1913.

U. S. DEPARTMENT OF AGRICULTURE.

BUREAU OF PLANT INDUSTRY—BULLETIN NO. 285.

WILLIAM A. TAYLOR, *Chief of Bureau.*

THE WATER REQUIREMENT OF PLANTS.

II.—A REVIEW OF THE LITERATURE.

BY

LYMAN J. BRIGGS,
Biophysicist in Charge of Biophysical Investigations,

AND

H. L. SHANTZ,
Plant Physiologist, Alkali and Drought Resistant Plant Investigations.

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GOVERNMENT PRINTING OFFICE.
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Issued October 6, 1913.

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BUREAU OF PLANT INDUSTRY.

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LETTER OF TRANSMITTAL.

U. S. DEPARTMENT OF AGRICULTURE,
BUREAU OF PLANT INDUSTRY,
OFFICE OF THE CHIEF,
Washington, D. C., June 16, 1913.

SIR: I have the honor to transmit herewith a paper entitled "The Water Requirement of Plants. II.—A Review of the Literature," by Dr. Lyman J. Briggs, Biophysicist in Charge of Biophysical Investigations, and Dr. H. L. Shantz, Plant Physiologist, Alkali and Drought Resistant Plant Investigations. This paper was prepared in connection with their investigations of the water requirement of crop plants in the Great Plains and consists of a review of the various measurements which have been made dealing with the water requirement of crops. It is hoped that this paper may prove of value, not only as a presentation of the present state of our knowledge regarding the amount of water required by crops in the production of a unit weight of dry matter, but in indicating as well the lines along which future investigations in this subject can be most profitably carried on.

I have the honor to recommend the publication of this paper as Bulletin No. 285 of the Bureau series.

Respectfully,

WM. A. TAYLOR,
Chief of Bureau.

Hon. D. F. HOUSTON,
Secretary of Agriculture.

CONTENTS.

ILLUSTRATIONS.

THE WATER REQUIREMENT OF PLANTS.[1]

II.—A REVIEW OF THE LITERATURE.

INTRODUCTION.

The review of the literature relating to the water requirement of plants here presented was begun in connection with the writers' investigations on this subject in the Great Plains. The literature proved to be much more extensive than was anticipated, and it has consequently seemed desirable to present independently a summary of the investigations bearing on this subject, particularly since some of the papers are not readily accessible and since a review of the whole subject has apparently not been undertaken heretofore. In reviewing the papers it has appeared desirable to group them with reference to the various factors which affect the water requirement. When more than one phase of the subject is dealt with in the same paper, the special material relating to each phase of the work has been considered in its appropriate place. In summarizing the papers the endeavor has been to give in tabular form the essential data of each investigation. This will enable the reader to draw his own conclusions from the experimental results independently of any interpretation which the writers may have given.

Among the different subjects which have been investigated in relation to their effect upon the water requirement may be mentioned soil-moisture content, type of soil, cultivation, amount of soil used, fertilizers, temperature, light, humidity, carbon-dioxid content of the air, relative leaf area, defoliation, and duration and period of growth, as well as the water requirement of different kinds of plants when grown under comparable conditions. The division of the subject into these groups has been largely determined by the character of the investigations which have so far been made, and is not presented as an ideal division of the water-requirement problem. The papers which deal with any of the above phases of the water-requirement problem, so far as the writers have been able to consult them, are discussed in the following pages. The full title and reference are given under "Literature cited" at the end of the bulletin. The year of publication in parentheses in the text following the author's

[1] The preparation of this bulletin was carried on in cooperation at every stage between the Office of Alkali and Drought Resistant Plant Investigations and the Office of Biophysical Investigations. The authors' names have been placed alphabetically on the title-page.

name serves to indicate a citation and to identify the paper to which reference is made.

In the general subject of transpiration an immense amount of work has been done, and it is possible in this review to consider only that phase of the subject which related directly to the water requirement. The term "water requirement" is here used to indicate the ratio of the weight of water absorbed by a plant during its growth to the dry matter produced. In most of the investigations described the plants were grown in open pots, and in some cases no correction for the water evaporated directly from the soil was attempted. In such instances we have designated the ratio of the water lost to the dry matter produced as the "water requirement including evaporation."

Much of the work on the effect of the soil or of the nutrient solution on plant growth and transpiration has been done with seedlings. In the measurement of the water requirement, however, the exact determination of the amount of growth is as important a factor as the measurement of the amount of water transpired. When the period of growth is short and the plants are harvested during the seedling stage it is difficult to determine the amount of dry matter produced. If the total dry weight of the plant at the end of the experiment is taken to represent the increase in dry matter, the water requirement will be too low, owing to the error of including much of the original dry matter contained in the seed. If a correction is made for the initial weight of the seed, the final weight may show a loss rather than a gain in dry matter (Le Clerc and Breazeale, 1911, p. 10), and even if a gain in weight is recorded it is impossible to determine how much weight was lost during the early stages of germination. If only the aerial portions of the plants are weighed, the recorded increase is largely due to translocation of material and may bear no direct relation to actual increase of dry matter. It is therefore necessary to lengthen the growth period of the plant until a sufficient amount of dry matter has been produced to make the error due to the initial weight of the seed so small as to be inconsequential if water-requirement measurements or transpiration measurements based on the increase in weight of the plant are to be of value. For the above reasons it was decided, after summarizing the data, to omit from the following discussion, except in special cases, water-requirement measurements based on the weight of seedlings.[1]

Investigations like that of Höhnel (1881), in which the water requirement of forest trees was based on the weight of the leaves

[1] The following publications (arranged chronologically) contain water-requirement measurements based on the weight of seedlings:

SORAUER, PAUL.

1880. Studien über Verdunstung. Forschungen auf dem Gebiete der Agrikultur-Physik, Bd. 3, pp. 351–490.

1883. Nachtrag zu den Studien über Verdunstung. Forschungen auf dem Gebiete der Agrikultur-Physik, Bd. 6, pp. 79–96.

alone, instead of on the total weight of dry matter produced, have also been omitted.

The earliest water-requirement measurements appear to have been made by Woodward (1699). Lawes (1850) was, however, the first to extend his experiments so as to include the entire growth period of annual crop plants. References to some of the earlier papers dealing with this subject are given by Burgerstein (1904, pp. 154–158) in his work on transpiration. The methods employed in some of the more recent investigations of the water requirement of plants have been summarized by Montgomery (1912).

EFFECT OF SOIL FACTORS ON THE WATER REQUIREMENT.

EFFECT OF SOIL-MOISTURE CONTENT ON THE WATER REQUIREMENT.

IL'ENKOV'S EXPERIMENTS.

The effect of soil-moisture content on the water requirement was first investigated by Il'enkov (1865, p. 162). Buckwheat (*Polygonum fagopyrum*) was planted in five flowerpots containing garden soil, and seven plants were grown in each pot. The pots were exposed in the windows of a room which received the sun at midday. The experiment

PAGNOUL, A.
1898. Essais relatifs à la transpiration des plantes. République Française, Departement du Pas-de-Calais, Station Agronomique, Bulletin, pp. 10–15.
LIVINGSTON, B. E.
1905. Relation of transpiration to growth in wheat. Botanical Gazette, v. 40, no. 3, pp. 178–195. Reprinted as Contributions from the Hull Botanical Laboratory, 67.
——— BRITTON, J. C., AND REID, F. R.
1905. Studies on the properties of an unproductive soil. U. S. Department of Agriculture, Bureau of Soils, Bulletin 28, 39 pp.
——— JENSEN, C. A., BREAZEALE, J. F., PEMBER, F. R., AND SKINNER, J. J.
1907. Further studies on the properties of unproductive soils. U. S. Department of Agriculture, Bureau of Soils, Bulletin 36, 71 pp.
HARTWELL, B. L., AND PEMBER, F. R.
1908. Relation between the effects of liming and of nutrient solutions containing different amounts of acid upon the growth of certain cereals. Rhode Island Agricultural Experiment Station, 20th Annual Report, 1906–7, pp. 358–380.
——— WHEELER, H. J., AND PEMBER, F. R.
1908. Effect of the addition of sodium to deficient amounts of potassium upon the growth of plants in both water and sand cultures. Rhode Island Agricultural Experiment Station, 20th Annual Report, 1906–7, pp. 299–357, 1 pl.
KRAUSS, F. G.
1908. Rice investigations. Report of first year's experiments. Hawaii Agricultural Experiment Station, Annual Report, 1907, pp. 67–90, pls. 5–9.
GARDNER, F. D.
1908. Fertility of soils as affected by manures. U. S. Department of Agriculture, Bureau of Soils, Bulletin 48, 59 p.
REED, H. S.
1910. Effect of certain chemical agents upon the transpiration and growth of wheat seedlings. Botanical Gazette, v. 49, no. 2, pp. 81–109, 9 figs.
BOUYOUCOS, G. J.
1912. Transpiration of wheat seedlings as affected by soils, by solutions of different densities, and by various chemical compounds. Proceedings, American Society of Agronomy, v. 3, 1911, pp. 130–191, 16 figs. See also Transpiration of wheat seedlings as affected by different densities of a complete nutrient solution in water, sand, and soil cultures. Beihefte, Botanisches Centralblatt, Abt. 1, Bd. 29, Heft 1, pp. 1–20, 3 figs., 1912.
DACHNOWSKI, ALFRED.
1912. The nature of the absorption and tolerance of plants in bogs. Botanical Gazette, vol. 54, no. 6, pp. 503–514.

was continued for 57 days. The results of the experiments are shown in Table I. The water-requirement ratio is based on the water added to each pot instead of on the water actually used.

