled one inch deep on April 12 in rows 18 inches apart in the seed-bed earlier prepared. Similar seeding but 1.5 inches deep was done on the dry-land plats at the same time. On May 26 the crop was thinned so that the plants were 12 inches apart in the rows. The plats were also subjected to shallow cultivation at this time and on several other occasions during the earlier part of their growth. The water-content to the time of the first root excavations on June 7–9 may be found in table 10.

TABLE 10.—*Holard of beet plats in excess of hygroscopic coefficient, 1922.*

Date, etc.	0 to 0.5 foot.	0.5 to 1 foot.	1 to 2 feet.	2 to 3 feet.	3 to 4 feet.
Dry land:	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
Apr. 19	6.6	3.3	1.3	4.4	4.6
May 8	3.9	3.8	3.4	0.1	3.8
29	2.7	3.4	2.6	−1.5	−1.3
June 12	5.4	8.2	6.0	......	......
July 8	2.1	3.8	2.4	1.5	......
Sept. 13	−0.7	0.8	1.5	0.9	4.0
Hygro. coef	4.2	5.4	4.4	4.3	5.6
Lightly irrigated:					
Apr. 19	6.0	10.3	12.4	12.0	10.8
May 8	5.3	8.4	12.9	10.5	6.1
29	6.6	8.8	11.6	12.7	5.4
June 12	3.9	9.0	12.8	12.2	6.1
July 8	0.2	2.7	8.2	6.2	5.3
15	−1.1	−1.4	−0.4	3.5	......
15	(20.0)	(20.2)	(14.1)	(1.9)	......
Aug. 19	0.1	−0.2	3.3	9.5	......
19	(13.0)	(13.3)	(8.5)	(2.2)	......
Sept. 13	0.5	2.6	9.4	11.0	14.2
Hygro. coef	4.6	4.9	8.0	6.8	4.0
Fully irrigated:					
Apr. 19	5.2	10.1	10.4	10.1	11.3
May 8	5.7	8.5	12.6	10.0	6.0
29	6.3	8.4	11.9	12.4	4.8
June 12	4.0	9.6	12.3	12.0	5.1
28	2.6	1.4	2.5	4.5	5.3
28	(16.3)	(16.0)	(10.4)	(2.8)	......
July 8	3.3	7.8	10.9	6.0	9.1
22	1.1	0.9	0.6	5.9	......
22	(14.7)	(14.5)	(15.1)	(8.8)	......
Aug. 19	2.6	2.4	7.5	11.6	......
19	(10.5)	(10.4)	(3.8)	(3.9)	......
Sept. 13	0.8	4.8	8.6	12.6	16.1
Hygro. coef	3.5	3.7	3.5	3.2	2.8

The chresard was much more favorable in the irrigated plats, although no water had been added. Although the plants were slightly less than 2 months old, they had from 8 to 10 leaves each. Those in the dry land were about 4 inches tall, while in the irrigated area they averaged an inch higher.

As is well known, sugar beets are characterized by a strong tap-root (fig. 10). Striking differences in size, depth of penetration, and branching habit occurred in the different plats. Those in the dry land averaged about 5 mm. in diameter, while in the irrigated plats this was nearly 2 mm. greater. They tapered off rapidly and in descending 3 or 4 inches lost half of their width.

A maximum depth of only 14 inches was found in dry land, where practically no water was available in the second foot during April and very little during May, and 28 inches in the irrigated plats, where the root could

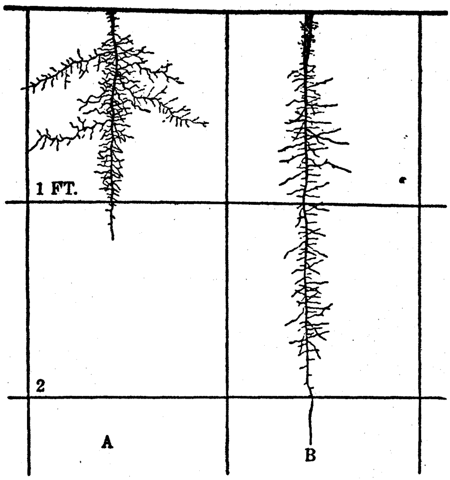


FIG. 10.—Sugar beets about 2 months old: *A*, dry land (practically no chresard in second foot); *B*, irrigated soil, 1922.

develop more normally. Just below the soil surface and for a distance of 2 to 4 inches, laterals occurred in two rows on opposite sides of the root. They were grouped in clusters of 2 to 4. They seldom exceeded 1.5 inches in length, but this root zone was more extensive (about 4 inches long) on the larger roots in the moister soil. Larger branches originating from all sides of the root occurred in the deeper soils, extending much nearer to the end of the tap-root in the dry land. Here they were 1 to 7 inches in length, the longer ones being profusely rebranched, while in the irrigated soil they were not only much shorter (2.5 inches or less), but were very poorly furnished with laterals. Moreover, these primary branches were less numerous (6 to 8 per inch) than in dry land, where 8 to 12 occurred regularly on an inch of tap-root. Differences in lightly and fully irrigated soil consisted of lateral branches on the roots, in the former being somewhat more numerous and their sublaterals longer. Thus these white, succulent, rather tender beet roots are considerably modified by environment.

Excavations were again made and the roots examined just a month later, on July 7–8. As already stated, no efficient rainfall occurred during this period and the soil became almost depleted of available water in the dry land, where only 2 to 4 per cent remained to a depth of 3 feet (table 10). The chresard of the surface foot was also low in the lightly irrigated plat, but a good supply occurred deeper. The fully irrigated crop had been watered on June 28, and here the plants had made their best development.

In all the plats, in addition to 12 to 14 nearly full-grown leaves, each plant had 3 or 4 only partly developed, these being somewhat more advanced in the fully watered plat, where the leaves were also considerably larger. They were 5 inches high in dry soil and increased progressively to 12 and 14 inches in the moister plats. The lateral spread of tops, which was 9 to 12 inches for the dry-land plants, reached 18 inches in the irrigated plats, those in the fully irrigated field being more turgid and assuming a more erect position (plate 3).

The roots had made a most remarkable growth during the 30-day interval, branching profoundly and extending well into or beyond the third and fourth foot of soil (fig. 11). Thus, they had doubled in length and increased the absorbing area many fold. Differences in development were even more pronounced than at the earlier examination, the outstanding features of the root system in the fully watered plat being the marked growth of the shallow absorbing system and the development of long, deeply penetrating branches in the subsoil. The dry-land plants had neither of these habits, but were characterized by large numbers of horizontally spreading major

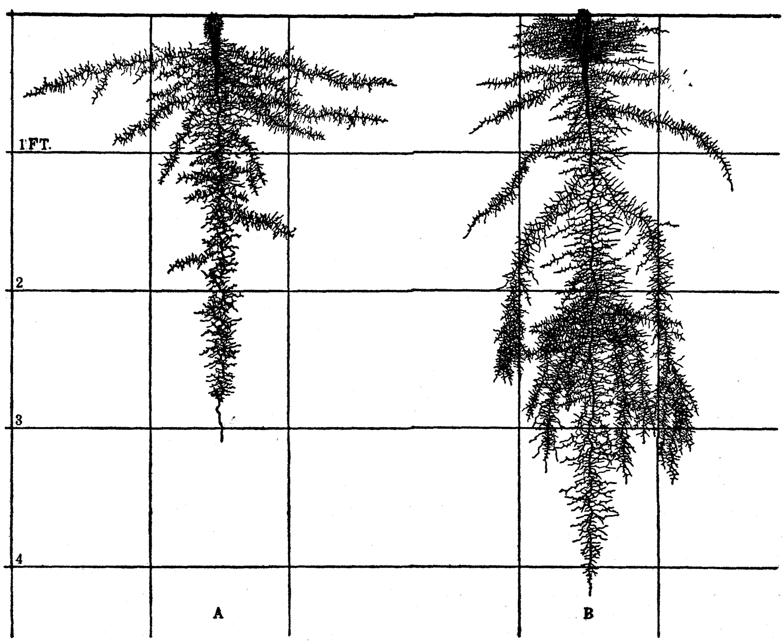


FIG. 11.—Sugar beets about 3 months old: *A*, dry land with low holard of subsoil; *B*, fully irrigated soil, 1922.

laterals in the surface 12 to 18 inches, where soil moisture had been constantly more abundant. Among the dry-land plants the tap-roots were slightly less than 2 inches in diameter, but in the fully watered plat they were 2.5 inches. All tapered so rapidly that even the larger ones were scarcely half an inch in width 6 inches below the surface. In the hard soil of the dry land they zigzagged downward to depths of 30 to 46 inches, while in moist soil they pursued a more even vertical course, reaching 50 to 54 inches depth.

Branches in the surface soil were very limited on dry land; only tiny rootlets less than an inch in length occurred. Their growth had apparently been stimulated by very recent showers and they were not yet clothed with root-hairs. In striking contrast, the beets which had been irrigated about 9 days earlier had developed 60 to 75 roots per linear inch in zones 4 or 5 inches long on two sides of the tap-root. They spread horizontally for distances of 3 to 5 inches and were profusely branched with secondary laterals at the rate of 8 to 12 per inch. This portion of the root system, which had failed to develop in the drier soil, added materially to the absorbing area of the rapidly developing plants. The smaller dry-land plants gave off many strong, wide-spreading laterals in the surface foot, a response no doubt to the very low water-content of the deeper soil. These became progressively younger and shorter downward, but the number throughout the course of the tap-root was usually 4 to 7 branches per inch. The sublaterals were also long and rebranched. In the moist soil, however, long branches occurred regularly in the first, second, and third foot, some being over 2 feet long. The direction of these roots away from the horizontal was marked. Like the tap-roots, they were profusely branched and rebranched with both long and short laterals. The roots of the lightly watered beets were in many ways intermediate to those described. The course of the tap-root was somewhat irregular, but not to so great an extent as in the dry land. The surface roots were in extreme cases an inch long, but as a whole poorly developed, since water in the surface soil was scarce, while the larger branches ran off more horizontally than in the more normally developed fully watered plants.

In both of the irrigated plats some interesting cases of root stratification due to soil structure were encountered. In one trench, at a depth of 16 inches, there occurred a local stratum of harder clayey soil a foot in thickness. Another shallow layer similar in nature was encountered at 3.5 feet. At both depths, undoubtedly due to the greater nutrient content in these non-sandy soils, long, densely branched roots ran off horizontally in great profusion, contrasting in a striking manner with the more poorly branched parts above and below. This local irregularity in soil structure clearly shows the effects of different partial environments upon root development. Similar cases have been found among native plants (cf. Weaver, 1919 : 10).

A final study of the beets was made on September 12. A heavy rain (0.7 inch) on July 29 and another (1.2 inches) on August 3 had somewhat replenished the soil-water (table 6), although in the unirrigated plat very little water was available at any time (table 10). The lightly watered plat was irrigated for the first time on July 15 and again on August 19, the fully irrigated one 3 times, viz, on June 28, July 22, and August 19.

The plants at this time had 20 to 30 leaves each, those in dry land being only 9 inches long, while in the irrigated plats they were twice this length and had three or four times as much photosynthetic area, those in the fully watered plats being the larger. Effects of drought were very evident. Some of the plants in the dry land had died and on all many of the outer leaves were dead, while the others frequently wilted so badly that they did not recover even at night. The diameter of the tops of these drooping plants was 19 inches, as was also that of the lightly watered plants, while in the other plat they were 23 inches in width. In the fully irrigated plat some of the older outer leaves were dead or drying, but this condition was more pronounced in the lightly watered area.

Root development was correlated with that of tops. The fleshy tap-roots were 3 to 6 inches in diameter in the irrigated soil but only about 2.75 inches in the dry land. Moreover, while the dry-land plants had increased their depth from the third-foot level to about 3.5 feet (maximum 4.5 feet) since the last examination, those in the irrigated plats, which were about 4 feet deep, now occupied the fifth and a part of the sixth foot of soil (maximum depth 6 feet). While the root plan of the irrigated plants, with their widely spreading horizontal surface system and rather vertically descending and deeply penetrating major branches, was fairly well blocked

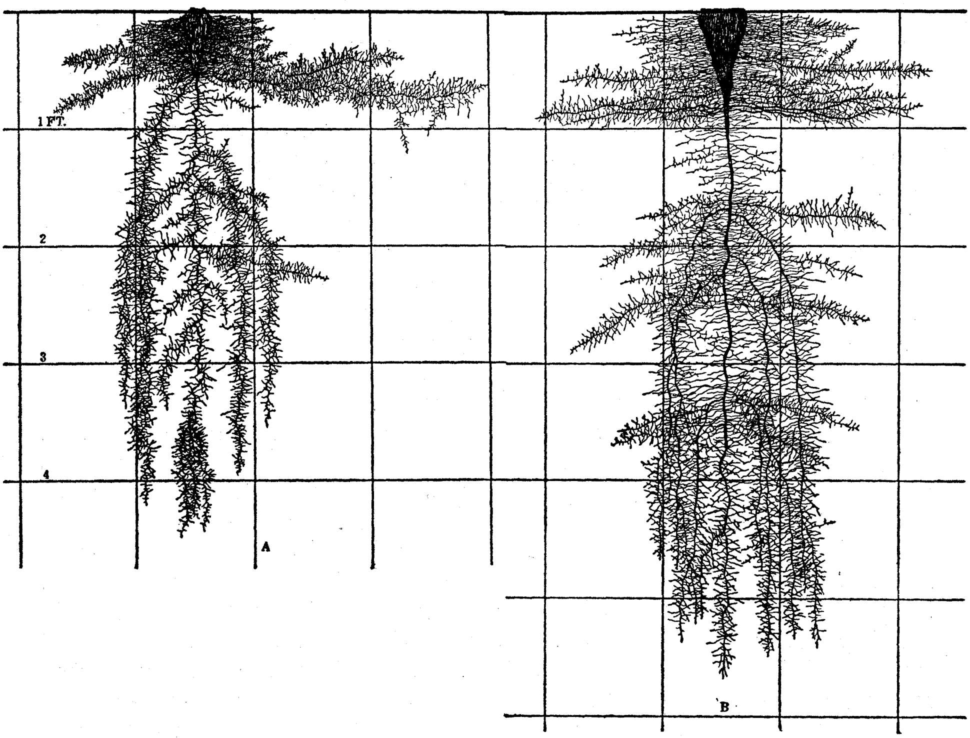


FIG. 12.—Sugar beets on September 12: *A*, dry land; *B*, fully irrigated soil, 1922.

out on July 7 at the preceding examination, marked changes had occurred in the root habit of the dry-land plants (fig. 12). Here the two zones of surface laterals, which had then just appeared, were now well developed. At a depth of 1 to 7 inches these arose in great profusion from two sides of the tap-root and ran off horizontally for distances of 3 to 7 inches, in response to the increased surface moisture due to rains. Near the lower edge of these zones they were supplemented by larger and longer roots which spread 10 to 34 inches and were rebranched to the fifth order at the rate of 10 to 14 rootlets per inch, the whole forming a close network in the dry soil. On the larger roots of the irrigated plants these lateral root-producing zones were longer, as were also some of the smaller roots, but the larger ones, originating from the base, did not extend beyond 2 feet and were less profusely branched.

A root habit frequently found in the harder soils of dry land, and also met occasionally in the lightly watered plat, was that of the tap-root breaking up into two or three or sometimes more branches of similar diameter. This frequently occurred at depths of only 6 or 8 inches, but sometimes deeper. Among 7 individuals examined in the mellow moist soil of the irrigated plat, only 1 showed this behavior, and here it divided at 12 inches depth.

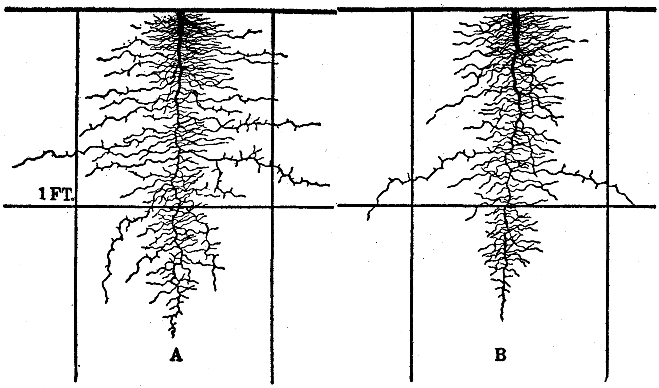


FIG. 13.—Sugar beet roots about 2 months old: *A*, dry land; *B*, irrigated soil, 1923.

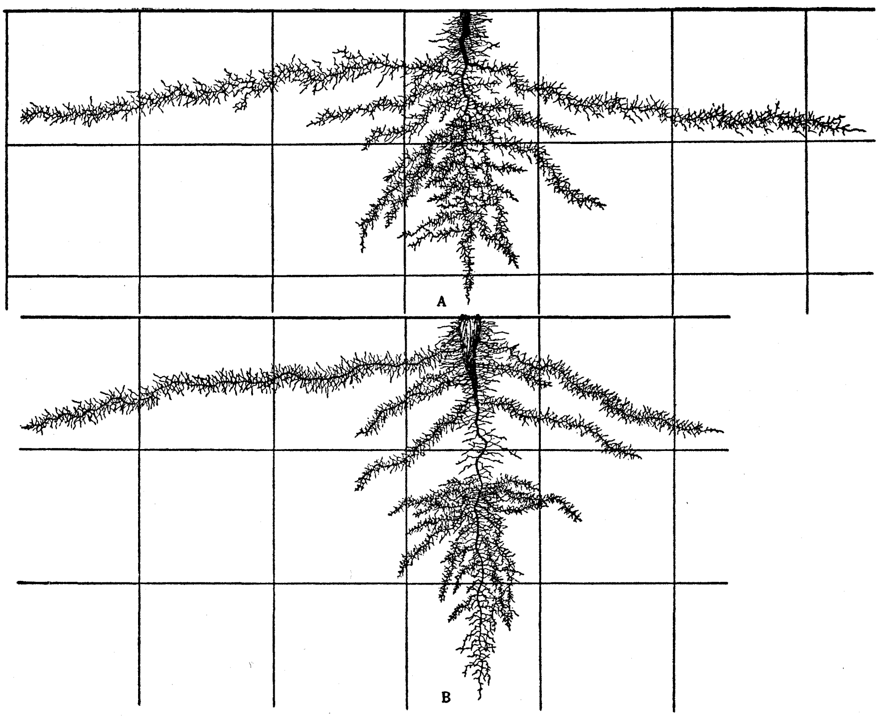


FIG. 14.—Sugar beets about 3 months old: *A*, dry land; *B*, irrigated soil, 1923.

Many of the deeper and formerly short branches in the dry land had now reached 2 or 3 feet in length. Their course was almost invariably rather obliquely downward, in this respect resembling the dry-land alfalfa, practically none spreading laterally through a distance greater than 7 inches. These, with their profuse branches, occupied the third and sometimes a part of the fourth foot of soil more or less completely. In the irrigated plants the roots usually spread more widely in the clayey stratum, in some instances, to 2.5 feet.

Seepage water occurred late in the season at about 5 feet depth in the fully irrigated plats, and the root penetration was not so great as in the lightly watered one, probably because of deficient aeration. Branching was similar in the two plats, except for a greater tendency for a wider lateral spread of roots in the shallower soil of the drier land. The sublaterals were longer, sometimes reaching 25 inches, while none were found to exceed 8 inches in the more moist soil. The surface root system of the fully watered plants contained a greater number of roots in the furrow slice, but they were hardly as long as in the drier soil of the lightly irrigated plats.

The beets in the dry-land plat yielded at the rate of only 2.5 tons per acre, those in the lightly watered plats 21 tons, while the fully watered plats yielded 22.5 tons per acre. They were harvested on September 26.

EXPERIMENTS WITH POTATOES.

Bliss's Triumph potatoes, widely grown in the region as an early variety, were planted in the three plats on May 6. Large pieces of tubers of uniform size were placed at 14-inch intervals in furrows 3 feet apart and covered to a depth of 3 or 4 inches. By frequent shallow tillage the plats were not only kept free from weeds, but also a good soil mulch was maintained in the dry land.

The first examination of the root habit was made on June 21–23. The May rainfall (1.3 inches) fell from the 27th to 31st, while the 0.25 inch in June added nothing to the water-content of the soil. Table 6 shows

TABLE 11.—*Holard of potato plats in excess of hygroscopic coefficient, 1922.*

Date, etc.	0 to 0.5 foot.	0.5 to 1 foot.	1 to 2 feet.	2 to 3 feet.	3 to 4 feet.
Dry land:	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
May 8	3.8	3.5	3.9	−1.0	3.8
29	2.7	3.4	2.6	−1.5	0.0
June 17	0.8	3.0	4.0	1.1	0.0
23	0.0	0.8	3.8	...	...
July 5	1.8	3.9	3.1	...	...
Hygro. coef	4.2	5.4	4.4	4.3	5.6
Lightly irrigated:					
May 8	5.3	8.9	13.1	10.0	6.0
29	6.6	8.8	11.7	12.8	5.6
June 23	2.1	4.4	9.2	10.6	...
28	3.8	3.6	13.1	11.4	...
28	(14.5)	(14.5)	(7.3)	(5.4)	...
July 5	5.0	6.6	9.0	10.3	...
15	4.5	4.3	13.0	12.8	...
15	(8.0)	(8.0)	(2.9)	(2.1)	...
22	7.2	7.0	14.4	13.6	...
22	(4.9)	(4.7)	(2.4)	(0.0)	...
Hygro. coef	2.9	3.1	3.0	5.0	4.1
Fully irrigated:					
May 8	5.0	9.0	13.5	10.4	5.9
29	6.2	8.4	11.3	12.9	5.8
June 23	2.5	4.4	7.4	11.5	...
23	(10.8)	(10.8)	(5.7)	(2.4)	...
28	8.6	8.3	12.6	8.1	...
28	(9.0)	(9.2)	(6.2)	(4.8)	...
July 5	8.9	8.6	11.5	10.9	...
5	(5.0)	(5.2)	(2.6)	(0.0)	...
15	5.2	4.9	9.7	9.3	...
15	(6.0)	(6.2)	(4.9)	(1.2)	...
22	10.9	10.6	7.6	10.8	...
22	(4.4)	(4.4)	(6.9)	(0.7)	...
Aug. 3	5.0	4.7	9.9	10.8	...
3	(6.2)	(6.3)	(1.7)	(0.8)	...
Hygro. coef	4.6	4.9	8.0	6.8	4.0

that no water was available in the third foot and only a small amount in the surface soil. Although neither of the irrigated plats had been watered, enough moisture was present to promote good growth. Two to four stalks occurred in a hill, and the plants were 8 to 11 inches tall, being slightly smaller in the dry-land plats.

The profound differences in the extent and branching of the roots in the two plats are shown in figure 15, A, B. In all the plats 50 to 85 roots per plant originated either about the old tuber or from the nodes above. Many of these in dry land extended horizontally throughout their whole length, penetrating the surface soil and ending at depths of only 1 to 8 inches. Others, after extending outward for 12 to 18 inches, gradually turned downward and ended at depths of 1 to 1.5 feet; usually 3 to 5 would take a rather vertically downward course, some reaching the 23-inch level. All were supplied with laterals as thickly as 15 to 20 per inch, of which the longest were 18 inches, although the average scarcely exceeded 5 inches. These were very thickly rebranched to near their tips. Thus, the surface foot of soil, beginning just beneath the dust mulch, was filled with an absorbing net-work of white, succulent, tender roots, while the second foot was beginning to be exploited to satisfy the heavy demands for water. Root habit in the two irrigated plats was at this time identical and differed from that in the dry land in a slightly smaller penetration, fewer roots occurring in the second foot of soil, and especially in fewer and shorter branches. For example, the maximum lateral spread seldom exceeded 20 inches and was usually much less as compared to the usual spread in the dry land of 18 inches, with a maximum exceeding 2.5 feet. Clearly, the scarcity of water in the dry land had resulted in an extraordinary root growth. Young tubers only 2 or 3 mm. in diameter had begun to appear in great numbers on all of the plants.

Owing to hot, dry weather, coupled with a very low chresard, which at certain levels was practically nil, the crop in the dry land had not increased in height by July 7, when again examined. The plants wilted almost daily and regained partial turgidity only during the cool nights. Under these conditions growth was poor. The crop, which had been irrigated on June 28, was 18 inches tall, of a healthy dark-green color, and was growing rapidly, a few blossoms having appeared (June 11). Where water had been provided at two intervals (June 23 and June 28), the plants were 2 inches taller, growing luxuriantly, and coming well into blossom (plate 4). Correlating with this excellent above-ground development, the roots had grown proportionately. But just as little change had occurred in the tops in the dry land; so, too, the roots had developed scarcely beyond the stage reached two weeks earlier. In fact, the lateral spread and branching had not changed, except that the branches now extended to the very root-tips, indicating the cessation of root elongation. However, the working depth had been increased about 6 inches and the maximum penetration to 26 inches. None penetrated into the hardpan at 26 inches depth. Shortage of water had caused a cessation of development, and in spite of the wonderfully extensive root system, the plants were losing ground. The tubers had developed scarcely at all. Only a very few were 6 mm. in diameter, rarely as large as 15 mm.

The fully watered potatoes had increased their absorbing area by extending their roots both outward and downward (cf. fig. 15, A and B), thus keeping pace with the growth of the tops. The lateral spread had now reached a maximum of 2 feet on all sides of the plant. Although the great bulk of the roots occurred in the surface foot, they were not infrequently deeper, a few having penetrated an inch into the third foot of soil.

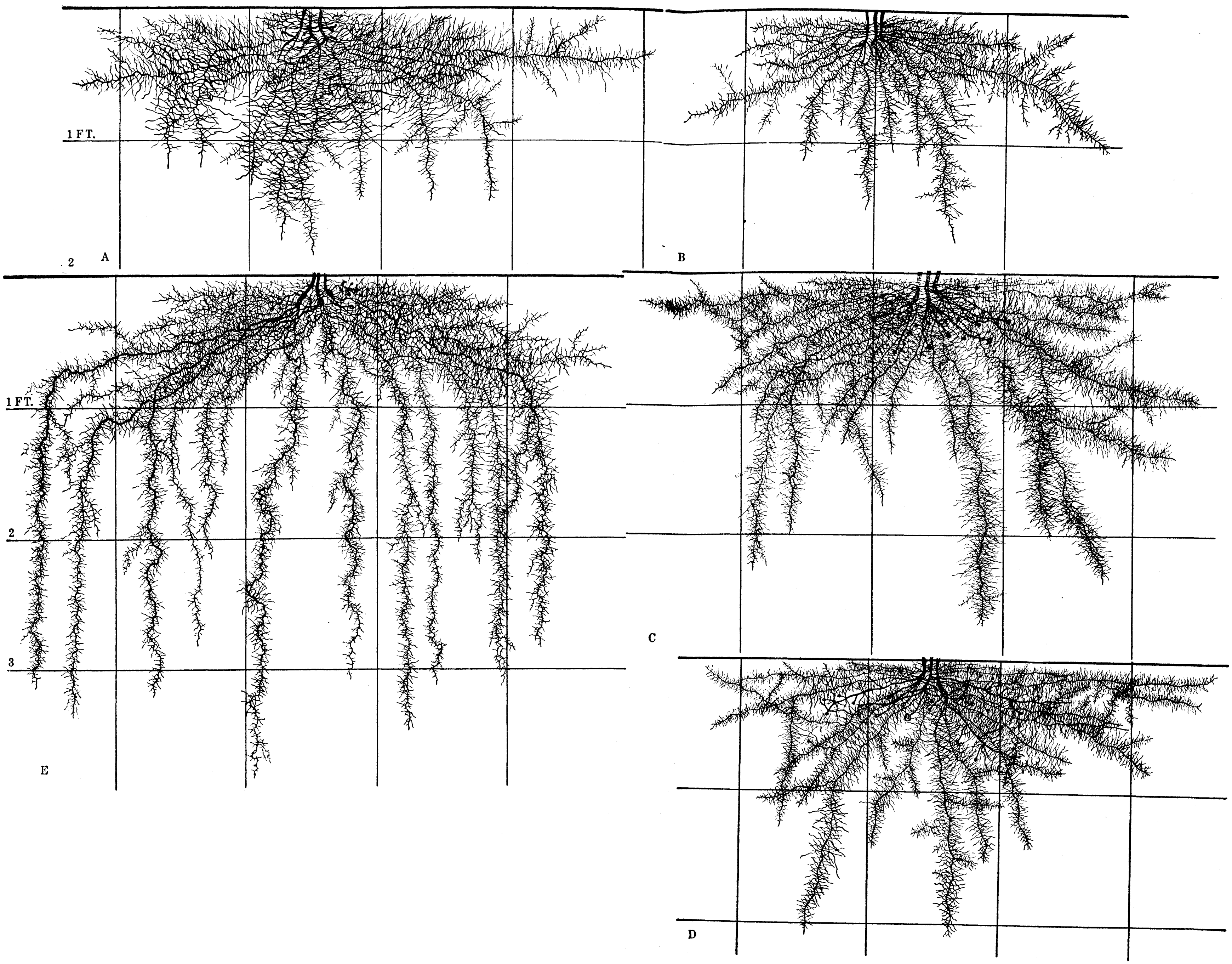


FIG. 15.—One-half of the root system of potatoes when 6 weeks old: *A*, dry land; *B*, irrigated soil. And about 9 weeks old; *C*, lightly watered, and *D*, fully irrigated soil, 1922; *E*, mature plants, dry land, 1923.

Root habit in the lightly watered area differed not only in lateral extent and depth of penetration, but also in more profuse branching. Surface roots were sometimes 4 inches longer in this drier soil, while more roots were found that took a vertical or nearly vertical course downward. Thus the second foot of soil became much more thoroughly occupied, the working depth reaching 2 feet as compared with 16 inches in the wetter soil; the maximum penetration likewise was 7 inches deeper (fig. 15, c).

As regards branching, 12 to 20 smaller laterals regularly occurred per inch, as against 9 to 16 in the fully irrigated soil, but the branches in the two cases were very similar in length. Moreover, the main roots showed a much greater tendency to break up into 3 or 4 long branches in the drier soil. Tubers were abundant in both plats, being larger (6 to 33 mm. in diameter) in the fully irrigated one. Moreover, the rhizomes upon which they were borne were longer (sometimes 15 inches in extent) than those growing in the harder, drier soil. Thus, root development in the three fields was distinctly different, the differences being readily correlated with differences in the available water-supply. The yield at maturity in the dry land was at the rate of 19 bushels per acre, all the tubers being small, in the fully watered plats 160 bushels, while in the lightly watered plat 303 bushels per acre were grown.

EXPERIMENTS WITH CORN.

A yellow dent corn, Minnesota No. 13, a variety considered the best adapted for this region, was planted in the three plats on May 10. Shallow furrows, 3 feet apart, were made with a plow and the kernels dropped into these 16 inches apart and covered to a depth of 3 inches. In all the plats the crop was given shallow cultivation from time to time in order to prevent the growth of weeds and also to furnish a mulch in the dry land. Sufficient moisture was present even in the latter to cause good germination and early growth (table 12).

TABLE 12.—*Holard of corn plats in excess of hygroscopic coefficients, 1922.*

Date, etc.	0 to 0.5 foot.	0.5 to 1 foot.	1 to 2 feet.	2 to 3 feet.	3 to 4 feet.
Dry land:	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
May 17	5.8	5.0	2.9	0.0	0.2
June 22	4.2	5.7	7.3	...	...
July 5	0.0	2.0	4.5	2.7	...
Sept. 12	0.1	1.7	4.1	1.9	3.7
Hygro. coef	4.2	5.4	4.4	4.3	5.6
Lightly irrigated:					
May 17	4.9	8.4	13.2	9.0	8.0
17	(9.0)	(9.0)	(0.8)	(3.3)	...
June 22	2.0	6.8	14.2	14.8	...
July 5	1.6	1.4	6.9	9.7	...
5	(11.0)	(11.7)	(7.3)	(5.7)	...
Sept. 12	0.0	2.1	2.8	8.6	10.5
Hygro. coef	2.9	3.1	3.0	5.0	4.1
Fully irrigated:					
May 17	4.7	8.5	13.0	9.2	7.9
17	(8.8)	(9.2)	(0.9)	(3.4)	...
June 22	0.2	3.4	8.6	12.8	...
22	(17.0)	(17.1)	(7.7)	(0.0)	...
July 15	4.0	1.4	7.6	3.0	...
15	(7.0)	(7.2)	(1.6)	(5.4)	...
Aug. 3	3.2	5.8	5.2	9.3	...
3	(6.3)	(6.0)	(4.6)	(3.5)	...
19	6.9	4.3	9.5	5.7	...
19	(5.8)	(6.0)	(1.0)	(3.1)	...
Sept. 12	3.7	12.9	10.5	10.7	9.0
Hygro. coef	5.5	8.1	8.0	4.5	2.3

The first examination of root habit and development was made on June 21–23, when the plants were about 6 weeks old. In the dry land and lightly watered plat (which had been irrigated a week after planting) the plants had 7 or 8 leaves each and were 12 to 15 inches tall, those in dry land being about 2 inches the higher. Like those in the other plat, which had also been irrigated on May 17, they were making a good growth. The latter, however, were only 10 to 14 inches tall and had but 5 or 6 leaves.