TABLE I.—*Effect of different amounts of water on the water requirement of buckwheat, according to Il'enkov (1865, p. 162).*

Pot No.	Water added.		Dry weight (grams).	Water requirement.
	Relative.	Liters.		
1	1	25.0	6.20	4,030
2	1/2	12.5	13.94	900
3	1/4	6.25	6.28	995
4	1/8	3.12	1.93	1,616
5	1/16	1.56	.39	4,000

Water was not added daily, but pot No. 1 was kept nearly saturated. The table shows that the water requirement was very high, owing probably to the fact that the experiment was conducted in porous pots. Since no account is taken of evaporation or of the initial and final moisture content of the soil, the results are far from conclusive.

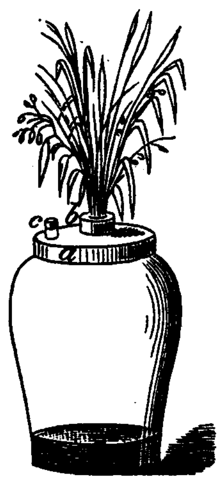

FIG. 1.—Glass jar employed by Fittbogen (1873) in measuring the water requirement of plants.

FITTBOGEN'S EXPERIMENTS.

Fittbogen (1873) conducted a series of careful experiments on the influence of soil-moisture content on the water requirement of the oat plant. He used glass jars of the form shown in figure 1. Each jar contained 3 to 4 kilograms of soil, which rested on a 4-centimeter layer of gravel. The jar was closed with a zinc cover (*a*) having two tubulures. The center tubulure carried a cork (*b*) bored with a 6-millimeter hole, through which the stems of the three oat plants passed. The other tubulure was kept closed with a cork stopper (*c*) except when water was being applied. Fittbogen thus had a nearly closed system, and the evaporation loss must have been small.

Five series of experiments were made with different soil-moisture contents, as shown in Table II.

TABLE II.—*Effect of different soil-moisture contents on the water requirement of oats, according to Fittbogen (1873, p. 359).*

Production.		Water content, in terms of moisture-holding capacity.				
		10 to 20 per cent.	20 to 30 per cent.	30 to 40 per cent.	40 to 60 per cent.	60 to 80 per cent.
Dry matter	Mean weight, grams[1]	1.6	7.8	12.8	12.2	13.7
	Water requirement	405±14	414±10	444±7	457±9	534±14
Grain	Mean weight, grams	0.6	4.1	6.1	5.3	6.0
	Water requirement[2]	1,022±96	790±12	934±25	1,050±16	1,213±59

[1] 4 pots used in each determination; 3 plants per pot. [2] Computed from Fittbogen's data.

Table II shows that the production of dry matter was very much reduced by the low soil-moisture content. The water requirement also decreased gradually but consistently with the decrease in the water content of the soil, except for grain production in the case of the lowest moisture content, which was apparently too low to support good growth, as is shown by the small amount of dry matter produced.

HELLRIEGEL'S EXPERIMENTS.

Hellriegel (1883) gives the results of three years' observations on the effect of soil-moisture content on the water requirement of barley. The pots used in his investigation contained about 4 kilograms of soil. Surface evaporation in the experiments conducted in 1871 was reduced by the use of covers cemented to the pots. The size of the opening for the plants is not stated. In his earlier experiments a correction for the direct evaporation was made, based upon the loss from the check pots. Hellriegel's results are given in Table III.

TABLE III.—*Effect of different soil-moisture contents on the water requirement of barley, according to Hellriegel (1883).*

Year and production.[1]		Water content, in terms of moisture-holding capacity.						
		5 per cent.	10 per cent.	20 per cent.	30 per cent.	40 per cent.	60 per cent.	80 per cent.
1869.								
Dry matter	Mean weight...grams			17.9		23.9	25.4	24.5
	Water requirement			254±10		258±2	281±13	298±4
1870.								
Dry matter	Weight...grams	0.1	3	14.6	19.8	21.8	22.8	19.7
	Water requirement	940	180	168	223	216	240	277

Year and production.[1]		Water content, in terms of moisture-holding capacity.			
		5 to 15 per cent.	15 to 25 per cent.	20 to 60 per cent.	40 to 80 per cent.
1871.					
Dry matter	Weight...grams	8.1	31.3	49.0	38.9
	Water requirement	192	239	261	287

[1] Three pots used in each determination in 1869; single pots in 1870 and 1871.

These results indicate also that the water requirement of plants decreases within limits as the soil-moisture content is lowered, but is also accompanied by a decrease in dry matter. In the duplicated series of experiments the reduction of the moisture content from 80 per cent saturation to 20 per cent reduced the water requirement of barley about 15 per cent.

MAERCKER'S EXPERIMENTS.

Maercker (1896) investigated the influence of soil-moisture content on the water requirement of white mustard in connection with certain fertilizer experiments. A summary of his results is given under "Effect of fertilizers on the water requirement" (Table XXVII, p. 36). He found that white mustard grown in soil 20 per cent saturated had a water requirement nearly 30 per cent less than when grown in soil 60 per cent saturated. His pots were not protected from surface evaporation.

SCHROEDER'S EXPERIMENTS.

Schroeder (1896) investigated the water requirement of barley when grown in sand moistened with nutrient solutions of different concentration. The effect of different amounts of solution was also investigated, three series of pots being maintained, respectively, at 80, 40, and 20 per cent of the moisture-holding capacity. His results are given in Table IV. The data for 1894 show a consistent reduction in the water requirement accompanying a reduction of the moisture content of the soil. Schroeder placed less confidence in the results for 1893 on account of the imperfect prevention of direct evaporation by the layer of cotton employed for that purpose.

TABLE IV.—*Effect of different amounts of nutrient on the water requirement of barley in Russia, according to Schroeder (1896, pp. 194–211).*

Year.	Soil moisture, in terms of water-holding capacity.	Concentration of nutrient solution.	Dry matter.	Water requirement.
	Per cent.	*Per cent.*	*Grams.*	
1894 [1]	80	0.6	38.93	568
		.4	28.22	547
		.3	20.81	586
		.2	15.42	576
		.1	6.40	513
	40	.6	20.07	505
		.4	16.84	470
		.3	9.50	536
		.2	7.72	424
	20	1.2	15.35	338
		.8	10.66	399
		.6	6.36	400
		.4	5.87	429
		.2	3.53	360
1893 [2]	70 to 100	1.7	8.15	579
	40 to 70	2.4	6.25	516
	5 to 40	4.3	3.50	472
	40 to 70	1.2	4.33	414
	40 to 70	3.7	7.67	541
	5 to 40	6.4	4.54	467
	70 to 100	.85	6.28	329

[1] Experiments were conducted in glass pots filled with 5 kilograms of sterile sand. The soil surface was covered by oilcloth and a layer of cotton. The pots were taken into a shelter during the night and in bad weather. Growth continued from 70 to 88 days. Only one pot was used in each culture. The initial weight of the seed was deducted in estimating the water requirement. The nutrient solution was the same as that used by Hellriegel (p. 13).

[2] As in 1894, but the pots contained sand plus 150 grams of peat. The surface of the pot was covered with only a layer of cotton. Growth continued from 71 to 113 days.

VON SEELHORST'S EXPERIMENTS.

Von Seelhorst (1899) has determined the effect of different percentages of soil moisture on the water requirement of oat plants which were harvested just before the milk stage. Pots containing about 10 kilograms of soil were used. His results, which are expressed in terms of air-dry weight and include also the effects of fertilizers on the water requirement, are given in Table XXVIII (p. 38). The range in soil moisture in these experiments was small, and the effect upon the water requirement is not marked.

WILMS'S EXPERIMENTS.

Wilms (1899) investigated the effect of different soil-moisture contents on the water requirement of potato tubers (green weight) and obtained results which are in accordance with those already noted. The pots contained about 17 kilograms of soil and were not covered, but the water was applied through a Liebscher air-circulation tube, so that the surface soil always remained dry. The results of the investigation, which includes also the effect of various fertilizers on the water requirement, are given in Table XXIX (p. 39). The mean values obtained by Wilms are as follows:

Moisture-holding capacity	per cent..	33, 58, 80
Water requirement	green weight..	39, 50, 62

DASZEWSKI'S EXPERIMENTS.