The general root habit of corn at this age, as well as the differences in habit, is clearly shown in figure 16. Even a glance reveals marked differences in the several plats. Each plant was furnished with 10 to 16 thick, fibrous roots. In the dry land, while some ran off rather horizontally, most of them grew outward and downward 1 or 2 feet; the longest extended to 2.5 feet, when it turned downward into the second foot of soil. In fact, this latter tendency was marked, the roots seeming to seek moister soil. The longest penetrated a little into the third foot; a few younger and shorter roots ran rather straight downward and branching throughout was profuse.

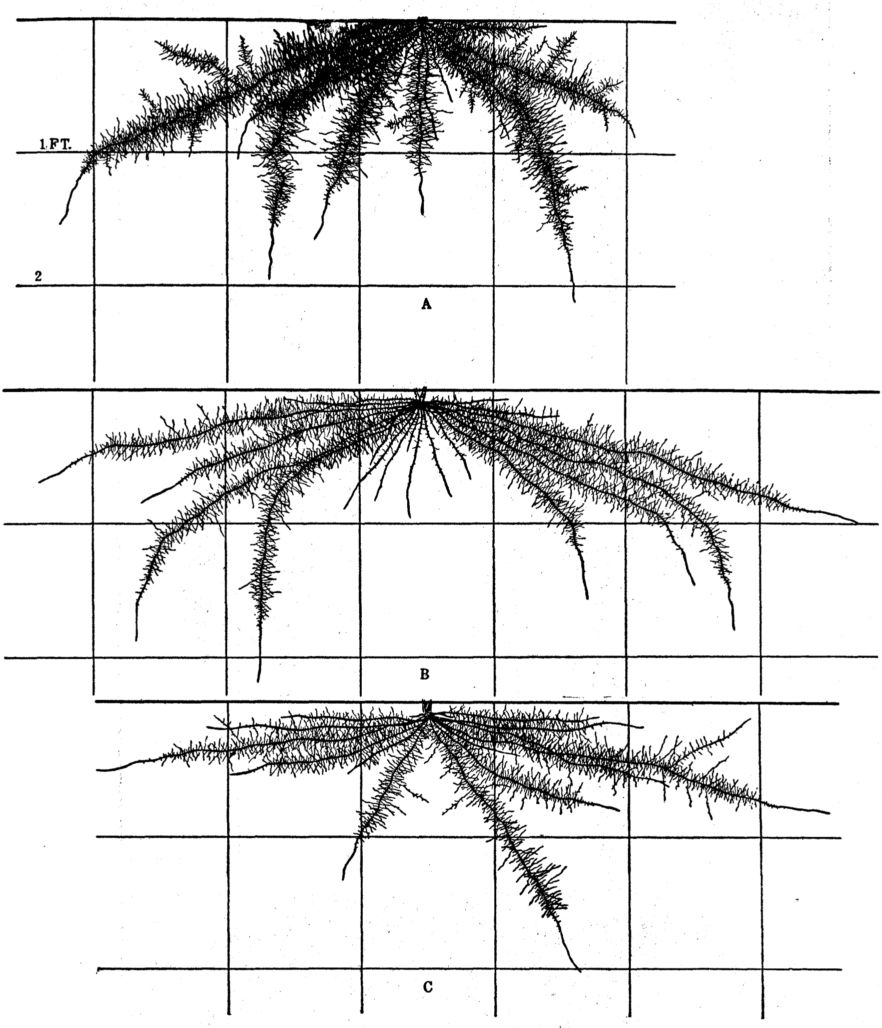


FIG. 16.—Root system of 6-weeks-old corn: *A*, dry land; *B*, lightly irrigated; *C*, fully irrigated soil.

In the fully watered plat the roots ran much more horizontally, spreading even 2 or 3 feet at a depth of only 6 to 10 inches. Vertically penetrating roots were practically absent, and only a few entered the second foot of soil. In fact, the bulk of the root system was in the first 6 inches. This normal surface-rooting habit (cf. Weaver, Jean, and Crist, 1922 : 21) is in marked contrast to that of dry land. Moreover, great differences were found in the degree of branching. While in the watered plat the laterals averaged 12 per inch, they occurred at the rate of 20 to 35 per inch in dry land. Here they averaged 4 inches in length and were rebranched

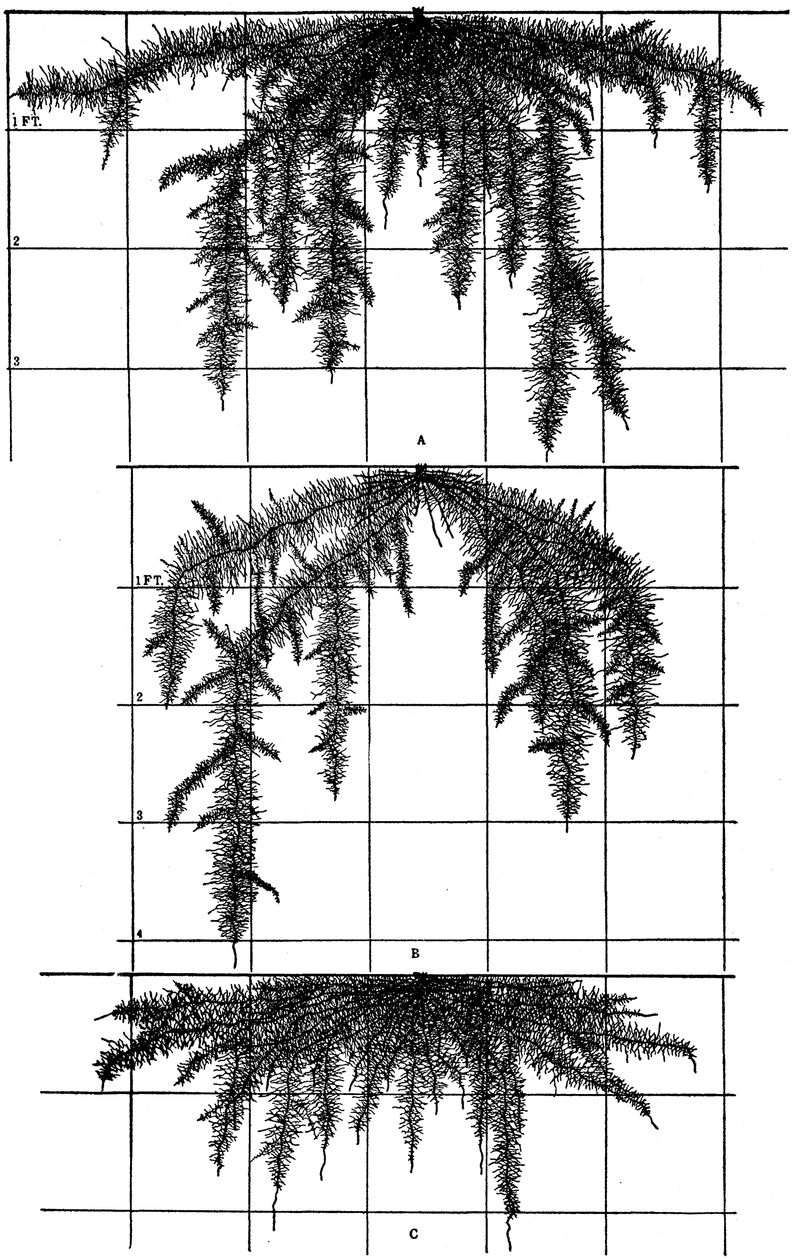


FIG. 17.—Corn about 8 weeks old: *A*, dry land; *B*, lightly irrigated; *C*, fully irrigated soil.

at the rate of 18 per inch, while in the moist soil the average scarcely exceeded 2 inches and only 9 branchlets per inch occurred.

Conditions in the lightly irrigated plat were intermediate, an effect brought about by differences in soil, the water-content being much the same as in the fully irrigated one. In the latter, a heavier subsoil underlay the furrow slice of sandy loam, while in the lightly irrigated plat the sandy loam extended beyond the second foot. Here the widely spreading, shallow, horizontal roots were fewer and shorter, a pronounced tendency to run off obliquely and especially to turn vertically downward being manifest. Many entered well into the second foot of soil and some reached depths of 27 inches. A good growth of younger, vertically descending roots, quite absent in the other watered plat, was probably a response to the dry, hot weather of the 10 days preceding, which caused the leaves to curl in the afternoons. The branching closely resembled that in the other watered plat, but was slightly greater.

The next examination was made over 2 weeks later, on July 8–10. No efficient rain had fallen and no water was available in the surface 6 inches of the dry land, while only 2 to 4 per cent remained in the deeper soil (table 12). The lightly irrigated soil was also very dry until it was watered on July 5, but the other plat had been irrigated a second time on June 22. The crop in the fully watered plat was 34 inches high, 37 inches in the lightly watered soil, but only 24 in dry land. In all three fields the tassels were just beginning to appear. The crop was in a flourishing condition, except in the dry land, where it showed the effects of the marked drought. The leaves were tightly rolled during the hottest part of the day and sufficient water was not available for them to recover even during the cool nights (plate 5).

In response to the low water-content, the roots had made a more marked growth in the dry land than in either of the other plats (fig. 17). The lateral spread, especially of the shallower roots, had been greatly increased, reaching a maximum of 42 inches, furnishing water from an area hitherto unoccupied. New roots had been added in such abundance that a total of 33 to 45 was found on each plant, as in the other plats. These added greatly to the occupation of the first and second feet of soil, while the older roots had extended their area far into the third and fourth feet. An average depth of 30 inches was determined and a maximum penetration of 46 inches. Long, profusely rebranched laterals were exceedingly abundant. These, like the larger roots, were often tortuous in their course because of the difficulty in penetrating the hard, dry soil. Growth was still occurring, as was shown by the presence of new main roots only a few inches long.

Thus, while the dry-land corn was deeply rooted, that in the fully irrigated field, with stalks a foot taller, was largely confined to the surface foot of soil, where moisture was rather constantly abundant. The lateral spread of roots was much less than in dry land, but more of the roots ended in the surface foot. The working level was only 2 feet deep and the maximum penetration 4 inches greater. Branching, as at the preceding examination, was much less pronounced and the laterals were much shorter.

Root systems in the lightly watered, more sandy soil differed from those last described in three well-defined ways. The first was the shortness of the newer roots in the surface soil, most of which had evidently grown

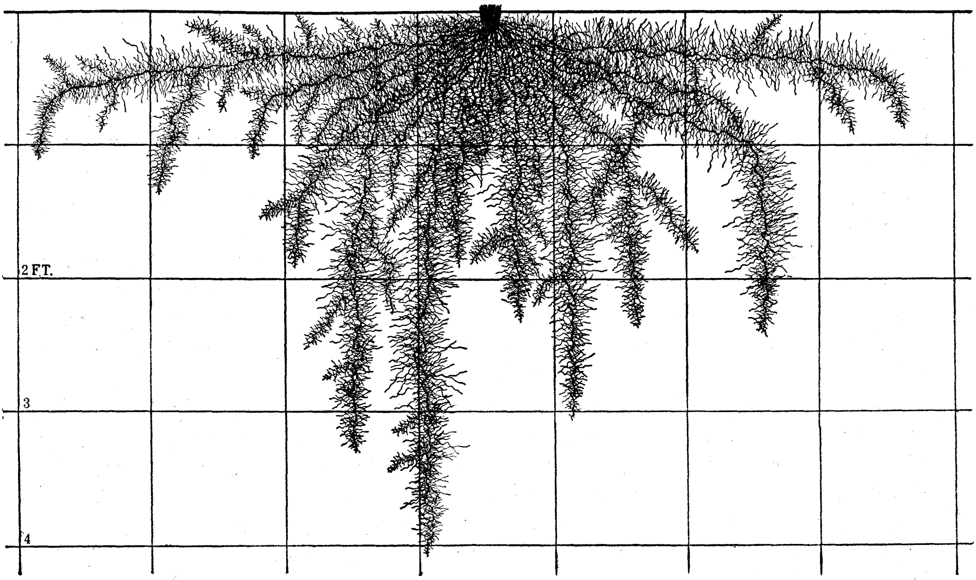


FIG. 18.—Dry-land corn on September 12.

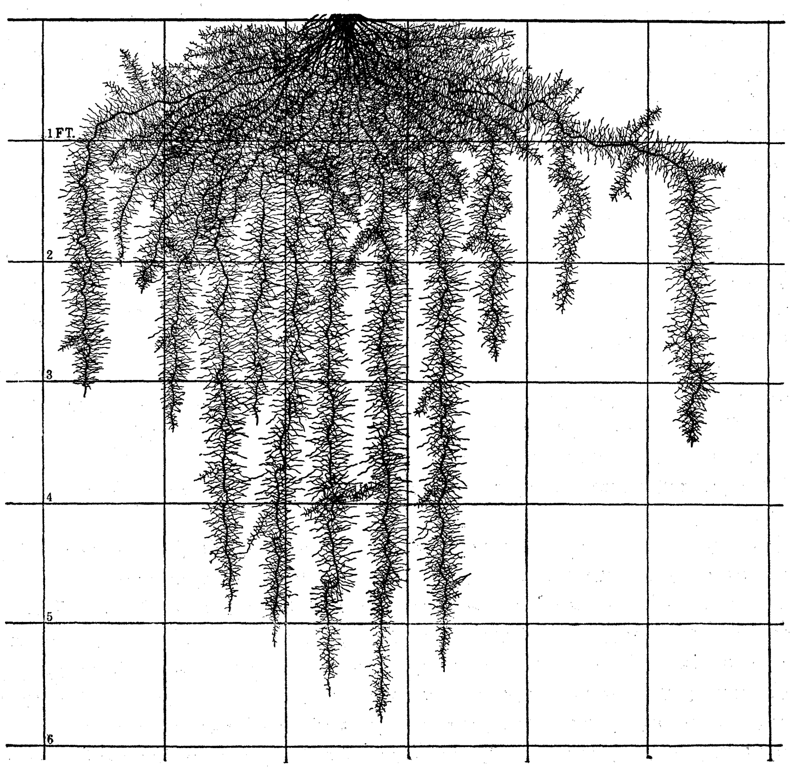


FIG. 19.—Corn in fully irrigated soil, September 13.

since the plat was irrigated only 5 days earlier. They were only 1 to 5 inches long, densely covered with root-hairs, but entirely unbranched. Absorption in the surface soil was much more poorly provided for than in the more moist plat, where the lateral spread of roots was also greater. A second difference was the great depths to which the older roots had penetrated. A working-level of 33 inches had been attained (exceeding that in dry land, where the deeper soil was without available water) and a maximum depth of 52 inches. Finally a great increase in branching (especially in length of laterals) had occurred when compared either with its earlier development or with that in the fully irrigated plat. During the week preceding irrigation the soil was so dry that the corn showed a marked rolling of its leaves, and it was probably in response to this condition that, as in the dry land, the growth of the branches occurred.

A final study of root habits of corn was made on September 12 and 13. Aside from a heavy rain (0.7 inch) on July 29 and another (1.2 inches) on August 3, no efficient moisture fell during the interval since the last examination. Thus, drought conditions prevailed in the dry land, although at the time of root excavation some available moisture remained in the second foot of soil, the corn having "fired" and lost most of its leaves during July, thus greatly reducing transpiration. The lightly watered plat had not been irrigated since July 5, and table 12 shows that the first 2 feet of soil were very dry. Water had been added to the other plat on July 15 and on August 3 and 19, and hence an excellent holard was maintained. In the dry land the crop showed little growth, having reached a height of only 3.5 feet, so extreme was the drought. The plants in the irrigated plats were rather uniformly 7 feet high and were furnished with large, well-filled ears. The leaves were dry and the husks were almost dry, while the kernels of corn were well dented and nearly dry. These conditions were somewhat more pronounced in the lightly irrigated field.