Daszewski (1900) determined the dry weight of the tubers from a few of Wilms's pots. The combined data (Table V) show that the water requirement was greatly increased in the soil with the higher water content.

TABLE V.—*Effect of different amounts of soil moisture on the water requirement of potato tubers.*[1]

Fertilizer used.	Water content, in terms of moisture-holding capacity.				Mean water requirement.
	33 per cent.		58 per cent.		
	Dry tubers.	Water requirement.	Dry tubers.	Water requirement.	
	Grams.		*Grams.*		
None	50.7	98	72.5	156	127
Na_2SO_4	58.8	84	68.8	161	122
K_2SO_4	61.2	85	98.1	131	108
KNO_3	90.9	87	147.0	136	111
$MgSO_4$	55.7	92	78.7	150	121
Mean		89		147	

[1] Combined from Wilms (1899, p. 288-289) and Daszewski (1900, p. 240); the data as given are the mean of two pots.

FORTIER'S EXPERIMENTS.

Fortier (1903), using pots 18 inches in diameter, 30 inches deep, and containing 19 plants of Swedish Select oats, obtained the results given in Table VI. The first column of the table gives the total amount of water added to each pot expressed in terms of inches of rainfall. The water lost apparently includes the evaporation from the soil, though this is not definitely stated. The pots were apparently weighed o at the beginning and at the end of the experiment. Although dry matter increased progressively with the increased supply water, the water requirement reached its minimum with the use from 20 to 22 inches of water, increasing with either a greater or smaller supply of water.

TABLE VI.—*Effect of the amount of water added on the water requirement of oats, Bozeman, Mont., according to Fortier (1903, p. 107).*

Water added.	Dry matter.	Water requirement.
Inches.	*Grams.*	
2	55	501
6	76	574
14	145	525
20	235	434
22	252	433
22	264	413
32	312	528
38	316	552

VON SEELHORST AND BÜNGER'S EXPERIMENTS.

Von Seelhorst and Bünger (1907) conducted a fertilizer test wit high and low soil-moisture content, using open pots containing 1. kilograms of soil. This experiment was made on spring wheat The results (Table XXXII, p. 44) indicate a higher water requirement in soil of high moisture content.

OHLMER'S EXPERIMENTS.

Ohlmer (1908) also employed two different soil-moisture contents in connection with a fertilizer experiment with wheat at Gottingen (Table XXXIII, p. 45). The comparison was made with 11 different combinations of fertilizers, and in every instance the lower soil-moisture content gave the lower water requirement. The average of all the tests shows that a decrease in the soil-moisture content from 70 per cent of the water-holding capacity to 45 per cent decreases the mean water requirement by 12 per cent. Open pots were used.

WIMMER'S EXPERIMENTS.

Wimmer (1908) published the results of an extensive series of experiments to determine the effect of fertilizer on the water requirement of carrots and ray-grass. Open pots were used, the method being the same as that employed by Wilfarth and Wimmer (1902).

The results (Table VII) show no significant differences that can be attributed to the different soil-moisture contents employed. In several of the series differences are found which might be considered significant if they were at all consistent. As a whole, the data indicate that within the limits of this experiment different soil-moisture contents do not affect the water requirement of crops. The difference in soil-moisture content was very small, usually not more than 3 per cent. In view of this slight difference, combined with the uncertainty introduced by using open pots, it is not surprising that Wimmer's results do not show the influence of moisture content on the water requirement that other investigators have observed.

TABLE VII.—*Effect of different soil-moisture contents on the water requirement of carrots and ray-grass, according to Wimmer.*[1]

Year, period, and plat.	Previous fertilizer.	Soil per pot.	Fertilizer per pot.	Soil moisture.	Mean dry matter.	Water requirement.
CARROTS.[2]						
		Grams.	*Grams.*	*Per ct.*	*Grams.*	
May 3 to Oct. 30, 1903: Waldau 33, 34, 35	No potash since 1902	7,556	0.280N	14	21.4	420±25
			.280	17	31.0	419±19
			.280	20	32.1	466±31
			.700	14	22.2	302±25
			.700	17	31.0	412±14
			.700	20	43.8	386±16
F 1, 3, 5, 7	do	7,556	.280	14	19.6	458±17
			.280	17	31.9	352±10
			.280	20	32.1	442±22
			.700	14	17.3	470±46
			.700	17	28.5	393±14
			.700	20	44.2	309±15
RAY-GRASS.[3]						
May 1 to Nov. 1, 1903: Waldau 33, 34, 35	No potash since 1902; 0.284 gram P_2O_5 per pot.	7,556	.280	12	34.1	230±20
			.280	15	35.4	372±32
			.280	18	44.0	329±38
			.700	12	43.8	254±10
			.700	15	52.2	232±10
			.700	18	53.7	322±10
F 1, 3, 5, 7	do	7,556	.280	12	33.9	323±12
			.280	15	44.9	302±12
			.280	18	48.3	319±19
			.700	12	39.6	285±8
			.700	15	51.7	259±4
			.700	18	57.7	293±7
June 1 to Oct. 18, 1904: B 1[4]	No potash, 1891 to 1904; stable manure, 1891 to 1895; green manure, 1901.	6,766	....	15	66.9	302±1
			....	18	76.7	307±21
			.155K_2O	15	63.6	295±34
			.155	18	78.5	343±34
			.776	15	69.9	266±3
			.776	18	80.3	316±4
B 3[4]	None, 1891 to 1904	6,903	....	15	71.5	302±8
			....	18	84.5	283±5
			.155	15	66.3	322±22
			.155	18	85.9	275±11
			.776	15	68.7	324±3
			.776	18	72.9	312±27
B 5[4]	Same as B 1	6,791	....	15	57.0	365±14
			....	18	69.4	367±1
			.155	15	60.8	386±55
			.155	18	66.6	376±5
			.776	15	67.8	290±17
			.776	18	78.4	283±11
E 3	No potash since 1901	6,397	....	12	39.7	346±8
			....	15	44.7	346±13
			....	18	49.9	347±9
Waldau 87, 88, 89	No potash since 1900	7,359	....	12	32.8	343±16
			....	15	45.7	321±11
			....	18	55.3	398±42

[1] Computed from Wimmer's data (1908, pp. 43–89); mean of three determinations except as noted.

[2] The same data in Table XLIII (p. 55), under "Effect of nitrogen," are recorded under 12, 15, and 18 per cent of water, respectively. The original does not show which record is correct.

[3] Each pot received 0.284 gram of P_2O_5 in 1903 and 1.120 grams N and 0.284 gram P_2O_5 in 1904.

[4] The mean of two determinations.

TABLE VII.—*Effect of different soil-moisture contents on the water requirement of carrots and ray-grass, according to Wimmer*—Continued.

RAY-GRASS—Continued.

Year, period, and plat.	Previous fertilizer.	Soil per pot.	Fertilizer per pot.	Soil moisture.	Mean dry matter.	Water requirement.
		Grams.	*Grams.*	*Per ct.*	*Grams.*	
Apr. 17 to Sept. 26, 1905: B 3[1]	None, 1901 to 1905	7,919	....	15	92.4	313±4
			....	18	95.6	333±17
			0.155	15	93.8	306±21
			.155	18	98.7	336±1
			.776	15	92.5	310±7
			.776	18	100.4	350±16
F 3[1]	do	7,768	....	15	90.0	305±13
			....	18	113.4	290±4
			.155	15	88.4	319±32
			.155	18	104.3	303±7
			.776	15	90.0	312±17
			.776	18	102.1	311±7
H 3[1]	No potash, 1902 to 1905	7,344	....	15	80.2	341±32
			....	18	90.6	345±12
			.155	15	84.7	311±11
			.155	18	93.5	369±7
			.776	15	96.2	262±9
			.776	18	95.9	331±3
F 3[1]	No potash since 1901	7,768	.280N	12	41.5	406±5
			.280	15	46.2	440±4
			.280	18	50.9	439±27
Waldau[1] 87, 88, 89	No potash since 1903	8,042	.280	12	39.9	352±19
			.280	15	48.6	397±18
			.280	18	46.9	458±11
F 6[1]	Kainit since 1902	7,808	....	12	43.0	373±35
			....	15	46.0	454±19
			....	18	46.3	523±6
Juetrichau sand[1]	....	8,000	....	9	41.5	423±6
			....	11.5	44.0	441±5
			....	14	46.4	461±4
Buhlendorf sand[1]	....	8,000	....	7	26.0	521±14
			....	9	36.0	422±23
			....	11	33.8	490±27

[1] The mean of two determinations.

PREUL'S EXPERIMENTS.