Practically no change had occurred in the root habit in the dry land (fig. 18). The occupation of the soil in the zone directly below the plant was somewhat more thorough and branches now occurred on all the roots to their very tips. The plants were unable to furnish sufficient water to keep the leaves turgid, and these in turn failed to supply the needed materials for further root growth. But in the fully irrigated plat marked changes had occurred (fig. 19). The roots, formerly confined to the first foot or two of soil, now extended into the fifth and sixth foot, while many of the horizontal laterals had likewise turned downward and penetrated deeply. The deepest roots, however, were the rather vertically descending ones of later origin. A working depth of 40 inches and a maximum penetration of 70 inches were found. Seepage water was encountered at the 6-foot level.

This remarkable root system was surpassed, however, by that which developed in the drier, somewhat sandier soil in the lightly irrigated plats (fig. 20). As in the former case, 50 to 70 major roots occurred. Also, the general form of the root system was similar to that just described, but some outstanding differences were found. The number of fine surface roots within the first 15 inches of soil was markedly fewer, due no doubt to the much drier soil. The lateral spread of the main roots was also slightly less, but the depth of penetration was greater. The roots, which were just well started on July 7, had now reached a working-level in the fifth foot, many penetrating far beyond, and, with the downward growth of the older, widely spreading ones, thoroughly occupied the third, fourth, and much of the fifth foot of soil. The working-level and maximum pene-

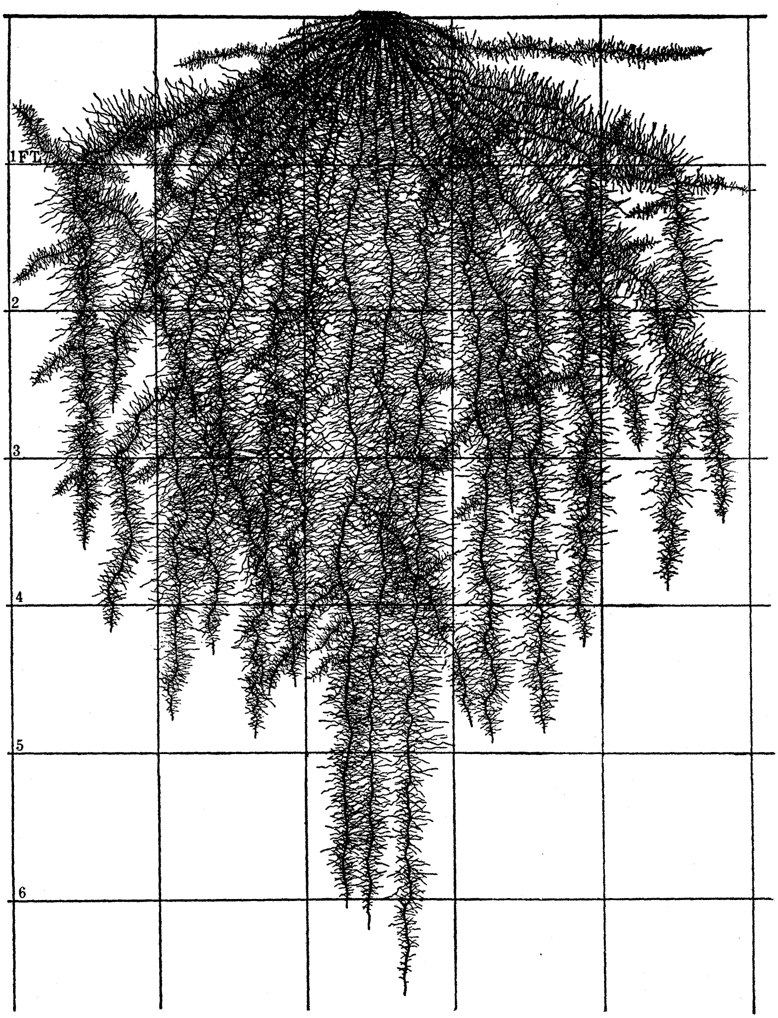


Fig. 20.—Corn in lightly irrigated soil, September 13.

tration were 58 and 80 inches respectively, as compared with 40 and 70 inches in the plat more freely watered. Even greater depths might have been attained except for the presence of seepage water at 73 inches. Moreover, branching was much more profuse throughout. For example, in the wetter soil, branches of the first order ranged from 12 to 20 per inch, while they were 18 to 25 per inch in the drier soil. Also, below the 15-inch level, the branches averaged nearly 2 inches longer and they were more thoroughly rebranched. The root system as a whole was very impressive and well fitted to supply the 275 pounds of water normally needed to mature a corn plant (cf. Kiesselbach, 1916). Thus, with crop plants, as with native species, too dry soil retards root growth, but a fairly moist, deep one permits maximum development, the roots becoming less extensive in soils supplied constantly with an abundance of water. The plants with the best root systems gave the greatest yield, the rate being 115 bushels per acre. The fully watered plats yielded 102 bushels and the dry land 25, the quality in the latter being very poor.

ENVIRONMENTAL CONDITIONS, 1923.

The season of 1923 had an abnormally high rainfall, an excess of 1.4 inches falling in March and 3.2 in June, that for April and May totaling only 1.3 inches below normal (table 8). Moreover, the showers were heavier than usual and quite well distributed, thus promoting a good crop growth even on the dry land, especially until midsummer.

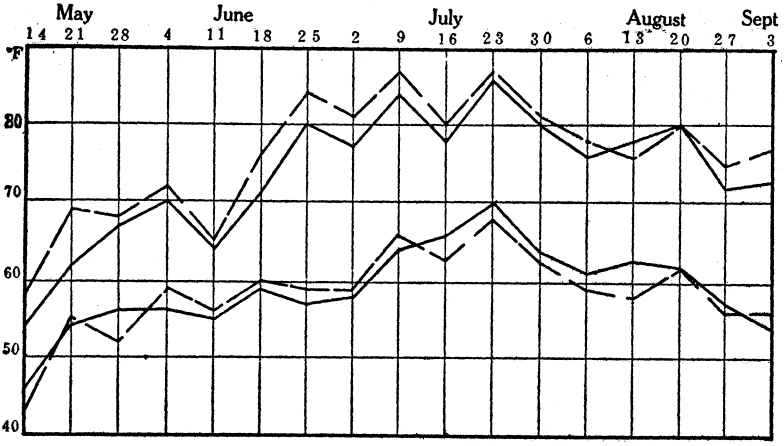


Fig. 21.—Average day air-temperatures (upper lines) and average night air-temperatures (lower lines) in dry-land (solid lines) and irrigated plats (broken lines), 1923.

Spring was 2 or 3 weeks later than usual. The average daily air-temperature, which was very similar in the two experimental areas throughout the season, was 11.8° F. lower than the preceding May, and 3.9° F. lower for June, and in general lower throughout the summer than in 1922 (cf. figs. 2 and 21). The extreme differences between day and night tempera-

Table 13.—*Soil temperatures in the dry-land and irrigated plats, 1923.*

Date.	Depth, 2 feet.		Depth, 3 feet.		Depth, 4 feet.	
	Dry land.	Irrigated.	Dry land.	Irrigated.	Dry land.	Irrigated.
	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*
Apr. 16	9.0	8.0	10.0	7.5	8.5	7.0
23	8.0	8.0	11.0	9.0	11.0	9.0
30	10.0	11.0	9.5	9.0	9.0	9.0
May 7	12.5	12.5	11.5	11.5	10.5	10.0
14	12.0	12.0	11.5	11.5	11.0	11.0
21	14.0	14.0	13.0	13.0	12.0	12.0
28	15.0	15.5	14.0	14.0	12.5	13.0
June 4	18.5	17.0	17.0	16.5	16.0	15.5
11	16.0	16.0	16.0	16.0	16.0	15.5
18	19.0	17.5	17.5	16.5	17.5	15.5
25	21.5	21.0	19.0	18.0	17.0	17.0
July 2	22.0	22.5	20.0	21.0	19.0	20.5
9	24.5	23.0	22.5	22.0	20.0	20.5
23	24.5	24.5	22.5	22.5	21.0	21.0

tures were again marked. While the mid-afternoon temperatures often reached 95° to 100° F., they frequently fell towards morning to 55° or 60° F. Differences in soil temperatures were no more in evidence than during 1922

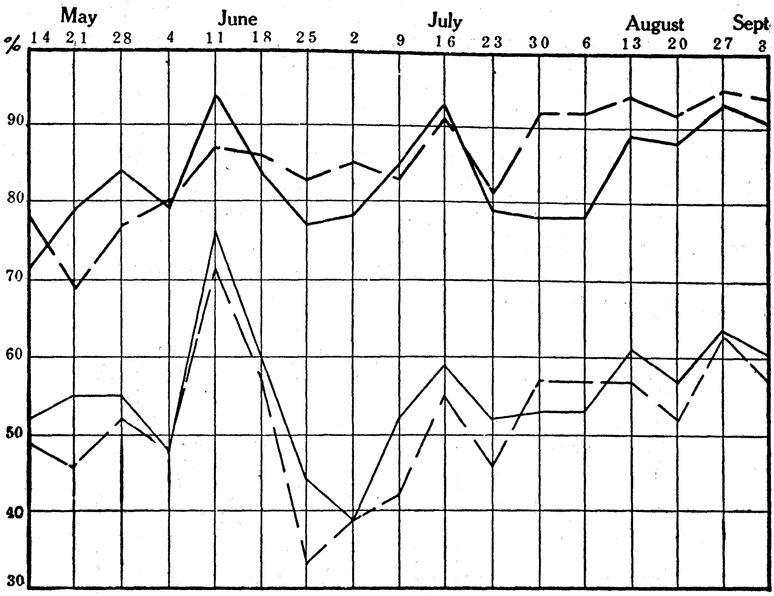


FIG. 22.—Average day humidity (lower lines) and average night humidity (upper lines) in the dry-land plat (solid lines) and in the irrigated plats (broken lines), 1923.

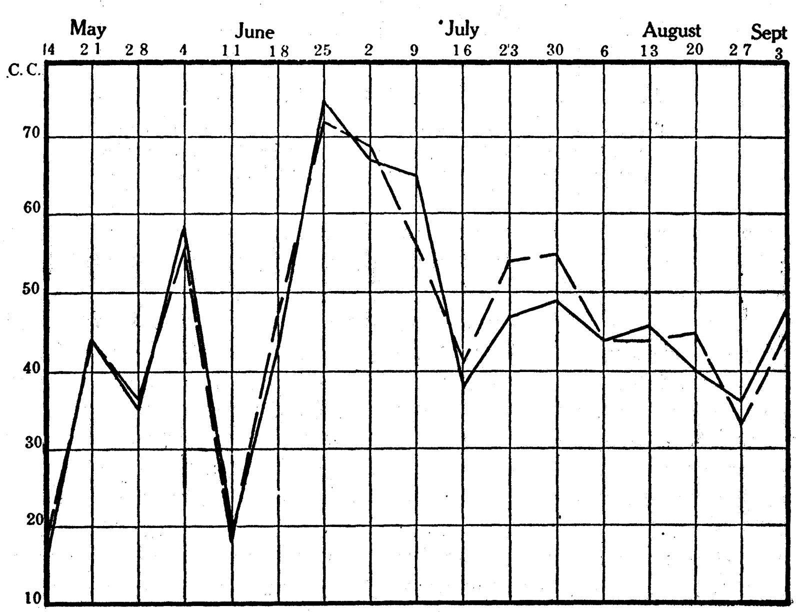


FIG. 23.—Average daily evaporation in dry-land (solid line) and irrigated plats (broken line), 1923.

(fig. 24). A comparison with the data of 1922 (fig. 4) shows that owing to cold rains and snow they were much lower during April and May, the temperatures not increasing consistently until after the third week in May. At depths of 2 to 4 feet the temperatures were not only quite alike in the two plats, but similar to those of the preceding season (table 13).

The average day and night humidity at the two stations is shown in figure 22. No difference in the dryness of the air at the two stations is apparent. A comparison of the average day and night humidity at the dry-land station shows that it is nearly always much higher than during 1922 (table 4 and fig. 22). The average daily evaporation at the two stations is also almost identical (fig. 23). Compared with that of 1922, for example (fig. 3), the evaporation for May at the dry-land station was only 45 per cent as great, for June 71 per cent, for July 80 per cent, and 70 per cent as great for August.

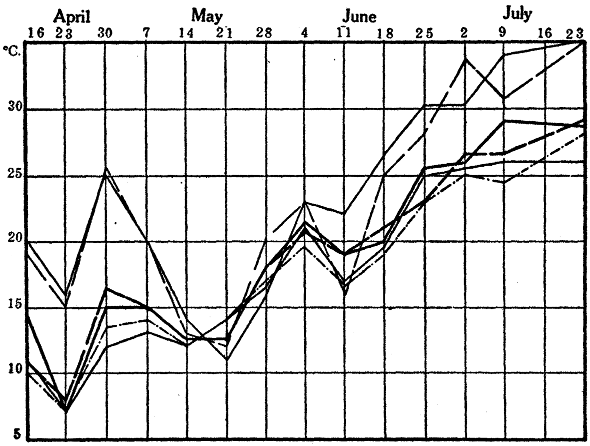


Fig. 24.—Soil temperature in dry-land (solid lines) and irrigated plats (broken lines) at depths of 3 inches (light upper lines), 6 inches (heavy lines), and 12 inches (lower light lines), 1923.

Summarizing, the growing-season of 1923, which opened late, had a great excess of rainfall, lower temperatures than in 1922, especially in the earlier part of the season, a higher humidity, and less evaporation. The air factors in the two cropped areas, which were only slightly different the preceding season, were this year almost identical. Consequently, differences in root development may be attributed almost solely to soil factors.

The dry-land crops in 1923 were grown in the same field as before, but in a portion that had been summer-fallowed the preceding year and thus kept free from weeds. This and the irrigated fields were plowed about 8 inches deep and repeatedly harrowed on April 9, the spring being about 3 weeks later than usual and the soil too wet for earlier cultivation. All of the irrigated plats, however, had been previously fertilized with barnyard manure at the rate of 5 tons per acre. The wheat was again drilled 2 inches deep in rows 8 inches apart at the rate of 90 pounds per acre. This was done on April 10, the crop in the lightly watered plats following potatoes, and that in the fully irrigated one following corn. This selection of plats was made so as to have the soil in any two as nearly alike as possible for the same crop. The beets were drilled an inch deep in rows 18 inches apart on April 16. Onions had been grown the preceding year in the beet plats. On May 30 the crop was thinned to a single plant per foot in the row. Both corn and potatoes were planted on May 12, the rows being 3 feet apart. The corn, which followed beets in the lightly watered plats and summer-fallow in the heavily watered, was planted 2 inches deep and the kernels 16 inches apart in the row. The potatoes, which followed wheat and onions respectively in the lightly and heavily irrigated plats, were cut into large pieces which were planted 14 inches apart and 3 inches deep. Shallow tillage, so as not to disturb the root systems, was again used from time to time as in 1922 in the plats of corn, beets, and potatoes.

A very severe hail occurred on June 14; damage to the irrigated crops being much greater than to those in the dry land. In the former, alfalfa was entirely defoliated and the stems bruised or broken, but that in the dry land was only slightly harmed. Similarly, the dry-land wheat was scarcely affected, but that in the other plats was so badly damaged that only about 10 per cent headed, the original crop being largely replaced by one derived from the tillers sprouting from the base of the plants. Potatoes in the irrigated plats were entirely defoliated and some of the stems broken. The corn, which at this time was about a foot high, was also badly damaged. Immediately after the hail, about half of the corn was replanted, so that normal field conditions were maintained as to competition. The sugar beets at the time of the storm had 8 or 10 leaves each, but of these only remnants were left. Owing, however, to very favorable weather and the previous vigorous growth, all of the crops (except potatoes) recovered rapidly in a most remarkable manner.

On May 17 soil samples were secured from all the plats for purposes of nitrogen determination (table 14). Determinations were made with the phenoldisulphonic-acid method, nitrogen in the form of NO_3, with whatever combined, being ascertained.