Preul (1908) investigated the effect of different soil-moisture contents for varying periods upon the water requirement of wheat. The experiments were conducted with two different soils and the soil moisture was maintained at 45 and at 80 per cent of the moisture-holding capacity. Open pots were used in these experiments. A correction based upon the evaporation from check pots was made for evaporation, although it was not clear that a check was provided for each series of observations. The results (Table VIII) show a gradual decrease in the water requirement with the increase of the period during which the lower soil-moisture content was maintained. The lowest water requirement was obtained in the soil kept continuously at the lower water content.

TABLE VIII.—*Effect of different soil-moisture contents on the water requirement of squarehead summer wheat,*[1] *according to Preul (1908, pp. 12–13).*

Soil moisture, in terms of moisture-holding capacity during period.		Water requirement in—	
45 per cent.	80 per cent.	Rich soil.	Poor soil.
Mar. 12[2] to July 31		158±1	224±4
Mar. 12 to July 1	July 1 to July 31	147±6	220±7
Mar. 12 to June 15	June 15 to July 31	228±7	274±3
Mar. 12 to June 1	June 1 to July 31	235±2	281±4
Mar. 12 to May 15	May 15 to July 31	248±2	268±4
Mar. 12 to May 1	May 1 to July 31	251±1	261±3
	Mar. 12[2] to July 31	248±5	259±1
July 1 to July 31	Mar. 12 to July 1	209±1	263±4
June 15 to July 31	Mar. 12 to June 15	207±4	259±2
June 1 to July 31	Mar. 12 to June 1	207±3	222±5
May 15 to July 31	Mar. 12 to May 15	194±1	256±4
May 1 to July 31	Mar. 12 to May 1	187±3	246±3
Mean		210	253

[1] Zinc pots were used in these experiments. They were 33 centimeters in height, 25 centimeters in diameter, and contained 20.5 kilograms of soil. Each series consisted of 3 or 4 pots, 96 pots being used in all. The poor soil consisted of good soil mixed with heath sand. Each pot contained 1.47 grams K_2CO_3 and 1.65 grams $CaH_4(PO_4)_2$. In addition, each pot of good soil received 9.11 grams $NaNO_3$ and each pot of poor soil 3.04 grams of $NaNO_3$. Each pot of good soil contained 18 wheat plants and the pots of poor soil 9 wheat plants each. Several minor errors occurring in the original data have been corrected here.

[2] The pots of good soil were planted Mar. 12 and those of poor soil Mar. 16.

WIDTSOE'S EXPERIMENTS.

Widtsoe (1909) investigated the effect of the soil-moisture content on the water requirement of wheat, sugar beets, corn, and peas (Table IX). Maximum water contents of 10 and 20 per cent of saturation were chosen, and when any plant needed water all pots were brought up to weight. The pots were of galvanized iron, 24 inches in diameter and 30 inches high. A single open pot of each crop was used for each moisture content, the evaporation from a bare control pot being deducted. The results for the same crop fluctuate to such an extent from year to year as to render conclusions uncertain except in the case of corn, where the lower moisture content consistently gave the higher water requirement.

TABLE IX.—*Influence of soil-moisture content on the water requirement of certain crops, according to Widtsoe (1909, p. 39).*

Crop.	Saturation.	Water requirement.				Ratio of water requirement, low to high soil moisture.				
		1902	1903	1904	1905	1902	1903	1904	1905	Average.
	Per cent.									
Wheat	10	258	340	755	356	0.51	0.65	1.13	1.36	0.91±0.16
	20	511	523	664	261					
Sugar beets	10	639	227	645	570	1.52	.33	1.60	1.21	1.17± .20
	20	420	696	403	469					
Corn	10	490	280	424	697	1.21	1.09	1.54	2.28	1.53± .19
	20	406	256	276	306					
Peas	10	1,658	269	510	525	2.05	.34	.30	......	.90± .46
	20	808	789	1,704	......					

LEATHER'S EXPERIMENTS.

Leather (1910) has also investigated the influence of the soil-moisture content on the water requirement of wheat and corn at Pusa, India. His determinations are given in detail in Table XXXIX (p. 51), each determination being based upon a single open jar. From these measurements the writers have computed the mean water requirement obtained for each soil-moisture content when different fertilizers were used. These means are to be found in the last columns of the tables referred to and are, of course, comparable only in so far as they apply to jars of the same size and to the same series of fertilizers. A summary of the observations for each soil-moisture content, obtained by averaging the mean values found with pots of different capacity, is also given in Table X. The results are seen to be in agreement within the limits of experimental error. In other words, an increase in the moisture content of Pusa soil from 10 to 20 per cent of the saturation content did not affect the water requirement by an amount exceeding the experimental error.

TABLE X.—*Effect of soil-moisture content on the water requirement of wheat and corn at Pusa, India, according to Leather (1910, p. 133).*

Crop.	Year.	Total pots used with each water content.	Water requirement with—		
			10 per cent water.	15 per cent water.	20 per cent water.
Wheat	1906–7	8	747	707	737
	1907–8	6	562	....	743
Corn	1907	9	414	404	436

KIESSELBACH'S EXPERIMENTS.

Kiesselbach (1910) has measured the effect of soil-moisture content on the water requirement of corn at Lincoln, Nebr., using covered 4-gallon glazed stone jars, containing 14.5 kilograms of dry loam.

Water was added through a tube to a reservoir formed by inverting a 4-inch flower pot in the bottom of the jar. Surface evaporation was prevented by the use of gravel and paraffined parchment paper. The plants were grown in a cornfield, one plant to a jar. An oilcloth cover was used on each jar to keep out rain, and a temporary canvas cover was put on during rainstorms. The jars were weighed once in 48 hours and sufficient water added each time to restore the original weight. The variation in degree of saturation during this period ranged from 5 to 10 per cent. The plants were harvested shortly after the silking stage. The results are shown in Table XI. The plant grown in soil 20 per cent saturated wilted when the conditions gave rise to high transpiration. This may be associated with the slightly lower water requirement recorded in the case of these plants.

No differences in the water requirement greater than the probable error occur in the case of the plants grown at other degrees of saturation.

TABLE XI.—*Influence of soil-moisture content on the water requirement of corn, according to Kiesselbach (1910, p. 125).*

Saturation.	Average dry weight, without roots.	Water requirement based on dry weight.	
		Excluding roots.	Including roots.
Per cent.	*Grams.*		
98	91.1	270	242±5
80	93.1	272	239±9
60	100.6	256	227±10
40	92.9	270	233±7
20	83.2	239	201±5

KIESSELBACH AND MONTGOMERY'S EXPERIMENTS.

Kiesselbach and Montgomery (1911) extended Kiesselbach's investigation with corn, using large pots in which the plants were brought to maturity. Single plants were grown in galvanized-iron pots 16 inches in diameter and 3 feet deep. The construction of their potometer is shown in figure 2. Water was added through a perforated $\frac{3}{8}$-inch brass pipe 15 feet long bent in the form of a helical coil. Evaporation from the soil was minimized by a layer of gravel 3 inches deep. Rain was excluded with the aid of a galvanized-iron lid having a 4-inch opening in the center for the plant, the opening being covered with oilcloth closely fastened about the cornstalk. The potometers were located in a cornfield and were apparently sunk in trenches so that the tops of the pots were level with the surface of the surrounding field. The potometers were mounted on small, individual trucks and were run on tracks to a platform scale which was mounted on a cross track.

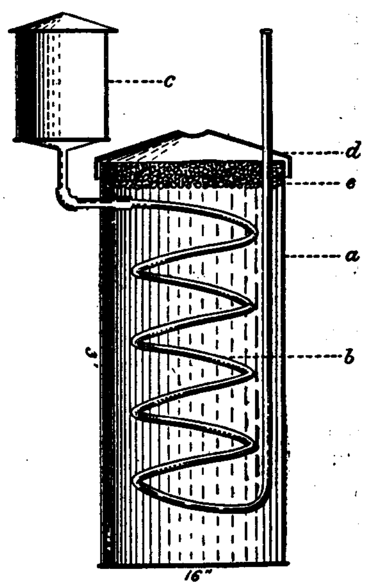

FIG. 2.—Pot employed by Kiesselbach and Montgomery (1911) in measuring the water requirement of corn.

Five different degrees of soil saturation were maintained, namely, 100, 80, 60, 45, and 35 per cent. Saturation was regarded as the amount of water retained by the soil when drainage had ceased after pouring water on the soil surface. One hundred pounds of water out at other times. The experiments extended from April 29 to July 16 and July 30. The results of these investigations are given in Table XIII. The plants were grown in open pots, without bare check pots, but a correction for loss due to evaporation from the soil surface was made in the following way: The mean value of the water consumption and of dry matter, respectively, for four pots from each moisture-content series, grown without nitrogen, was subtracted from the water consumption and dry matter of each individual fertilized pot of that series. The ratio of the remainders was taken to represent the water requirement of the plants grown in that pot. This correction ranges from nearly one-half of the total water consumption in the case of the low-nitrogen pots to about one-seventh of the water consumption in the high-nitrogen pots.

An analytical examination of this method of correcting for evaporation shows that it can not be justified.

Let t_0 = total water transpired and evaporated from pot without nitrogen.
t = total water transpired and evaporated from pot with nitrogen.
e_0 = water evaporated from soil of pot without nitrogen.
e = water evaporated from soil of pot with nitrogen.
w_0 = dry weight of unfertilized plants.
w = dry weight of fertilized plants.
r_0 = water requirement of unfertilized plants.
r = water requirement of fertilized plants.

Then, by definition,
$$\frac{t_0-e_0}{w_0}=r_0 \qquad (1)$$

and, similarly,
$$\frac{t-e}{w}=r. \qquad (2)$$

Subtracting equation 1 from equation 2, we have—
$$t-t_0+e_0-e=rw-r_0w_0. \qquad (3)$$

Pfeiffer, Blanck, and Flügel, in calculating the water requirement, took the difference between the water loss from the fertilized and unfertilized pots and divided this by the corresponding difference in dry weight. The quotient was considered to be the water requirement of the plants in the fertilized pot. Expressed as an equation, this becomes—
$$\frac{t-t_0}{w-w_0}=r \qquad (4)$$

or,
$$t-t_0=rw-rw_0. \qquad (5)$$

Subtracting equation 5 from equation 3, we have—
$$e_0-e=(r-r_0)w_0, \qquad (6)$$

which is the assumption that Pfeiffer, Blanck, and Flügel really make in following their method of reducing the results. Writing equation 6 in the form—
$$\frac{e_0-e}{w_0}=r-r_0,$$

it will be seen, first, that their assumption is that the difference in the transpiration ratios of two series is proportional to the difference in the amount of soil evaporation from the series, factors which obviously have no dependence one upon the other; and, second, that if the soil evaporation from the two series was made equal, the water requirement of the two series would have to be equal, irrespective of the method of treatment! It is evident from this analysis that the method of reduction employed by Pfeiffer, Blanck, and Flügel is not sound, and that consequently no weight can be attached to the data as given. The data without the correction for evaporation are, unfortunately, not given in the original paper.

TABLE XIII.—*Effect of different soil-moisture contents on the water requirement of oats,*[1] *according to Pfeiffer, Blanck, and Flügel (1912, p. 230).*

Nitrogen applied per pot.[2]	Water requirement with—				
	High water content, 10 per cent.	Low water content, 7 per cent.	Varying water content, 4 to 10 per cent.	High water content and shade, 10 per cent.	Mean.
Grams.					
0.355	397±5	348±5	344±1	406±2	374
.710	388±4	341±2	281±4	419±2	357
1.065	372±3	304±7	273±3	392±4	336
1.420	373±6	371±3	292±4	401±4	359
1.775	397±4	386±5	307±4	433±4	381
2.130	414±7	372±4	301±4	383±4	368
Mean	390±2	354±2	300±2	410±2 [3]	363

[1] Twenty-four plants of Ligowo oats were grown in each pot. The pots contained 18 kilograms of sand of low moisture-holding capacity. There were four pots for each determination. The dry matter produced is not given.
[2] Applied as ammonium nitrate.
[3] Pfeiffer, Blanck, and Flügel omitted four pots in calculating this mean because the plants were not artificially shaded. These pots apparently formed the series whose mean is 383±4.

CONCLUSIONS.

In general, the results of the experiments herein recorded show an increase in the water requirement when the water content of the soil approaches either extreme. Many of the experiments were conducted in open pots and the evaporation estimated by means of check pots, which is an uncertain procedure. Extreme moisture conditions might, however, affect the water requirement indirectly. With a high water content, the aeration would be reduced and the soil solution would be diluted. In the case of soils kept at a low water content, the small amount of water required from time to time to bring the pot to normal weight is sufficient to moisten only a comparatively small portion of the soil mass. In effect, then, the low soil-moisture plants are growing in a very restricted soil mass as compared with plants grown with an optimum soil-moisture content. This condition might cause an increase in the water requirement of plants grown in a comparatively dry soil due to a deficiency of plant food. In view of these considerations the writers believe that the direct influence of soil-moisture content on the water requirement can not be established without further investigation.

EFFECT OF SOIL TYPE ON THE WATER REQUIREMENT.

MARIÈ-DAVY'S EXPERIMENTS.

Mariè-Davy reports experiments (Table XIV) which were designed to show the effect of different soils on the water requirement of wheat for grain production. In the first series (1875), 2-liter glass containers with small necks were employed and direct evaporation practically eliminated. Each soil was given 10 different treatments, but since the different soils received the same series of treatments, a comparison on the basis of the soil is possible. In the later experiments (1876) large, open casks, 1 meter square, were employed. A single cask of soil was used in each treatment, leaf mold being added in varying amounts. The addition of the leaf mold does not appear to have had beneficial effects except in the case of soil from Saint-Ouen. In all other cases it increased the water requirement of wheat for grain production. The total dry matter is not recorded and no adequate description of the soils is given. The differences recorded are probably due partly to soil differences, although the lack of agreement in the two tables indicates rather high experimental errors. It is probable, however, that had the water requirement been computed on the total dry matter the results would have been modified. The addition of leaf mold often increases the straw as compared with the grain yield, and this may account for the high water requirement for grain when leaf mold was employed.

TABLE XIV.—*Effect of different soils on the water requirement of wheat, according to Mariè-Davy.*

Soil employed.	Period.	Dry grain.	Water requirement, based on grain.
Montsouris plus fertilizer	1874 [1]	3.99	1,126
Saint-Ouen plus fertilizer		5.48	1,034
Gravelle plus fertilizer		5.65	1,010
Dornecy (brown) plus fertilizer		4.13	1,435
Ivry plus fertilizer		5.09	1,056
Vincennes plus fertilizer		6.06	1,015
Fontenay sand [2] plus fertilizer		4.20	1,364
Montsouris plus 25 kilograms leaf mold	1874.[3] Feb. 1 to July 23	394	964
Saint-Ouen plus 25 kilograms leaf mold		....	....
Saint-Ouen plus 50 kilograms leaf mold		300	1,160
Gravelle plus 25 kilograms leaf mold		380	913
Gravelle plus 50 kilograms leaf mold		303	1,122
Dornecy (brown) plus 50 kilograms leaf mold		256	1,387
Peat		328	1,047
Dornecy (red) plus 50 kilograms leaf mold		324	1,015
Vincennes plus 25 kilograms leaf mold		312	1,087
Vincennes plus 50 kilograms leaf mold		308	1,163
Ivry plus 25 kilograms leaf mold		313	1,105
Ivry plus 50 kilograms leaf mold		236	1,576

[1] 1875 (pp. 306–310). Ten pots of each soil each of 2 liters capacity and each receiving one of the fertilizers given in table. Evaporation from the soil practically eliminated. In Mariè-Davy (1874) many of the data given in this table are presented in a somewhat different form. The water requirement there recorded is based on total water loss and total dry matter produced by all pots, while the water requirement here given is the mean for the series of pots.

[2] Fontenay sand received different fertilizers and only 9 pots were used.

[3] 1876 (p. 387). Conducted in open pots of 1 cubic meter capacity and 1 square meter surface. No correction was made for evaporation.

TABLE XIV.—*Effect of different soils on the water requirement of wheat, according to Marié-Davy*—Continued.

Soil employed.	Period.	Dry grain.	Water requirement, based on grain.
Montsouris plus chemical fertilizer	1875.[1] Feb. 1 to July 16	394	918
Saint-Ouen plus chemical fertilizer		372	956
Do		474	728
Gravelle plus chemical fertilizer		479	760
Do		425	837
Dornecy (brown) plus chemical fertilizer		262	1,385
Peat plus chemical fertilizer		435	841
Dornecy (red) plus chemical fertilizer		424	811
Vincennes plus chemical fertilizer		387	894
Do		379	966
Ivry plus chemical fertilizer		469	738
Do		379	957

[1] 1876 (p. 387). Conducted in open pots of 1 cubic meter capacity and 1 square meter surface. No correction was made for evaporation.

In 1875 commercial fertilizer was added to all pots. The differences in the water requirement in the different soils were approximately the same as during the previous year, although the water requirement was less for each soil than in 1874.

LIEBSCHER'S EXPERIMENTS.

Liebscher (1895) conducted a series of fertilizer experiments in clay and sand soils. His results are given in Table XXVI (p. 36). A comparison of the results for the two soils shows a slightly higher water requirement in the loam than in the sand, when the whole series is taken into account. The same is true also of the check plants grown without the addition of fertilizer.

KING'S EXPERIMENTS.