TABLE 14.—*Nitrogen-content of soil in the several plats, May 17, 1923, in terms of p. p. m. of nitric nitrogen.*

Plat.	0 to 0.5 foot.	0.5 to 1 foot.	1 to 2 feet.	Plat.	0 to 0.5 foot.	0.5 to 1 foot.	1 to 2 feet.
Alfalfa:				Potatoes:			
Dry land......	None	None	None	Dry land......	2.3	5.3	7.0
Irrigated......	1.4	Trace	None	Lightly irrigated.......	10.9	9.9	10.0
Wheat:				Fully irrigated.	5.9	10.7	7.1
Dry land......	4.2	5.2	8.1	Corn:			
Lightly irrigated.......	4.1	8.5	10.3	Dry land......	4.0	5.1	8.7
Fully irrigated.	2.8	3.8	2.6	Lightly irrigated.......	7.5	5.7	2.8
Beets:				Fully irrigated.	4.7	6.2	5.1
Dry land......	4.1	8.8	8.8				
Lightly irrigated.......	5.6	5.3	4.8				
Fully irrigated.	7.4	6.0	5.1				

EXPERIMENTS WITH ALFALFA.

The alfalfa, which was now a year old, was examined in the dry land on July 10 and that in the watered area 2 days later. The latter had been irrigated for the first time on July 2, but owing to the greater rainfall the soil was quite moist. A sufficient supply to permit root growth also occurred in the dry land, even to a depth of 9 feet (cf. table 15), although at the time of root excavation these deeper soils were very dry. Underlying the surface 1.5 feet of dark sandy loam in the dry land occurred a light-colored compact sandy clay. This gave way at 6 feet in depth to a very sandy soil, while between 7.5 and 9 feet there occurred a stratum of coarse rounded stones intermixed with gravel and sand. The roots, which in September of the preceding year had reached a maximum depth of only 5.5 feet, had made a marked growth and extended to the 9-foot level. The tap-root still maintained its habit of growing in a very tortuous course; it was well supplied with both large and small branches, the latter extending to near the tip.

TABLE 15.—*Holard of alfalfa plats in excess of hygroscopic coefficients, 1923.*

Date, etc.	0 to 0.5 foot.	0.5 to 1 foot.	1 to 2 feet.	2 to 3 feet.	3 to 4 feet.	4 to 5 feet.	5 to 6 feet.	6 to 7 feet.	7 to 8 feet.	8 to 9 feet.	9 to 10 feet.
Dry land:	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
May 24	4.8	2.5	3.0	2.4	2.2	.....	.....	.....	.....	.....	.....
July 11	−2.2	0.8	1.8	1.8	0.7	0.6	1.3	2.5	1.0	0.7	.....
Hygro. coef.	4.2	4.4	5.4	5.3	5.6	5.9	4.8	4.6	4.8	4.9	.....
Fully irrigated:											
May 24	6.4	3.2	6.5	8.2	9.6	.....	.....	.....	.....	.....	.....
July 2	1.7	1.9	7.7	7.9	.....	.....	.....	.....	.....	.....	.....
2	(16.5)	(16.5)	(5.2)	(6.0)	.....	.....	.....	.....	.....	.....	.....
11	8.6	12.7	17.9	12.6	3.7	0.9	3.9	6.4	13.4	16.1	20.6
Hygro. coef.	2.9	3.1	3.0	5.0	4.1	2.7	1.4	2.0	2.3	2.1	1.9

Plants in the irrigated plats had made a no less marked growth, the tap-root having deepened from 6 feet to nearly 10. The maximum depth (9.8 feet) would probably have been even greater, except for water which had seeped in and not only wetted the soil above but excluded the air at this depth (cf. Cannon, 1921). As in dry land, branches 1 to 8 inches long occurred, but these, like the larger branches, ran off much more horizontally. They were rebranched to the second order only, while many in the dry soil were still further rebranched. Also, the branches and tubercles were fewer in the deeper layers of soil than in the dry land. Both were especially abundant in the fifth foot, where considerable gravel occurred (fig. 7B). A comparison of figures 7A and 7B shows clearly the differences in the appearance of the root systems in the two fields.

The yield of a second cutting for 1923 made in the irrigated plat on July 21, when the plants were 26 inches high, was 1.6 tons per acre, as compared with 0.28 ton from the second cutting made on June 26 in the dry land when the plants were 6 inches tall and well in bloom.

EXPERIMENTS WITH WHEAT.

Wheat was first examined on May 24, when the plants in both areas were about 6 inches tall, and had 4 or 5 leaves and about 3 tillers each. Practically no differences were found in the root habits of the plants in the three plats. All had a working depth of about 18 inches and a maximum penetration of 2 feet. Thus, it seems clear that the shallower root habit but longer branches of the plants of similar age in the dry land the previous season was a direct response to a low chresard and the lack of a supply in the second foot.

A second examination was made on June 16–18, when the crop in the several plats averaged nearly 2 feet high, that in the fully irrigated field being slightly the tallest. In all fields some heads were beginning to appear. Just as the crop in the dry land was 11 inches taller than the one of similar age in 1922, so too, the roots occupied a much greater area. Although the lateral spread of 10 to 12 inches and the number of branchlets were about the same in the furrow slice as during the preceding year, 10 to 20 horizontal roots per plant now occupied this area as compared with only 6 or 8 during the drier year. As pointed out elsewhere, many of these roots started, but dried out and failed to develop in 1922. The crop was also more heavily tillered in 1923. Moreover, both the working depth and maximum depth of penetration were about 10 inches greater, owing to a deeper available water-supply (table 16). Branches were even better developed than in 1922 below the furrow slice, the case being clearly one of a fair top growth under conditions which now demanded an increasing water and nutrient supply. Thus, the root habit more nearly approached that in the irrigated plats. However, in the latter, shoot growth was more luxuriant and the roots still deeper. The working and maximum depths in the lightly and fully watered plats were respectively 35 and 40, and 48 and 54 inches. These levels were very similar to those of the preceding year. However, a direct comparison of the fully watered wheat with that of 1922 can not well be made because of differences in soil. While that in 1922 was grown in rather pure sand, the plat in 1923 had a clayey subsoil at 2 to 3.3 feet, above and below which the soil was very sandy. The form of the root was like that of the lightly watered wheat of the previous year. The latter, during 1922, was perhaps slightly more branched, especially in the furrow slice, than the fully irrigated crop which had been watered on June 8.

A final examination was made on July 13–14, when the grain was in the dough stage of ripening. The crop in the dry land, which had been scarcely damaged by the hail, was 3 feet tall, but that of the first growth in the irrigated plats only about 32 inches. Here a second growth of tillers, with heads only 2 inches long, reached a height of 20 inches (plate 6).

In June, 4.6 inches of precipitation fell, and even the deeper soils of the plats previously summer-fallowed had some available moisture (table 16). The root habit of the wheat was more nearly like that of the irrigated soil than of the dry land of the previous year (fig. 9D). It had a working depth (3 feet) fully a foot deeper than that of the previous year, while the maximum depth of 55 inches was likewise 18 inches greater. The yield was in accordance with the fine root development, being at the rate of 25 bushels of grain and 2.4 tons total dry matter per acre. In the lightly watered soil (irrigated June 23) the plants reached a working depth of 40 inches and a maximum of 54 inches, which was almost identical with that in the fully watered plat which had been irrigated on three different dates

TABLE 16.—*Holard of wheat plats in excess of hygroscopic coefficients, 1923.*

Date, etc.	0 to 0.5 foot.	0.5 to 1 foot.	1 to 2 feet.	2 to 3 feet.	3 to 4 feet.
Dry land:	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
Apr. 11	10.5	8.2	8.5	5.0	1.0
23	9.8	7.6	7.8	4.1	−0.2
30	8.8	5.6	13.1	12.1	6.7
May 24	5.5	3.7	9.0	8.6	9.0
June 8	4.7	1.5	7.1	6.1	7.4
June 16	9.8	5.3	5.1	3.8	2.2
July 17	4.2	0.0	2.5	2.3	4.1
Hygro. coef	4.2	5.4	4.4	4.3	5.6
Lightly irrigated:					
Apr. 11	11.7	17.1	19.3	21.0	18.2
23	9.6	9.5	10.7	9.0	7.1
30	6.5	7.1	10.4	10.1	9.2
May 24	3.6	4.4	5.3	10.7	8.4
June 8	4.2	1.4	1.9	4.6	11.3
16	8.0	8.9	14.8	15.3	10.3
23	5.6	5.4	9.7	11.0	....
23	(16.6)	(16.6)	(9.5)	(3.4)	....
July 17	2.9	2.8	8.9	10.3	7.1
17	(20.0)	(20.0)	(10.5)	(3.4)	....
Hygro. coef	2.9	3.1	3.0	5.0	4.1
Fully irrigated:					
Apr. 11	11.7	17.1	19.3	21.0	18.2
23	9.8	9.7	10.9	9.2	7.3
30	6.7	7.4	10.6	10.3	9.5
May 24	3.8	4.9	5.4	10.8	8.7
June 8	4.4	1.7	2.1	4.9	11.0
8	(13.1)	(13.1)	(14.2)	(10.8)	(4.1)
16	7.3	7.9	8.1	13.6	12.7
23	4.6	4.4	6.9	13.8	....
23	(12.7)	(12.7)	(8.8)	(2.0)	....
July 5	1.9	1.7	11.5	13.6	....
5	(15.9)	(15.9)	(0.4)	(0.2)	....
17	2.7	3.5	9.6	14.4	10.7
17	(14.4)	(14.4)	(7.6)	(3.4)	....
Hygro. coef	2.9	3.1	3.0	5.0	4.1

(table 16)). Both crops had fewer branches below the 2-foot level than in the dry land, while the lightly irrigated one had a few more and slightly longer rootlets than the one fully irrigated. For these crops no yield was determined because of the damage by hail.

In order to still further check the effects of differences of water-content on root development and crop growth, wheat was grown in the same soil, but under different degrees of moisture. Four oak barrels 20 inches in minimum diameter and 32 inches deep were filled with soil in the dry land, care being taken to place the soil in such a manner that after being tamped in place it occupied the same relative position as regards depth that it had previously occupied in the field. These were filled on April 14 and a week later planted with wheat at the rate of 20 plants per container. Two of these were supplied with larger amounts of water than the others, as is indicated in table 17, wooden roofs with an opening an inch wide to permit the growth of the plants being used to exclude nearly all of the rainfall.

TABLE 17.—*Holard in excess of hygroscopic coefficients in containers with wheat.*

Container.	Average water-content in excess of hygro. coeff. May 14.		Water added (gallons).				Average water-content in excess of hygro. coeff. July 20.
	Depth, inches.	Per cent.	June 1.	June 19.	June 26.	July 6.	
							p. ct.
Nos. 1, 2	0 to 6	3.2	......	......	......	3.0	2.2
	6 to 12	3.0	......	......	......	......	0.0
	12 to 24	5.2	......	......	......	......	2.7
	24 to 32	2.4	......	......	......	......	2.0
Nos. 3, 4	0 to 6	3.2	2.5	6.0	8.0	6.0	1.8
	6 to 12	3.0	......	......	......	......	1.3
	12 to 24	5.2	......	......	......	......	4.0
	24 to 32	2.4	......	......	......	......	7.0

At the time of harvest the plants in the drier and wetter soils respectively were 17 and 23 inches in height. The former had about 2 and the latter 4 tillers each. Differences in root development were very marked, especially in the lower layers of soil. In the wetter soil the roots filled the soil to the bottom, being rather evenly distributed throughout. In the drier soil below 2 feet only an occasional root was found; however, the soil was thoroughly occupied to 22 inches depth. Below 18 inches the roots in the drier soil were of greater diameter, the branches were nearly twice as numerous, and they were of greater average length. These data agree perfectly with those just given for field development.

EXPERIMENTS WITH SUGAR BEETS.

The first examination of beets was made on June 8, when the plants were nearly 2 months old, 3 to 5 inches tall, and possessed of 8 to 10 leaves each. The root habit in the three plats was almost identical, the branches in the dry land being slightly longer (fig. 13). An examination of tables 14 and 18 shows that both nitrate and water-content in the zone of root-growth were very similar in all the plats. The crop, although slightly younger than that of 1922 when first examined, showed a more advanced development, probably because it had been planted 10 days later in the season. It may be recalled that the previous crop had rapidly developed the two rows of surface roots in response to irrigation and belated rainfall respectively, but in 1923 the soil was sufficiently moist (table 18) to promote a good early growth. The deeper penetration in the dry land than during the preceding year (maximum over 19 inches), as well as the widespread horizontal branching, may also be attributed to a better water-supply in the surface 2 feet of soil.

On July 10–13 the plants had 15 or 16 rather fully expanded leaves, 10 to 12 inches long, and a top diameter of 15 to 16 inches, those in the dry land being the least developed in every way above ground. Larger roots than in 1922 occurred in the surface soil in all the plats, probably as a response to the rather constantly greater water-supply, especially earlier in the season (cf. tables 10 and 18); on the other hand, depth of penetration was also less (cf. figs. 11 and 14). In the dry land, usually below 6 inches depth, strong laterals arose and ran off nearly parallel with the soil surface, some for a distance of nearly 4 feet, and nearly all ended in the surface foot. The profuse branches absorbed much of the precipitation, which was 2.1 inches during May and 4.6 inches in June. The shallowest roots had not yet reached full development, being mostly short and unbranched. The characteristic branching in the second foot of soil is shown in figure 14, the maximum root penetration seldom exceeding 25 inches, as compared with 30 to 46 inches in the much drier soils of the preceding year.

Root habit in the fully irrigated plats also differed from that of the preceding year, being shallower and spreading more widely in the surface soil. These differences are probably due to the much more favorable water-content of the upper soil layers. Many horizontal branches were excavated which reached outward 20 to 30 inches, one being 3.4 feet long. A working depth of only 34 inches was determined and a maximum penetration of 40 inches as compared with 54 in 1922. The greater degree of branching in the more compact clay soil underlying the surface 16 inches of sandy loam is well shown in figure 14B. This was identical with the 1922 plat and also occurred in the lightly watered area. In the latter plats, which had not yet been irrigated, the tops had begun to wilt, and although the surface soil was better occupied with more and longer laterals than in the fully irrigated plats, root depth was not so great. A working depth of 25 inches (only 4 inches greater than that in the dry land) and a maximum penetration of 3 feet were determined. In both cases the best growth occurred in the moist surface soils. It is quite possible that the lower soil temperatures had some effect upon the root habit.

This study was completed on August 20–21. Growth was not yet complete, as was indicated by the presence of 6 or 8 partly grown leaves in addition to the 20 fully expanded ones (24 in fully irrigated soil). These varied in length in order of increasing water-content through 12, 21, and 24 inches. The total leaf areas of typical plants selected from each plat were, in order of increasing soil moisture, 7.26, 12.08, and 20.46 square feet. The spread of tops was 24 inches in the fully irrigated plats but only 20 to 22 in the others. For several weeks preceding, the tops had wilted badly in the afternoons in the dry land and some of the older leaves were dying.

In the dry land the root habit was similar to that of the previous excavation. The strong tap-root, now 2.3 inches in diameter, usually gave off 4 to 6 large laterals in the surface 10 inches of soil. These extended laterally 16 to 24 inches or more and then turned downward, often reaching a

TABLE 18.—*Holard of beet plats in excess of hygroscopic coefficients, 1923.*

Date, etc.	0 to 0.5 foot.	0.5 to 1 foot.	1 to 2 feet.	2 to 3 feet.	3 to 4 feet.
Dry land:	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
Apr. 16	3.9	6.2	6.0	5.1	6.7
23	9.8	7.6	7.8	4.1	6.3
30	8.8	5.6	13.1	12.1	6.7
June 8	9.2	8.0	8.4	6.1	1.0
July 11	0.0	4.9	6.3	5.9	1.1
Aug. 21	9.5	3.5	4.7	3.6	5.7
Hygro. coef	4.2	5.4	4.4	4.3	5.6
Lightly irrigated:					
Apr. 16	5.2	6.5	13.2	11.3	2.3
23	9.6	9.5	10.7	9.0	7.1
30	6.5	7.1	10.4	10.1	9.2
June 8	9.1	9.9	13.5	9.9	7.9
July 11	5.0	5.5	12.3	4.5	7.4
19	2.7	2.9	9.8	7.6	....
19	(14.6)	(14.6)	(8.2)	(6.2)	....
Aug. 21	6.7	7.0	15.1	10.9	13.8
Hygro. coef	2.9	3.1	3.0	5.0	4.1
Fully irrigated:					
Apr. 16	5.4	6.9	13.7	11.8	2.4
23	9.8	9.9	11.0	9.7	7.2
30	6.7	7.5	10.8	10.7	9.0
June 8	9.4	10.2	14.0	10.3	8.2
July 2	5.2	5.6	12.7	10.0	....
2	(11.6)	(11.6)	(6.2)	(3.9)	....
11	8.1	8.4	11.7	11.6	6.4
19	5.3	5.8	8.6	10.1	....
19	(10.5)	(10.5)	(7.7)	(3.8)	....
Aug. 21	8.0	9.8	14.5	10.2	13.6
Hygro. coef	2.9	3.1	3.0	5.0	4.1

working depth of 56 inches. This downward-turning tendency was very pronounced, even in the branches originating in the second foot of soil, and undoubtedly resulted from the drying-out of the surface layers (table 18), the branching, often to the fifth order, being so profuse as to thoroughly occupy the surface foot with a dense mass of rootlets. Within the week of the examination, however, the surface 8 inches had again been moistened and a mass of shiny white new rootlets 1 to 7 inches long came off in rows on either side of the tap-root to the very soil surface. The tap-root with its accompanying network of branches had now deepened its absorbing area to a working depth of 56 inches and a maximum penetration of 68 inches, the soil at 5 feet depth having a 5 per cent chresard.

The root habit in the fully watered plat was practically identical with that during the preceding year, except for one outstanding difference. This consisted of the wide lateral spread of the roots in the surface foot, a phenomenon already explained. The delay in the development of the deeper portion of the root system recorded at the last examination had now been fully made up. In fact, the even more luxuriant tops, with the leaves averaging 5 inches longer than the preceding year, made such heavy demands during the hot days of July and August that the roots had somewhat exceeded the depth of the last season, the maximum penetration being 80 inches and the working depth 72. Seepage water now filled the soil at the 65-inch level.

Soil strata in the lightly watered plat were identical with those described earlier for the fully irrigated ones, only 15 feet away. The root habit, too, was almost identical as regards surface branching, depth of penetration, etc. In fact, it seemed that the single irrigation on July 19, together with the heavy rains, furnished ample moisture for normal root-growth. The yield per acre of the dry-land beets was 6.7 tons, while those in the lightly and heavily watered plats yielded 17.7 and 23.8 tons respectively.

EXPERIMENTS WITH POTATOES.

Potatoes in the dry land were examined on July 6, when they were about 7 weeks old. There were about 4 stalks per hill and the plants averaged 9 inches in height. The general character of the root system, including the wide lateral spread (2.5 feet), was the same as that of the preceding year. Working depth and maximum penetration were 3 and 7 inches greater respectively, a difference probably due to the fact that the plants were a week older and growth conditions better than in 1922. An outstanding difference, and one which might be expected in the moister soil, was in the length of the branches. Although the same in number as before, they now averaged only 3 inches long (maximum 11 inches) as compared with 5 inches (maximum 18 inches) of the preceding year. Because of hail injury, the irrigated crops were not examined at this time.

TABLE 19.—*Holard of potato plats in excess of hygroscopic coefficients, 1923.*

Date, etc.	0 to 0.5 foot.	0.5 to 1 foot.	1 to 2 feet.	2 to 3 feet.	3 to 4 feet.
Dry land:	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
May 14	7.2	7.2	6.9	3.4	3.3
July 6	0.4	3.6	7.7	3.8	7.2
Hygro. coef	4.2	5.4	4.4	4.3	5.6
Lightly irrigated:					
May 14	11.6	11.4	17.5	15.0	5.1
July 19	6.1	6.8	11.9	11.1	....
19	(7.5)	(7.5)	(3.9)	(0.8)	....
Aug. 14	8.3	15.4	18.6	18.9	....
14	(5.5)	(5.5)	(3.0)	(0.3)	....
22	10.1	15.9	18.0	18.5	....
22	(5.3)	(5.3)	(3.2)	(1.0)	....
Hygro. coef	4.6	4.9	8.0	6.8	4.0
Fully irrigated:					
May 14	11.8	11.7	11.9	15.5	5.6
July 2	7.1	6.8	12.2	11.2	....
2	(6.2)	(6.2)	(1.7)	(0.7)	....
19	6.8	7.5	10.1	10.8	....
19	(8.9)	(8.9)	(3.0)	(2.4)	....
Aug. 14	10.4	13.2	17.9	18.6	....
14	(9.5)	(9.5)	(8.9)	(2.6)	....
22	12.2	13.5	17.1	18.7	....
22	(8.0)	(8.0)	(8.2)	(2.1)	....
Hygro. coef	4.6	4.9	8.0	6.8	4.0

These studies were concluded on August 7–8, when the 11-weeks-old crop was in full bloom. The rainfall for July was less than an inch, but a heavy rain fell on August 3. The lightly watered plats had been irrigated on July 19 and the fully watered ones in addition on July 2 (table 19). The crop in the dry land had made a much more luxuriant growth than during the preceding year, the 17-inch tops lacking only a foot of occupying all the space between the 3-foot rows. However, the plants showed plainly the symptoms of drought, many leaves having died, while others were half dry. Because of the severe hail damage (June 14), plants in the irrigated plats were much smaller than formerly, the tops not exceeding those of dry land in height, although spreading more widely and possessing much larger leaves.

The marked differences in root development in the dry land during the two seasons may best be understood by a comparison of figures 15A and 15E. While the general habit in the surface 18 inches is the same, the depth to which the root extended after turning downward is remarkable. In 1922, little top or root growth occurred after July 1, owing to lack of available water, but the subsoil the next season was sufficiently moist to promote a good root development to a working-level of 3 feet (table 19), a maximum penetration of 46 inches being attained. Branching was profuse throughout. The previous yield of 19 bushels per acre was increased to 29.3, the tops having made too luxuriant an early growth to resist drought, which later caused the crop to dry early and thus reduce the yield.

Root habit in the irrigated plats was very similar to that of the preceding year. In the fully watered area the maximum lateral spread (21 inches), working depth (17 inches), and maximum penetration (30 inches) were very nearly as before. In the drier soil of the lightly watered plat, the differences in root habit already pointed out again occurred, viz, longer surface roots, more vertically descending ones, more profuse branching, and greater working and maximum depths. However, in both cases, undoubtedly owing to the damage of the tops by the hail, fewer main roots occurred. In fact, they were scarcely more than half as numerous as before, only 35 to 54 occurring on a single plant. The yield was less than in dry land, owing to the severe hail injury to the irrigated crops.

EXPERIMENTS WITH CORN.

The corn was excavated on June 23, when the crop was 6 weeks old and about a foot tall, each plant having 7 or 8 leaves. The hail of June 14 had been especially severe in the irrigated plats. Plants in the dry land differed from those in the moister irrigated soil (table 20) chiefly in two respects. The widely spreading surface roots showed a more marked tendency to turn downward near their ends, some reaching depths of 20 inches or more, while those in the irrigated plats had mostly just started to turn downward. While in the moister soil a few vertically descending roots from the base of the plant had begun to appear, in the dry land these were quite prominent, some being 8 or 10 inches long. No difference was found in the two irrigated plats; in fact, the water-content was about the same in both. Contrasted with the preceding year, the dry-land plants retained more of the

TABLE 20.—*Holard of corn plats in excess of hygroscopic coefficients, 1923.*

Date, etc.	0 to 0.5 foot.	0.5 to 1 foot.	1 to 2 feet.	2 to 3 feet.	3 to 4 feet.
Dry land:	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
May 14	7.2	7.2	6.9	3.4	3.3
June 23	5.1	7.5	5.1	6.5	9.4
July 10	0.0	1.1	4.3	4.1	7.5
Aug. 17	6.3	1.8	1.2	0.9	1.2
Hygro. coef	4.2	5.4	4.4	4.3	5.6
Lightly irrigated:					
May 14	11.6	11.4	17.5	15.0	5.1
June 23	7.2	6.8	8.0	10.9	9.4
July 5	7.7	7.5	11.0	10.0	....
5	(4.5)	(4.5)	(4.3)	(1.7)	....
10	7.9	7.3	10.1	13.4	10.0
Aug. 17	10.1	3.4	4.6	9.1	11.6
Hygro. coef	2.9	3.1	3.0	5.0	4.1
Fully irrigated:					
May 14	11.9	11.8	17.9	15.5	5.4
June 23	7.5	6.9	8.8	11.0	9.9
July 5	7.9	7.8	11.5	10.6	....
5	(8.3)	(8.3)	(0.0)	(0.0)	....
10	8.9	6.6	6.9	10.2	10.0
21	2.8	2.9	8.0	11.1	....
21	(9.8)	(9.8)	(4.3)	(2.3)	....
Aug. 17	7.6	6.9	7.5	10.1	14.9
Hygro. coef	2.9	3.1	3.0	5.0	4.1

normal root habit, i. e., the roots spread more horizontally in the surface soil, and the branches were neither so numerous nor of such great length. Likewise, in the lightly watered plat, the roots did not spread so widely as in the drier soil of the preceding year, and they did not show such a marked tendency to turn downward near their extremities or penetrate so deeply. Moreover, the development of the vertically descending roots was not so great.

The second examination of corn was made on July 9–11. The average height in the several plats in order of decreasing dryness was 24, 33, and 40 inches. In all fields the crop had made an excellent growth and was just beginning to tassel. The low water-content in the dry land (table 20) was indicated by the leaves, which for a few days only had begun to roll during the hottest part of the day. In the dry land only 35 roots per plant were found, as compared with 33 to 45 the previous year. Moreover, the working-level was 3 inches less and the maximum penetration 12 inches short of that reached in the drier soil of the preceding season. Otherwise no differences were found. In the fully irrigated plats, where the clayey subsoil was of a much lighter type than in 1922, the roots had penetrated to a maximum depth of 46 inches and a working level of about 2.5 feet. Aside from the greater depth (plants of 1922 having a working depth of only 2 feet), little difference was noted. As before, the root branches were fewer and shorter than those in dry land.

This study was concluded on August 17. Owing to good rains, the crop, even in the dry land, had made a luxuriant growth, the height, in the order of increasing water-content, being 6.5, 7.3, and 7.6 feet. The ears were well filled and the kernels beginning to dent. On August 18, after a large number of measurements, a typical plant in each plat was selected and its leaf area (both sides of leaves) calculated. This was found to be 6.86 square feet in the dry land and 12.60 square feet in the lightly irrigated plat, while the plant in the fully watered plat had an area of 12.88 square feet. As for the growth of tops, the root system in the dry land far exceeded in extent that of the previous year. Although the spread was about the same (33 inches), the working-level had been lowered from 30 (1922) to 46 inches, and similarly the maximum penetration from 46 to 66 inches, the soils even at this depth having 2 or 3 per cent available moisture. Moreover, little difference was found either in total number of roots or number or length of branches. Root development in the fully irrigated plat differed scarcely at all from that of plants of similar age in 1922. They had the same wide lateral spread, and while the working depth (46 inches) was 6 inches greater than the year before, the maximum penetration (67 inches) was slightly less. Seepage water was found at this level.

Root habit in the lightly watered area was very similar to that in the adjacent fully irrigated plat. At all depths the number and length of branches were practically identical. Although the maximum penetration was slightly greater, the working-level was about 5 inches less, a difference due perhaps to the more compact clay subsoil. However, as in 1922, the first foot of soil was not nearly so well filled with roots as was the more constantly moist, fully irrigated soil (table 20). Moreover, the main roots had a more marked tendency to turn downward. Both of these differences were also found the previous year. The yield in the dry land was at the rate of 3 tons of dry matter and 51 bushels of grain per acre; in the lightly watered plat it was 5.8 tons and 96 bushels per acre, while the fully irrigated plat yielded at the rate of 6.7 tons of dry matter and 96 bushels of grain per acre.

Corn was also grown in barrels, the soil being placed as in the case of wheat, and two of the four containers freely supplied with water. Two stalks were permitted to grow in each container, the corn having been planted on May 12. The water-content and amount of water added are shown in table 21.

At the time of examination, the plants in the drier soil were 3.9 feet tall; the dwarfed leaves had been almost constantly wilted and partially rolled

TABLE 21.—*Holard in excess of hygroscopic coefficients in containers with corn.*

Container.	Average water-content in excess of hygro. coef. May 14.		Water added (gallons).						Average water-content in excess of hygro. coef. Aug. 17.
	Depth, inches.	Per cent.	June 1	June 19	June 26	July 6	July 20	Aug. 1	Per cent.
Nos. 1, 2..........	0 to 6	3.2	.....	.....	.....	.....	1	0.5	7.0
	6 to 12	3.0	.....	.....	.....	.....	.....	.....	1.8
	12 to 24	5.2	.....	.....	.....	.....	.....	.....	4.1
	24 to 32	2.4	.....	.....	.....	.....	.....	.....	3.4
Nos. 3, 4..........	0 to 6	3.2	1	2	2	3.5	2	3.5	6.7
	6 to 12	3.0	.....	.....	.....	.....	.....	.....	6.2
	12 to 24	5.2	.....	.....	.....	.....	.....	.....	7.9
	24 to 32	2.4	.....	.....	.....	.....	.....	.....	7.1

for many days. The plants in the wetter soil were 5.3 feet tall, were tasseling, and showed no signs of drought. An average of 24 roots was found on the 4 plants in the dry soil and the same number in the moist. Roots in the dry soil were of smaller diameter, more woody, and tougher. Twice as many roots were found below 16 inches in the wet soil as in the dry. Although repeated counts showed that the average number of root branches per inch was the same in the wet soil as in the dry, they averaged fully twice as long (8 inches) in the latter. These data, in general, confirm those found under similar conditions in the field.

SUMMARY AND CONCLUSIONS.

During the seasons of 1922–23 crops of alfalfa, spring wheat, sugar beets, potatoes, and corn were grown at Greeley, Colorado, in soils of a very similar nature as regards texture and chemical composition, but varying widely in water-content. The growing-season is sufficiently long and other conditions are favorable for plant growth, except the light, unevenly distributed rainfall (12.7 inches mean annual), which makes crop production hazardous.

Thirtieth-acre plats of each crop were grown in unirrigated, lightly irrigated, and fully irrigated sandy-loam soil. Aside from these differences, the rainfall during the second year of the experiments was so unusually heavy that a sharp contrast was offered in the holard of the same plats during the two seasons. This was still further checked by growing crops in large containers filled with similar soil but of different water-content. Continuous records of environmental conditions in the dry and watered areas were obtained. During 1923, air and soil temperature, humidity, and evaporation were almost identical, but during the drier year of 1922 aboveground conditions for growth were a little more severe in the dry-land plats. However, making due allowances for the small differences in both air and soil, other than water-content, consistent and marked differences in the development of the root systems were determined as the crops were examined at several periods during their growth. Extensive determinations of water relations were made from the time of planting until the maturity of the crops, and in every case root habit was found to be very responsive to variations of this factor. In general, the crops with the most extensive root-systems gave the greatest yield.

Turkestan alfalfa in the dry, hard land differed from that in the irrigated soil by pursuing a much more tortuous course, probably owing to difficulty of penetration, by having longer major branches, especially abundant in the first foot, which spread less widely and turned downward more abruptly, and in the earlier development of the plant often reached depths as great as those of the tap-root. Likewise, secondary and tertiary branches were often much longer, while owing to the slower growth of the tap-root and largest laterals, branches on them occurred much nearer the tip. The dry soil had a very retarding effect upon the growth of tubercles, none occurring at the end of the season, although they were abundant to 4 feet in irrigated soil.

By July 10 of the second season, which was very wet, the dry-land alfalfa had extended its area from 5.5 feet depth (where dry soil had occurred) to 9 feet. In the watered plats growth had ceased at the 6-foot level, owing to seepage water saturating the soil, but the roots now extended to nearly 10 feet. The yields of a single cutting in 1922 of 0.12 and 0.52 ton per acre had also been increased in proportion to root-growth to 0.28 and 1.6 tons in 1923.

Marquis spring wheat in the dry land, because of lack of moisture in the second foot, like alfalfa, spread more widely in the surface soil, where the moisture was replenished by the heavier summer showers. Here many of the roots died of drought and growth was greatly retarded. Those which finally turned downward first spread much more widely than in the plats with a moist subsoil. Although the number of primary branches was no greater in the dry land, they were longer, occurred nearer the root tips, and tertiary branches were much more numerous. Dry-land wheat grew but little after the middle of June, having extended its roots into the still rather dry second foot of soil to a working-level of only 2 feet, as contrasted with 3 feet in the lightly irrigated plats and 4.3 feet in the more loose sandy soil of the fully irrigated one. The height of crop and yield in the progressively moister soils were 15, 41, and 43 inches, and 3, 32, and 29 bushels per acre respectively, the sandier soil causing a decrease in the yield of the fully irrigated plat.