King (1905) used four different types of soil in his water-requirement investigations. Open pots 4 feet in diameter and 4 feet deep sunk in the ground in an open space were employed. Since the experiments were carried on at widely separated locations, differences due to climatic conditions must also be recognized. The results (Table XV) include the evaporation from the soil surface, which was unprotected. Direct-evaporation measurements were also made simultaneously in similar tanks in which no corn was grown. Taking the loss from direct evaporation as 100, the total loss from the soil tanks containing corn at the different stations in the order given in the table was 122, 84, 125, and 118. These ratios illustrate the uncertainty attending this method of measuring the water requirement of crops.

TABLE XV.—*Effect of different soils on the water requirement of corn,*[1] *according to King (1905, pp. 193–194.)*

Location.	Soil.	Duration.	Evaporation per square foot of soil surface per day.	Water requirement.
		Days.	*Pounds.*	
Goldsboro, N. C.	Norfolk sandy loam	97	1.1	387
Upper Marlboro, Md	Norfolk sand	126	.98	1,152
Lancaster, Pa	Hagerstown clay loam	128	.796	474
Janesville, Wis	Janesville loam	126	.938	336

[1] The variety of corn used was Iowa Goldmine.

VON SEELHORST'S EXPERIMENTS.

Von Seelhorst (1906) measured the water requirement of rye and potatoes in open pots, using loam and sand. The results (Table XVI) show that rye has a somewhat lower requirement in loam than in sand. With potatoes, however, the results were reversed, the sand giving a slightly lower water requirement. The data are too meager to be conclusive.

TABLE XVI.—*Effect of soil type on the water requirement of rye and potatoes at Gottingen, according to Von Seelhorst, (1906, p. 316).*[1]

Plant.	Sand.		Loam.	
	Mean dry matter.	Water requirement.	Mean dry matter.	Water requirement.
	Grams.		*Grams.*	
Rye	306	486±15	700	375
Potatoes	[1] 103	60±0	4,737	66

[1] The water requirement of potatoes is based on the green weight. Three determinations were made with each crop for sand, one determination for loam.

WIDTSOE'S EXPERIMENTS.

Widtsoe (1909) has measured the water requirement of corn and wheat at Logan, Utah, using four types of soil. Pots 24 inches in diameter and 30 inches high were employed. The College loam and Sanpete clay types were productive soils, while the sand and clay types were nonproductive. The experiments extended through a period of four years. The increased water requirement of crops when grown in nonproductive soils is clearly shown in the results, a summary of which is given in Table XVII.

TABLE XVII.—*Influence of soil texture on the water requirements of certain crops at Logan, Utah, according to Widtsoe (1909, p. 57).*

Crop.	Number of trials.				Water requirement.			
	Sand.	College loam.	Sanpete clay.	Clay.	Sand.	College loam.	Sanpete clay.	Clay.
Corn	11	46	12	3	561	386	408	601
Wheat	2	15	2	5	2,017	546	658	917
Sugar beets	....	11	....	....	....	497	....	....
Peas	....	10	....	....	....	843	....	....

LEATHER'S EXPERIMENTS.

Leather (1910, 1911) has investigated the water requirement of crops grown in several Indian soils. (See effect of fertilizing, Table XL, p. 52). The same crop sometimes showed a wide variation in its water requirement when grown in different soils. The water requirement of wheat grown in different unfertilized soil types in 1909–10, for example, was found to be 582, 842, and 526. Other variables enter in most cases, however, so that Table XL must be referred to for the comparisons.

CONCLUSIONS.

The water requirement, according to the data presented, is affected by the kind of soil used. The factor influencing the water requirement seems, however, to be plant food rather than the type of soil. The water requirement will be higher in a poor soil, whether it be sand or clay, than in a good soil. The data presented do not indicate that the water requirement is affected by soil texture alone, when plant food is equally available in the different soil types.

EFFECT OF CULTIVATION ON THE WATER REQUIREMENT.

SLËSKIN'S EXPERIMENT.

Slëskin (1908) conducted an experiment to determine the effect of cultivating the soil on the growth of the sugar beet. A portion of a uniform plat was covered with a layer of cement to prevent all loss of water by direct evaporation or gain by precipitation. Seventy-two stakes were driven into the ground where the beets were to be planted and the cement flowed in around these stakes. As soon as the cement had set, the stakes were withdrawn and the holes filled with sand. The beets were planted in these holes. The remaining portion of the plat was planted to beets, allowing the same distance between plants, and was given the best of cultivation. The results shown in Table XVIII indicate clearly that more dry matter was produced by the beets grown in the covered portion than in the open plat. The reduction in water content was less in the covered soil than in the exposed soil, notwithstanding the addition to the open plat of 11 inches of water in the form of rain.

From a single pot experiment in which 3 beet plants produced 479 grams of dry matter in a pot containing 420 pounds of soil, Slěskin found the water requirement of sugar beets, exclusive of evaporation, to be 337. The beets were grown in an open pot, but by alternately covering the soil surface and leaving it exposed the evaporation was computed. This in turn was used as a basis for computing the evaporation loss from the cultivated plat. If the computed evaporation loss is accepted, it follows that the water requirement of the beets, exclusive of evaporation, was less under the cement-covered than in the cultivated plat.

TABLE XVIII.—*Water consumption of sugar beets in cement-covered and in cultivated plats, according to Slěskin (1908).*[1]

	Cement-covered plat.	Cultivated plat.
Number of beets harvested	59	78
Weight of beets in kilograms	26.9	16.1
Water added to soil by rainfall ... millimeters		226
Computed loss by evaporation ... do		247
Loss in excess of rainfall ... do		21
Water content of the soil at the end of experiment ... per cent	3.4	2.7

[1] The writers are indebted to Raphael Zon, Chief of the Office of Silvics of the Forest Service, for assistance in translating Slěskin's and Schroeder's articles.

WIDTSOE'S EXPERIMENTS.

Widtsoe (1909) has investigated the effect of shallow cultivation on the water requirement of corn (*Zea mays*). The pots, 24 inches in diameter by 30 inches high, were cultivated 48 hours after surface irrigation, and then weekly until irrigated again. The cultivation was done with a gardener's comb to a depth of 1 inch. Four pots were used for each soil type investigated, two being cultivated. Corn was grown in one cultivated and one uncultivated pot. The other two pots were without crops. The difference in the amount of water lost from the cropped and barren pot in each treatment was taken to represent the transpiration loss of the crop. The experiment was conducted for three years. The results are given in Table XIX, and show in most instances a marked reduction in the water requirement, due apparently to the cultivation.

This is a subject regarding which it is extremely difficult to obtain reliable and concordant results. The uncertainty arises in the assumption that the evaporation loss from the cropped pots is the same as from the barren pots. The pots must be left open and freely exposed, and this means a high evaporation loss. In fact, the average transpiration of all the cropped pots in Widtsoe's experiments was but 55 per cent of the total loss, the extreme values being 14 and 82 per cent.

It seems remarkable that the cultivation of the surface inch of soil should have had an appreciable influence on the actual water requirement, and further experiments are desirable, using a larger number of pots to reduce the experimental error.

TABLE XIX.—*Effect of cultivation on the water requirement of corn, according to Widtsoe (1909, p. 19).*

Soil.	Saturation.	Treatment.	Water requirement.			Ratio, cultivated to uncultivated.			
			1902	1903	1904	1902	1903	1904	Mean.
	Per cent.								
Sand	15	Cultivated	732	281	411	1.61	......	......	1.61
		Uncultivated	454	......	......				
College loam	20	Cultivated	295	236	225	.56	0.62	0.25	.48±.09
		Uncultivated	523	378	908				
Sanpete clay	25	Cultivated	280	388	615	.64	.68	1.03	.78±.10
		Uncultivated	439	569	595				
Clay	30	Cultivated	582	......	......	.78	......	......	.78
		Uncultivated	753	468	......				

CONCLUSIONS.

The results of Slëskin and of Widtsoe lead to opposite conclusions regarding the effect of cultivation on the water requirement. Neither experiment is free from certain assumptions relative to the amount of evaporation from the soil, and consequently neither experiment can be considered as showing conclusively that cultivation has a direct effect on the water requirement independent of soil evaporation.

EFFECT OF THE SOIL MASS ON THE WATER REQUIREMENT.

HELLRIEGEL'S EXPERIMENTS.

Hellriegel (1883) measured the water requirement of red clover using culture jars of different sizes. The results are given in Table XLIX (p. 59). The differences shown in his experiments are without significance, owing to the high probable errors. A similar series dealing with barley is given in Table LII (p. 62). No consistent difference in the water requirement was found attributable to the amount of soil used.

LEATHER'S EXPERIMENTS.

Leather (1910) used in his fertilizer experiments jars ranging in capacity from 15 to 31 kilograms of soil. He states that this variation in the mass of soil used may affect the transpiration ratio 10 to 20 per cent, the smaller jars giving the higher water requirement. His results are given in Table XXXIX (p. 51) in connection with his fertilizer experiments. The writers have combined these results in Table XX, calculated with respect to the size of the jar used.[1] The mean values show with one exception that the use of the smaller jar gives a higher water requirement.

[1] The average result for each set of jars of a given size includes several fertilizer treatments. The kind of treatment and the number of jars used with each treatment are, however, uniform for a given crop and year for each size of jar, so that the results for the same crop and year are comparable.

Leather adopted for his later experiments jars containing about 50 kilograms of soil. Plants like maize and juar (jowar) were found to develop much better in these large jars than when grown in jars holding one-fourth as much soil.

TABLE XX.—*Effect of the amount of soil used on the water requirement of wheat and maize, according to Leather (1910).*

Crop.	Year.	Number of jars used.	Amount of soil used per jar.	Water requirement.
			Kilograms.	
Wheat	1906–7	12	15	722
			22	454
Do	1907–8	6	15	719
			27	590
Maize	1907	9	15	415
			21	441
			31	393

CONCLUSIONS.

Leather's data are conclusive in showing the influence of the soil mass on the water requirement. An insufficient soil mass increases the water requirement, probably as a result of an insufficient supply of plant food.

EFFECT OF FERTILIZERS ON THE WATER REQUIREMENT.

SOIL CULTURES.

LAWES'S EXPERIMENTS.

The earliest investigations regarding the effect of plant food on the water requirement were carried on with water cultures and will be considered in a subsequent section. Lawes (1850) appears to have been the first to use fertilizers in connection with soil cultures in investigating the water requirement. His results, which were obtained at the Rothamsted Station, England, are shown in Table XXI.

TABLE XXI.—*Effect of fertilizers on the water requirement of different crop plants, according to Lawes (1850, p. 54).*

Fertilizer and crop.	Dry matter.[1]	Water transpired.[1]	Water requirement.	Mean water requirement.	
				Wheat, barley, and clover.	All plants.
Unmanured:	*Grams.*	*Kilograms.*			
Wheat	29.7	7.35	247	258	248
Barley	30.2	7.78	258		
Clover	13.3	3.57	269		
Beans	34.8	7.27	209	....	
Peas	27.3	7.07	259	....	
Mineral manure:					
Wheat	28.6	6.35	222	236	227
Barley	32.5	8.32	256		
Clover	15.2	3.48	229		
Beans	34.8	7.64	219	....	
Peas	29.6	6.24	211	....	
Ammoniacal and mineral manure:					
Wheat	17.6	3.63	206	209	....
Barley	20.3	5.52	272		
Clover	6.0	.89	148		

[1] Data recalculated to metric units.

The jars used (fig. 3) were of glass, 14 inches deep, 9 inches in diameter, and held about 42 pounds of soil. The direct evaporation was cut off by the use of a glass plate cemented to the top of the pot, a ¾-inch hole being provided in the center for the plants. A check pot without a crop was supplied to determine the loss from evaporation through the central opening. The loss thus measured amounted to about 3 per cent of that from jars containing plants. This correction was not applied, however, Lawes believing "that the indications of this experiment should serve rather to prevent any too nice application of the numerical results obtained in relation to the plants than as providing any available means of correcting them."

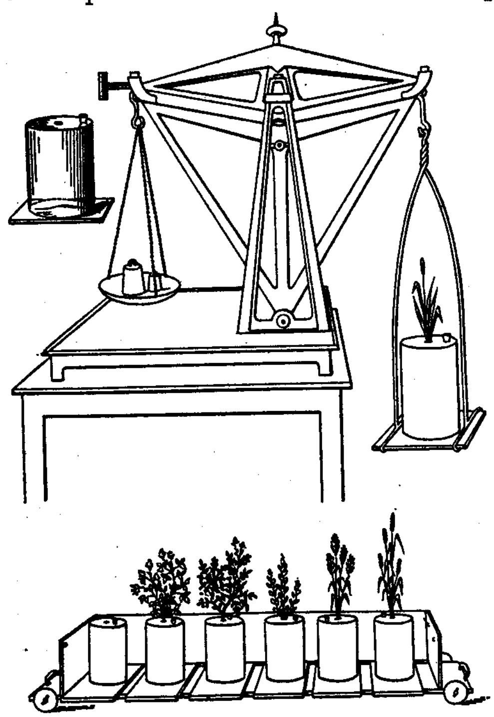

FIG. 3.—Apparat usused by Lawes (1850) in measuring the water requirement of plants.

The comparison of the two series will show that the water requirement was reduced by the use of mineral manures. The plants in the series in which ammoniacal salts were used made such a poor growth that Lawes attributed little significance to the results.

MARIÈ-DAVY'S EXPERIMENTS.

Mariè-Davy (1875) investigated the effect of various fertilizers on the water requirement of wheat for grain production. The pots used were 2-liter flasks with small necks, the direct evaporation from the soil being very small. The results of this experiment are recorded in Table XXII and represent the mean values obtained with six different soils. Each treatment lowered the water requirement as compared with the check series, which received no fertilizer.

TABLE XXII.—*Effect of fertilizers on the water requirement of wheat, according to Mariè-Davy (1875, pp. 305–309).*[1]

Treatment.[1]	Dry grain.	Water requirement of grain.
	Grams.	
Not fertilized	2.32	1,546
1.5 grams each per pot—		
$CaHPO_4$, KNO_3, and NaCl	5.40	968
KNO_3, $(NH_4)_3PO_4$, and NaCl	5.52	1,181
Na_2HPO_4, K_2CO_3, and $CaSO_4$	2.58	1,393
KNO_3, NaCl, and $CaSO_4$	4.98	1,006
Soil watered with solution containing 94 milligrams $(NH_4)_3PO_4$, 200 milligrams NH_4NO_3, 105 milligrams KNO_3, and 16 milligrams NaCl per liter	4.20	1,046
As above plus 10 per cent leaf mold	7.50	889
10 per cent leaf mold	4.18	988
20 per cent leaf mold	4.65	1,165
40 per cent leaf mold	9.72	981

[1] Each treatment was repeated on six different soils. (See Table XIV, p. 25.) The treatment given for this experiment by Mariè-Davy (1874) does not conform exactly to the record here given. It is not clear which is correct.

HELLRIEGEL'S EXPERIMENTS.

Hellriegel (1883) carried on several experiments to determine the effect of different amounts of fertilizer on the water requirement, using open pots containing 4 kilograms of quartz sand. His results (Table XXIII) show a great decrease in the water requirement as the amount of fertilizer is increased. The water requirement was doubled by the absence of potassium and trebled by the absence of nitrogen. A correction for direct evaporation from the soil had to be made, which introduced an element of uncertainty into the results. An abnormally high water requirement would, however, be expected in the case of a plant growing in a soil which was deficient in any essential element of plant food. Its growth would be arrested, but transpiration would still go on.

TABLE XXIII.—*Effect of calcium nitrate and potash on the water requirement of barley, according to Hellriegel (1883, pp. 629–631).*

Period.	Determination.	Milligram equivalents of calcium nitrate.[1]							
		20	16	12	10	8	6	4	0
Apr. 30 to Aug. 6, 1868, 98 days	Water requirement	338	......	......	349	352	425	481	982
	Dry matter.....grams	16.5	......	......	13.5	12.2	9.5	6.6	0.7
May 3 to July 24, 1869, 82 days	Water requirement	292	302	345	......	347	......	399	[2]796±53
	Dry matter.....grams	25.5	23.0	18.3	......	13.9	......	8.5	[2]1.1±0

Period.	Determination.	Milligram equivalents of potash.[3]						
		3.0	2.2	1.6	1.2	0.8	0.4	0
Apr. 30 to Aug. 6, 1868, 98 days	Water requirement	330	362	390	453	422	525	615
	Dry matter.....grams	20.8	18.4	17.3	15.7	15.4	10.8	6.4

[1] Soil used: Four kilograms of quartz sand plus 2 KH_2PO_4, 1 KCl, and 1.6 $MgSO_4$ in milligram equivalents.
[2] Mean of two measurements.
[3] Soil used: Four kilograms of quartz sand plus 1.6 $Ca(NO_3)_2$ and 1.6 $MgSO_4$ in milligram equivalents.

DEHÉRAIN'S EXPERIMENTS.

Dehérain (1892) reported experiments on the effect of different fertilizers upon the water requirement of ray-grass and clover (Table XXIV). To determine the water consumed, the amount of water which drained through the soil was deducted from the amount which fell upon the soil as rain. No correction was made for differences in the water content of the soil at the time of planting and at harvest, or for the direct loss by evaporation. The results show a lower water requirement in a manured soil than in a poor soil not manured.