In 1923, when the soils were equally moist, the first examination revealed no differences in root habit. Later the area occupied by the root system of the dry-land crop was much greater than in 1922, owing to a better shoot development, more tillers, and a subsoil with available moisture in which none of the roots died. The lateral spread was as great as formerly and the working depth was over a foot deeper. In fact, the root habit was more nearly like that of the irrigated soil than that of dry land of the preceding year. The crop was 3 feet high and the yield 25 bushels per acre. Root development in the irrigated soil was approximately the same as the preceding year. The difference in root habit in the two irrigated plats, which had been somewhat emphasized during 1922 because of variations in soil structure, consisted chiefly in more extensive branching in the drier soil. Both plats were damaged by hail and the yield was not determined.

Klein-wanzleben sugar beet in the dry land had its normally deeply penetrating tap-roots limited because of dry subsoil in its early development to only one-half the depth in moist soil, and throughout the season they were 1 to 1.5 feet shorter. Like the roots of other dry-land crops, they pursued a more tortuous course and were branched more nearly to the tip. Branching was more profuse and sublaterals more abundant than in fully irrigated soil. In all respects the lightly watered crop was intermediate. By midsummer the dry-land plants had neither the well-developed shallow portion of the root system nor the long, deeply penetrating branches (reaching depths of 3 feet) characteristic of those growing in the moist soil. They were characterized by large numbers of horizontally spreading major laterals in the surface at 4 to 18 inches depth where available water had been constantly most abundant, the branches becoming shorter with increased depth in this zone, and the tap-root with its profuse short branches alone penetrating to the 3-foot level. Roots in the lightly irrigated soil were again intermediate in having the shallow surface portion of the system poorly developed, but the deeper one, which was quite extensive, had its major branches much more widely spread than in the wetter fully irrigated soil. By mid-September the dry-land beets, which had suffered severely from drought, had only about one-fourth the leaf area of the irrigated plants, and the area occupied by roots was also much less. The surface roots, stimulated by showers, had reached a lateral spread exceeding that in moist soil, while abundant deeper-seated major branches had penetrated the dry subsoil 2 or 3 feet. As in alfalfa, these did not spread widely (seldom over 7 inches as compared with 1.5 to 2 feet in moist soil), but turned down abruptly. A maximum depth of 4.5 feet was attained, but roots in moist soil extended to 6 feet deep. The lightly watered crop had a lesser root extent in the surface soil than that in dry land, but greater than the fully irrigated crop. It was also intermediate in lateral spread of deeper branches, etc., as compared to plants in moist soil. The yield was 2.5, 21, and 22.5 tons per acre, increasing progressively with water-content.

During the much more humid season following, the beets in all plats were found to have root systems practically the same, and were thus in harmony with the uniformity in the holard. Later, because of a constantly good water-supply, the surface laterals spread much more widely in all plats than in 1922, and correlated with this was a lesser depth of penetration. As the surface soil in the unirrigated plat became drier, a pronounced tendency was found for the branches to turn downward. As a whole, the root habit more nearly resembled that in the irrigated plats than that of the previous dry-land plants, while the lightly watered soil was sufficiently wet so that little difference was found between the root habit here and in the fully watered plats, both resembling that of the fully watered plants of the preceding season. The yield per acre in the three plats, proceeding from the driest to the fully irrigated, was 6.7, 17.7, and 23.8 tons.

Bliss's Triumph potato had a smaller top but a much more extensive root system in the dry land late in June. Moreover, the branches were much more abundant and longer. Because of severe drought, little further growth occurred either above or below ground in the dry-land potatoes, the working depth being about 2 feet. The fully irrigated crop was rooted mostly in the surface 16 inches of soil, where the laterals spread nearly 2 feet on all sides of the plant. The lightly watered potatoes had an even greater lateral spread, more roots penetrated nearly vertically downward, and the second foot of soil was much more thoroughly occupied. Moreover, branching was much more profuse, although the branches were no longer. The yield varied from 19 bushels per acre in dry land to 303 in the lightly irrigated plat, where the soil was more sandy and production greater than in the fully watered one. The best developed root system was correlated with greatest yield. During the better season for growth in 1923, the dry-land potatoes, which had formerly been confined to the surface 2 feet, penetrated the moister subsoil to depths of nearly 4 feet, while the yield was increased to 29.3 bushels per acre. The root habit in the fully watered plats was about the same as the preceding year, while the lightly watered plants showed differences similar to those already pointed out for 1922. The yield was very low because of damage due to hail.

Corn showed marked differences in root habit, even when only 6 weeks old. Roots in dry land deviated from the normal shallow, widely spreading type, and more grew obliquely or directly downward; those in intermediately dry soil spreading and then turning downward. Number and length of branches increased directly in proportion to scarcity of water-supply. By midsummer the dry-land corn had practically completed its growth both above and below ground. Drought and excessive transpiration had stimulated a marked root growth. The widest lateral spread of shallow roots (about 3.5 feet) and most profuse branching now occurred here, but the working-level (2.5 feet) was limited by dry soil. In the fully watered plats with plants a foot taller, practically the entire root system was limited to the surface 16 inches of soil. Plants in the lightly irrigated soil differed in less thoroughly occupying the drier surface 4 inches, in a lesser development of new roots (also due to dry soil) and correlated with this, a much greater extent of the older ones to a working-level of 33 inches (maximum penetration over 4 feet).

The mature root systems in dry land, like the tops, showed little further growth after midsummer and the yield was only 25 bushels per acre. Those in fully watered soil had extended their roots well into the fifth and sixth feet, many of the horizontal laterals having also turned downward and penetrated deeply. The best root development was found in the lightly watered plats with somewhat sandier soil. Although the fine roots in the dry surface soil were fewer and the lateral spread of the main roots slightly less, the depth of penetration was greater (working-depth about 5 feet), the deeper soils being more thoroughly occupied, and branching was also greater. Here again the highest yield (115 bushels per acre) was correlated with the best developed root system, the fully irrigated plat yielding 102 bushels per acre.

In the moist soil of the unirrigated plats in 1923, the young roots showed a more normal surface spread with less tendency to turn downward, and the branches were also shorter than in the preceding year. The top growth was far more luxuriant and the roots made a much better growth. They had no greater lateral spread, but the working-level (46 inches) was 16 inches deeper, and the length of branches was again greater than in the irrigated plats. Fully watered plants developed as in 1922, and the lightly watered ones were not so different from them as during the preceding year. However, as before, in the latter case the first foot of soil was not nearly so well filled with roots, while the main roots had a more marked tendency to turn downwards. The dry land yielded at the rate of 51 bushels of grain per acre and the irrigated plats 96.

From the preceding account it is clear that the roots of the crops employed responded readily to the changed environment, consisting chiefly of differences in chresard and air-content, and that there is a striking correlation between the growth of underground and aerial plant parts. Although the root habits of a few species seem to be controlled largely by heredity and show little plasticity under changed conditions, the behavior in most species depends upon the operation of such factors as water-content, aeration, and nutrients.

Of 10 native grasses and other herbs studied by Weaver (1919) in two or more widely separated habitats, 7 showed very striking changes in their root habits as to depth of penetration, position and number of branches; 1 exhibited only moderate differences, while 2 showed practically no change. Pulling (1918) reported that several shallow-rooted forest trees as well as certain deeply rooted ones do not adapt themselves to changed soil conditions, but that others belonging to each class show considerable plasticity, and Haasis (1921) likewise found great variation in the roots of yellow pine. The great variability in the rooting habits of fruit trees and the significance of this in orchard practice is well summarized by Gardner, Bradford, and Hooker (1922 : 54, 586). The wide adaptation of black walnut to so many soils that it is almost universally used as stock for the English walnut in California is well known. Other fruit trees show much less adaptation, certain varieties failing unless grafted onto other stock the roots of which adapt themselves to soils underlaid with alkali (Kelley and Thomas, 1920) or containing excessive moisture (Sahut, 1885), or to very exposed or dry situations (Sorauer, 1920). Further extensive studies by Weaver (1920) have shown that not only do practically all of the native species studied vary widely in root habit, but also many field crops. A continuation of these studies with field crops showed that this variation was sometimes so great and the root habit so profoundly changed that the roots were scarcely recognizable as belonging to the same species (Weaver et al., 1922 : 69). Crops grown in soil of high fertility have roots that are shorter, more branched, and more compact than those in similar but less fertile soil, as has recently been confirmed by Crist and Weaver (1924). Marked contrasts in the degree of ramification of roots as they penetrate different soil strata may be attributed in part to differences in soil fertility (Bowman, 1911 : 66). The importance of proper soil aeration as affecting root development and crop yield can scarcely be over-emphasized (Clements, 1921). "In this direction [i. e. soil aeration by drainage] we have possibilities of improvement in wheat production [in India] which will settle the food supply of the world for generations to come" (Howard, 1916 : 19).

Thus, root distribution and the functioning of the part of the plant above ground, in so far as it is conditioned by the work of the roots, is under control to the extent that water-content, soil-air, nutrients, and soil-texture can be varied. Marked changes of root habit may thus be brought about by methods of tillage, use of fertilizers, crop rotations, cover crops, intercropping, and especially by irrigation and drainage.

The varying needs of different crops, periods when each is most sensitive to applications of water, the best method of applying water to each type of soil, and its effect upon the soil organisms, as well as the best rooting habit, must be kept constantly in mind. With respect to the latter, it should be clear that the ideal root system is not necessarily the one with the most extensive branching, but the one that fully occupies the soil to a sufficient depth and within a sufficient radius to secure enough water and nutrients at all times. Where the water-supply is limited, the roots must be deep and not held near the surface by early light irrigation. A low holard, within certain limits, stimulates greater root development, and this results in a greatly increased absorbing surface. However, this advantage may be overcome by the competition of the roots of too many plants grown in the same soil area. Notwithstanding this greater absorbing surface, if the water-supply is restricted, the portion of the plant above ground is often incapable of much development, as was strikingly shown in case of the dry-land potatoes (p. 34). Conversely, it is usual to secure extensive above-ground development from a limited root system in moist fertile soil (Weaver, 1919; Haasis, 1921). Unless the moisture-supply is constant, such a condition is dangerous in crop production, since even moderate drought at a critical period may enormously lower the yield. When the absorbing area of the root system is reduced by lack of aeration such as accompanies the rise of the water-table, the plant tries to adjust itself by the shedding of some of its leaves (and fruits) thus reducing its transpiring area. The amount of shedding is often directly proportional to the degree of injury to the root system (Howard, 1916 : 8; Balls, 1919 : 72). Since the roots are killed from a prolonged lack of aeration, subsequent lowering of the water-table due to drought is often very disastrous to the crop. Under conditions of unfavorable water-supply, not only does the growth of the plants and fruits cease, but water and food materials may actually be withdrawn from the storage places to be used in the vegetative parts (cf. Coit and Hodgson, 1917).

Finally, it should be kept firmly before the investigator that the criterion of yield under irrigation should not be the maximum production per acre, but per acre-inch of water used. Water, not land, is the limiting factor, and we will learn to use it more effectively in proportion as our knowledge of the extent, distribution, and activities of the water-absorbing organ, the root system, is increased.

BIBLIOGRAPHY.

BALLS, W. L. 1919. The cotton plant in Egypt.

BOWMAN, I. 1911. Forest physiography.

CANNON, W. A. 1919. Modification of root habits by experimental means. Carnegie Inst. Wash. Year Book No. 17, pp. 83–85.

———. 1921. Root-growth in relation to a deficiency of oxygen or an excess of carbon dioxide in the soil. Carnegie Inst. Wash. Year Book No. 20, pp. 48–51.

CLEMENTS, F. E. 1921. Aeration and air-content. The rôle of oxygen in root activity. Carnegie Inst. Wash. Pub. No. 315.

COIT, J. E., and R. W. HODGSON. 1917. The June drop of Washington navel oranges. Cal. Agr. Exp. Sta. Bull. No. 290.

CRIST, J. W., and J. E. WEAVER. 1924. Absorption of nutrients from subsoil in relation to crop yield. Bot. Gaz., 77, pp. 121–148.

GARDNER, V. R., F. C. BRADFORD, and H. D. HOOKER. 1922. The fundamentals of fruit production.

HAASIS, F. W. 1921. Relations between soil type and root form of western yellow pine seedlings. Ecology, 2, pp. 292–303.

HARLAN, H. V., and S. ANTHONY. 1921. Effect of time of irrigation on kernel development of barley. Jour. Agr. Res., 21, pp. 29–45.

HARRIS, F. S. 1916. The irrigation of wheat. Utah Agr. Exp. Sta. Bull. No. 146, pp. 3–31.

———. 1917. The irrigation of sugar beets. Utah Agr. Exp. Sta. Bull. No. 156, pp. 3–24.

———. 1918. Corn under irrigation. Trans. Utah Acad. Sci., 1, pp. 120–121.

———. 1920. The agronomist's part in the world's food-supply. Science, 52, pp. 395–400.

HEMPHILL, R. G. 1922. Irrigation in northern Colorado. U. S. Dept. Agr. Bull. No. 1026.

HOLE, R. S. 1918. Recent investigations on soil-aeration, part II, with special reference to forestry. Agr. Jour. India, 13, pp. 430–440.

HOWARD, A. 1916. Soil aeration in agriculture. Agr. Res. Inst., Pusa, Bull. No. 61.

———. 1918. Recent investigations on soil-aeration, part I, with special reference to agriculture. Agr. Jour. India, 13, pp. 416–429.

——— and G. L. C. HOWARD. 1915. Soil ventilation. Agr. Res. Inst., Pusa, Bull. No. 52.

——— and G. L. C. HOWARD. 1919. The saving of irrigation water in wheat growing. Fruit Exp. Sta., Quetta, Bull. No. 4, Ed. 2.

——— and G. L. C. HOWARD. 1919. Drainage and crop production in India. Agr. Jour. India. Special Indian Science Congress Number, 1919, pp. 377–387.

——— and G. L. C. HOWARD. 1920. Some aspects of the indigo industry in Bihar. Mem. Dept. Agr. India, Bot. Ser. 11, p. 1.

KELLEY, W. P., and E. E. THOMAS. 1920. The effects of alkali on citrus trees. Cal. Agr. Exp. Sta. Bull. No. 318, pp. 305–337.

KNAPP, G. S. 1922. Relation of crop yields to quantity of irrigation water in southwestern Kansas. Kans. Agr. Exp. Sta. Bull. No. 228, pp. 3–29.

KIESSELBACH, T. A. 1916. Transpiration as a factor in crop production. Nebr. Agr. Exp. Sta. Res. Bull. No. 6, pp. 3–214.

PULLING, H. E. 1918. Root habit and plant distribution in the far north. Plant World, 21, pp. 223–233.

SAHUT, F. 1885. Rev. Hort., 57, p. 305.

SEELHORST, C. VON. 1911. The importance of water in the life of cultivated plants. Jour. Landw., 59, pp. 259–291.

SORAUER, P. 1920. Manual of plant diseases. Ed. 3, transl. by F. Dorrance, 1, p. 841.

STEWART, G. 1921. Alfalfa production under irrigation. Utah Agr. Exp. Sta. Circ. No. 45, pp. 3–48.

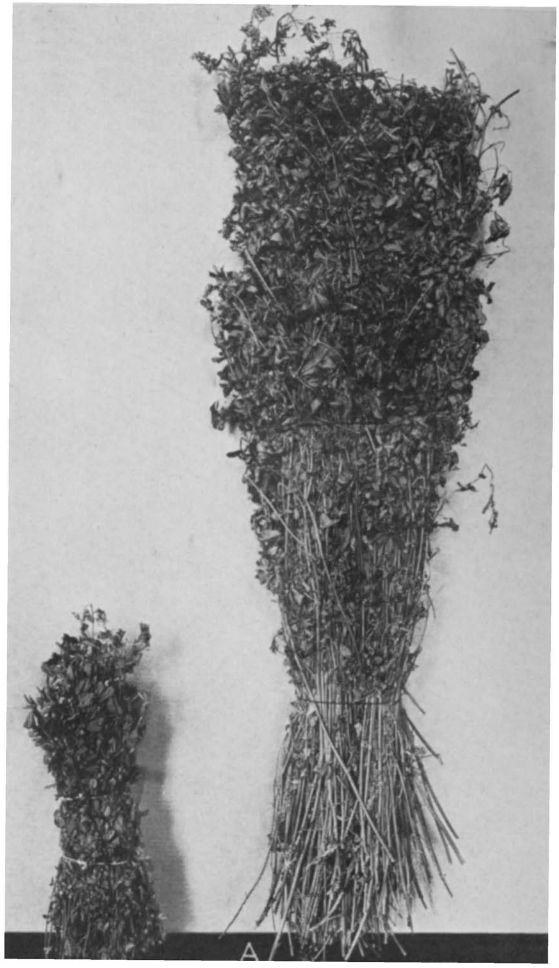
WEAVER, J. E. 1919. The ecological relations of roots. Carnegie Inst. Wash. Pub. No. 286.

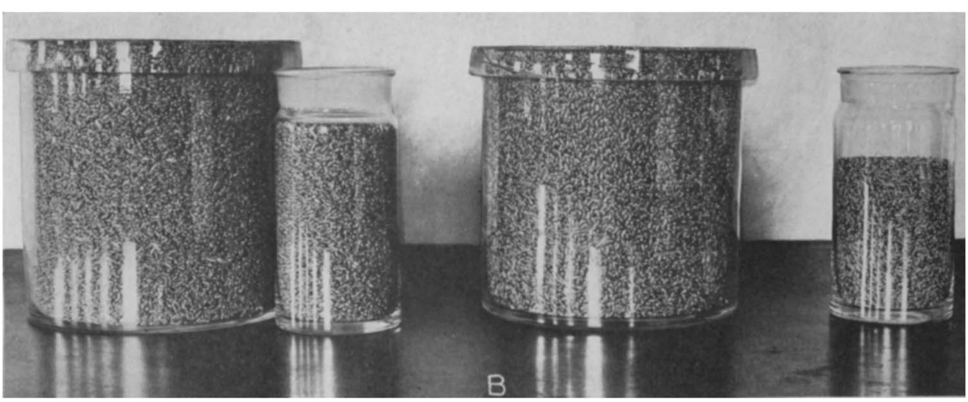
———. 1920. Root development in the grassland formation. Carnegie Inst. Wash. Pub. No. 292.

———, and J. W. CRIST. 1922. Relation of hardpan to root penetration in the Great Plains. Ecology, 3, pp. 237–249.

———, F. C. JEAN, and J. W. CRIST. 1922. Development and activities of roots of crop plants. Carnegie Inst. Wash. Pub. No. 316.

WIDSTOE, J. A. 1914. The principles of irrigation practice.

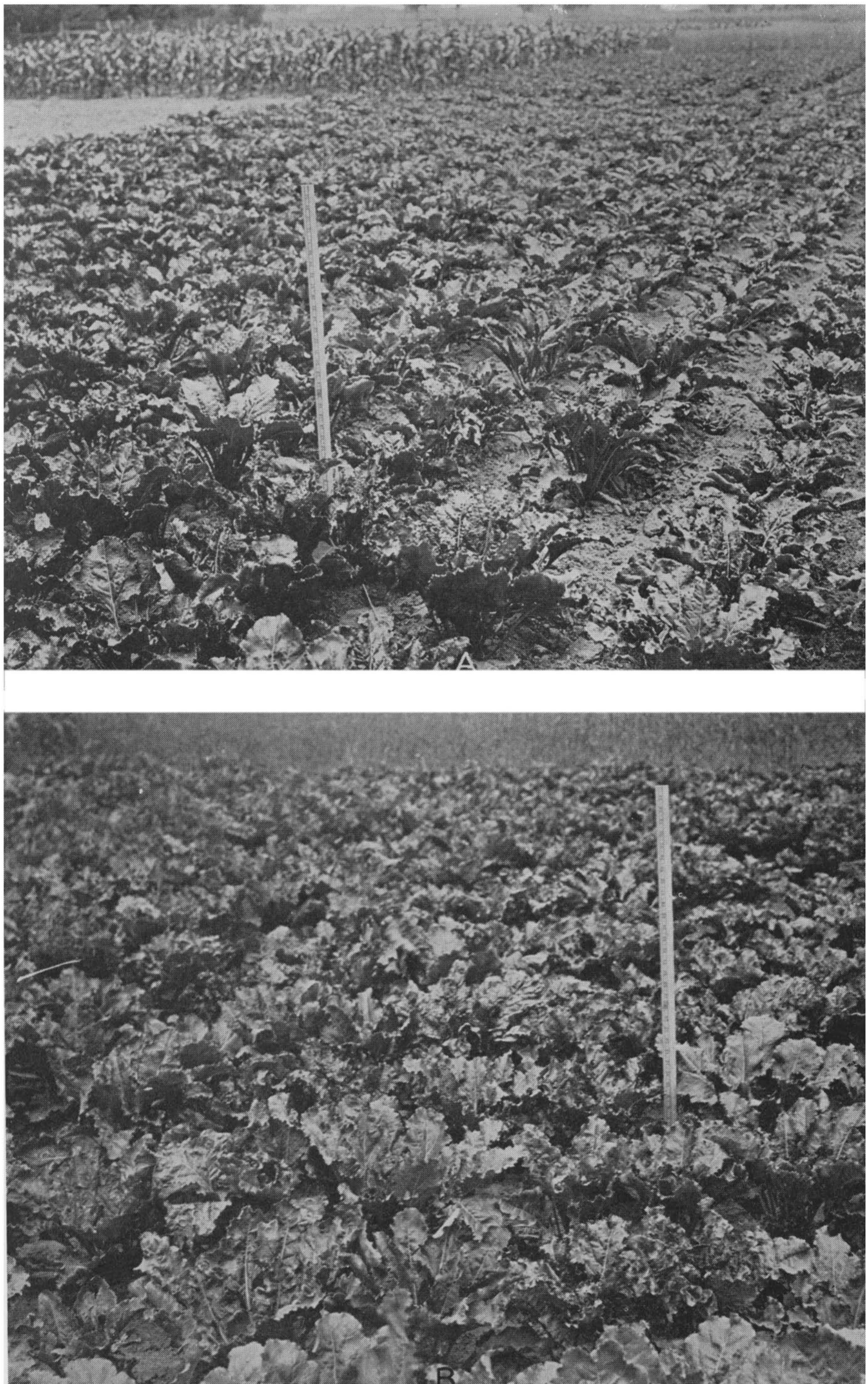




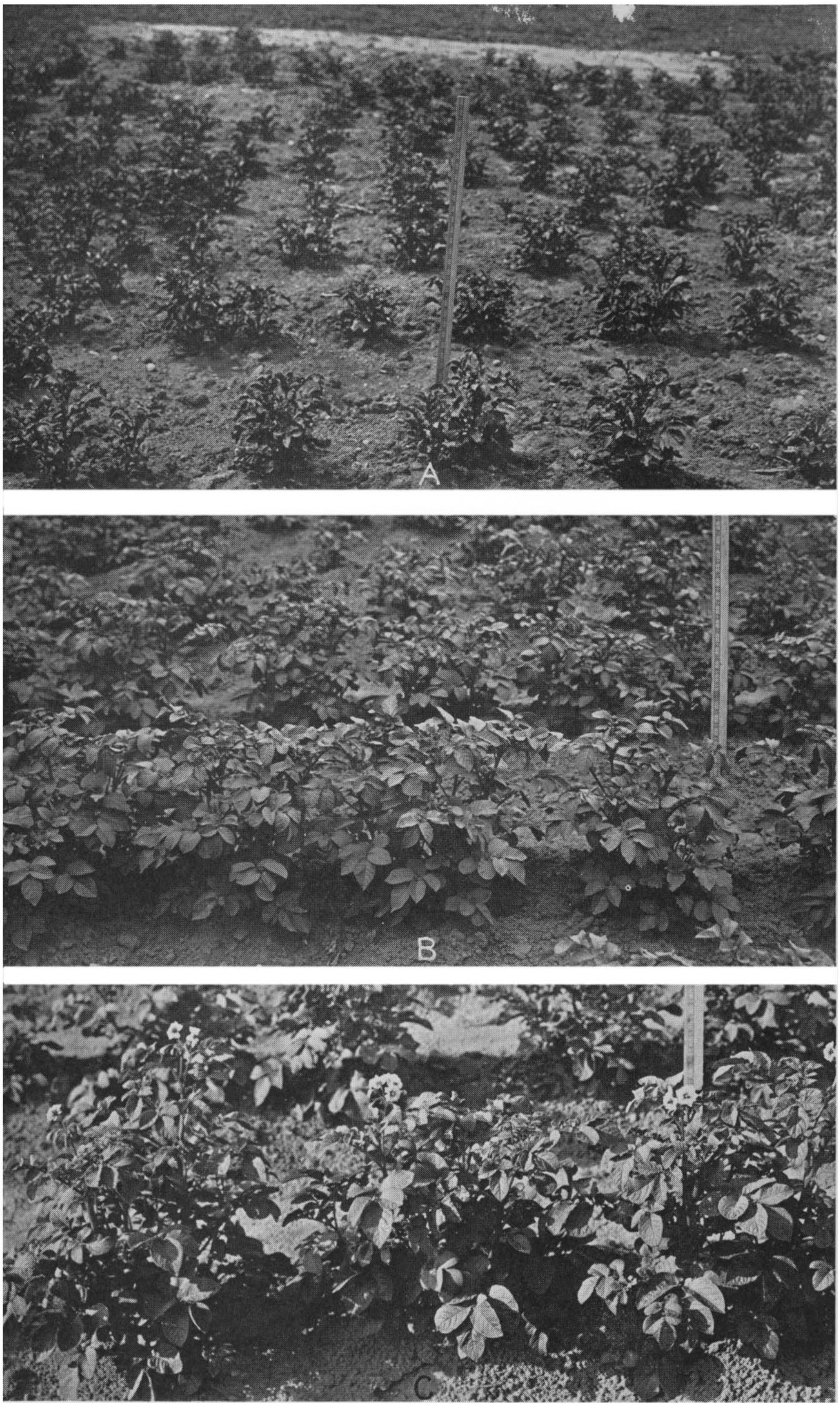
A.—Yield of alfalfa from one square rod of dry land (left) and irrigated land (right) on July 26, of first season's growth.

B.—Yield of grain from one square rod of lightly irrigated wheat (two containers on left), fully irrigated but more sandy soil (center), and dry land (right), 1922.

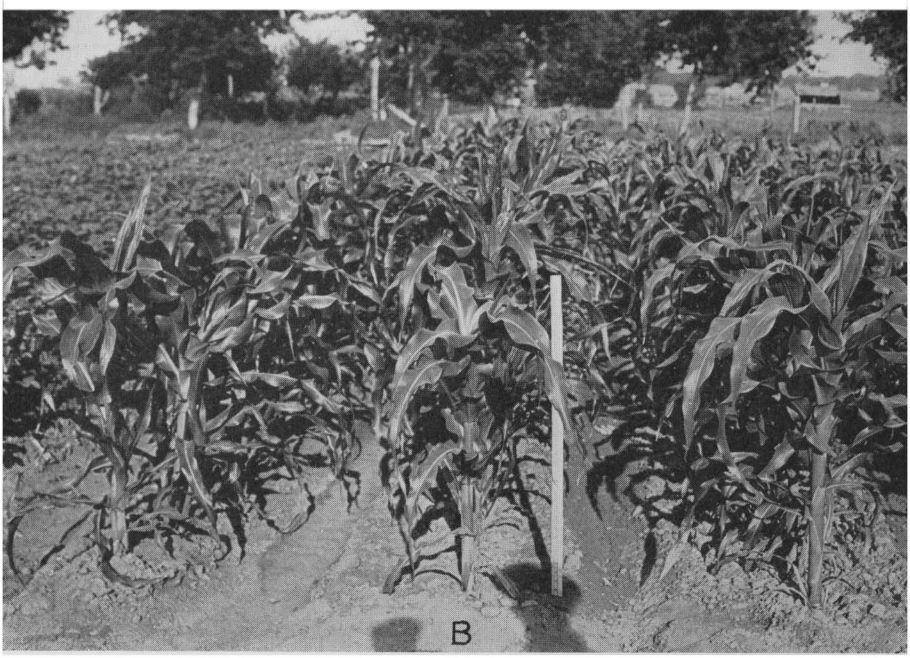
Wheat, 1922: A, dry land; B, lightly irrigated.



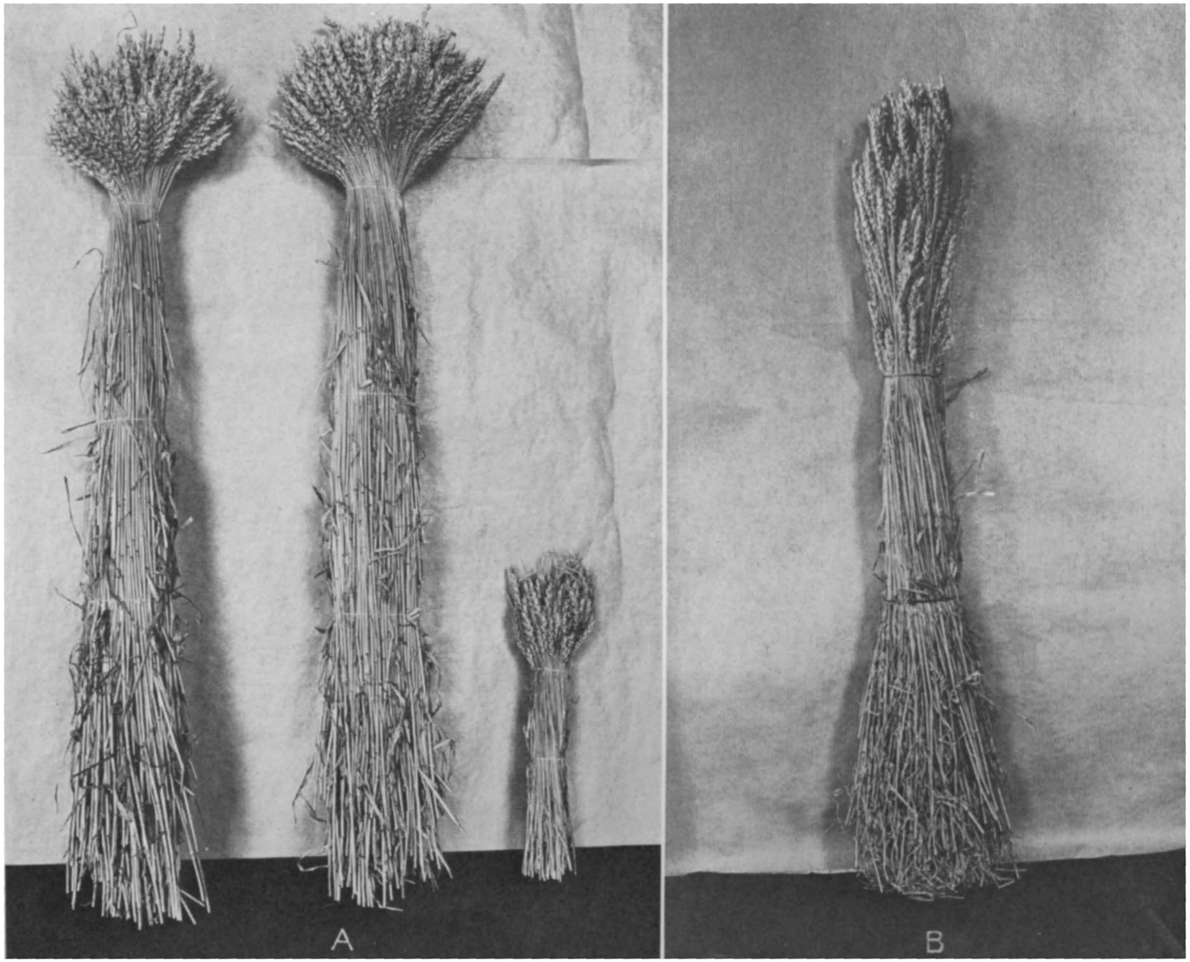
Sugar beets, July 8, 1922: A, dry land; B, fully irrigated.



Potatoes, July 7, 1922: A, dry land; B, lightly irrigated; C, fully irrigated.



Corn, July 10, 1922: A, dry land; B, lightly irrigated.



A.—Marquis spring wheat grown on fully irrigated soil (left), lightly irrigated but less sandy soil (center), and dry land (right), 1922.

B.—Wheat (3 feet high) grown on dry land, 1923, and photographed to the same scale.