TABLE XXIV.—*Effect of different fertilizers on the water requirement of ray-grass and clover, according to Dehérain (1892, pp. 471–473).*

Soil and treatment.[1]	Ray-grass.		Clover.	
	Dry matter.	Water requirement.	Dry matter.	Water requirement.
	Grams.		*Grams.*	
Good soil	45	630	89	322
Poor soil	39	682	65	454
Poor soil and K, N, and P fertilizer	102	[2] 266	72	398
Poor soil and manure water in 1890; K, N, and P fertilizer in 1891	64	435	99	255
Poor soil and manure water in 1890 and 1891; K, N, and P in 1891	65	449	95	272

[1] The water loss included evaporation. Each pot contained about 60 kilograms of soil, and the water content was assumed to be the same at the time of harvest as at the time of planting. The amount of K, N, and P was practically the same in the last three pots; the first contained N in the form of nitrate of soda and ammonium sulphate, while the last two contained organic nitrogen. The experiment continued from Apr. 7 to Sept. 4, 1891 (?).

[2] Dehérain erroneously gives 233.

KING'S EXPERIMENTS.

King (1894) investigated the effect of fertilizers on the water requirement of potatoes and corn, using large open pots. In the work with the potato, 6 galvanized-iron cylinders, 18 inches in diameter and 42 inches deep, were used. These stood above ground and were protected on the south side by a screen of boards. Each pot was watered through a 3-inch draintile set vertically in the pot against one side. The level of standing water in the pots was not allowed to rise over 6 inches from the bottom. The pots were protected at night and during rainy weather by a tent of heavy duck. The fertilized pots each received 5.3 grams of potassium nitrate before planting and the same amount the preceding year, during which time the pots were kept fallow. The results, which are given in detail in Table XXV, indicate that the use of potassium nitrate does not affect the water requirement of potatoes. In the case of corn the use of manure apparently reduced the water requirement markedly, but the result is affected with a large probable error.

TABLE XXV.—*Effect of fertilizer on the water requirement of potatoes and corn, according to King (1894, 1895).*

Pot No.	Crop.	Fertilizer.	Dry matter.	Tubers.[1]	Water.	Water requirement based on—	
						Dry matter.	Weight of tubers.
			Grams.	*Grams.*	*Kilos.*		
1	Potatoes[2]	KNO_3	151.4	75.5	88.8	587	1,176
2			227.1	99.1	109.2	481	1,102
3			204.3	97.2	105.6	517	1,086
	Mean					528±23	1,121±21
4	Potatoes[2]	None	227.7	112.2	107.5	472	958
5			163.1	87.2	97.4	[3] 597	1,117
6			246.1	104.4	112.8	458	1,081
	Mean					509±35	1,052±38
2	Corn[4]	Manured	639.1		142.7	223	
			413.9		106.5	257	
	Mean					240±14	
1	Corn[4]	Not manured	618.7		143.5	232	
			174.8		78.4	[5] 448	
	Mean					390±91	

[1] From King's data (1895, p. 246).
[2] King (1895, pp. 242, 243). The variety used was Alexander's Prolific.
[3] King gives 497 for this ratio, which is evidently an error.
[4] King (1894, p. 157). A flint variety was used. The amount of manure used is not stated. It is described as "a dressing," placed 5 inches below the surface.
[5] King gives 223 for this value, which from his data is evidently an error; the ratio was apparently taken in inverse order.

LIEBSCHER'S EXPERIMENTS.

Liebscher (1895) measured the water requirement of oats as affected by different fertilizers. The pots, which were open and contained from 9 to 11 kilograms of soil, were equipped with Liebscher's air-circulation apparatus (1895, p. 144). This consists of a half cylinder of zinc located at the bottom of the pot, with the opening on the under side. A zinc tube 1 centimeter in diameter is soldered to each end of the half cylinder and rises upward along the inner wall of the pot. One tube ends at the top of the pot; the other rises 15 centimeters above the upper edge. The pot is so oriented that the longer tube is on the south side, where it becomes strongly heated in the sun, and thus induces an air circulation through the half cylinder below. No statement could be found regarding the method of protecting the pots from rain, or as to whether the water was added through the ventilating apparatus or to the surface soil. The results are given in Table XXVI. These results are as a whole consistent and conclusive. The check series, both with clay and sand, gave a higher water requirement than any other series, while the complete fertilizer (KNP) gave the lowest water requirement. Phosphorus alone gave better results in the clay than in sand, while potassium gave a higher requirement than either nitrogen or phosphorus used singly. In the clay soil phosphorus and nitrogen combined gave a water requirement lower than either phosphorus and potassium or potassium and nitrogen. In the sand phosphorus and nitrogen gave the same result as potassium and nitrogen, while potassium and phosphorus gave a somewhat higher water requirement.

TABLE XXVI.—*Effect of different fertilizers on the water requirement*[1] *of oats at Gottingen, according to Liebscher* (*1895, p. 211*).

		Water requirement, using—								
		K	N	P	KNP	Check.	KN	KP	PN	Mean.
Clay, 9,160 grams; water, 2,210 grams..	Dry matter, grams.	32.1	45.6	43.2	123.2	[2] 32.1	42.2	42.6	122.8	278
	Water requirement.	344±9	311±1	270±7	173±3	349±9	319±7	264±2	177±2	
Sand, 11,700 grams; water, 1,740 grams..	Dry matter, grams.	35.2	129.7	35.7	149.3	34.0	133.3	36.0	139.7	251
	Water requirement.	313±8	194±2	307±5	178±1	332±7	192±2	299±6	192±1	

[1] Probable errors are computed by the writers from Liebscher's data; three pots were used in each determination. Three applications of fertilizer were made during the season, the amounts applied per pot each time being as follows: 0.475 grams of N; 0.482 grams of P_2O_5; and 0.906 grams of K_2O.
[2] Liebscher gives 32.7, which is evidently an error.

MAERCKER'S EXPERIMENTS.

Maercker (1896) investigated the effect of various potassium fertilizers and of sodium chlorid on the water requirement of white mustard. As a source of potassium he used kainit (a hydrous magnesium sulphate containing potassium chlorid) and carnallit (a hydrous chlorid of magnesium and potassium). The soil used was sand with an admixture of 2.5 per cent of peat. The capacity of the pots is not stated, but was probably small, 6 kilograms of soil being used in other fertilizer experiments with mustard. The pots were not covered, and check pots without plants were not used. The summary of results (Table XXVII) shows that all the fertilizers used, including sodium chlorid, reduced the water requirement.

TABLE XXVII.—*Effect of potassium and sodium salts on the water requirement of white mustard,*[1] *according to Maercker* (*1896, p. 21*).

Fertilizer per hectare.	60 per cent of moisture-holding capacity (18 per cent water).		20 per cent of moisture-holding capacity (8 per cent water).		Mean water requirement.
	Dry matter.	Water requirement.	Dry matter.	Water requirement.	
	Grams.		*Grams.*		
Without potash	24.4	357	12.6	282	320
1,000 kilograms kainit	25.5	309	12.1	226	268
2,000 kilograms kainit	25.3	305	9.5	143	224
2,000 kilograms carnallit	24.0	333	12.2	200	267
2,000 kilograms NaCl	16.6	321	9.9	197	259
Mean	....	325	....	210	....

[1] One pot only was used for each treatment. These data are also found in Maercker, 1896a (p. 15).

SCHROEDER'S EXPERIMENTS.

Schroeder (1896) used the same nutrient solution previously employed by Hellriegel. The results of his experiments given in Table IV (p. 14) do not show a decrease in the water requirement with an increase of concentration of the nutrient solution.

VON SEELHORST'S EXPERIMENTS.

Von Seelhorst (1899) has investigated the effect of different nutrients upon the water requirement of oats. His first experiments, the results of which are given in Table XXVIII, were made in zinc cans holding about 20 kilograms of earth. Two pots were used for each treatment, but the data for the individual pots are not given, so that it is not possible to calculate the probable error. Each fertilizer treatment was carried on with three different soil-moisture contents, so that the mean water requirement as given in the eighth column of the table represents the average of 6 pots in each case. It is interesting to note that the addition of potassium had no effect on the water requirement, phosphorus caused only a slight reduction, while a marked reduction accompanied the use of nitrogen, both alone and in combination.

In another experiment Von Seelhorst compared the water requirement of oats with the same crop following mustard. Two series of fertilized pots were prepared, one of which was planted to mustard, while the other remained fallow. The next year both series were planted to oats without additional fertilizer. These results, also given in Table XXVIII, are apparently limited to a single pot for each treatment. The introduction of the mustard crop increased the water requirement of the oat crop 67 per cent. The oats following fertilizer showed a slight reduction in the water requirement, due to the use of phosphorus, while the oats following mustard showed the greatest reduction with the nitrogen fertilizers.

TABLE XXVIII.—*Effect of different fertilizers and crop sequence on the water requirement of oats, according to Von Seelhorst (1899, pp. 372, 376–377).*

Fertilizer.[1]	Water content, in terms of moisture-holding capacity.[2]							Crop-sequence experiment.[3]			
	49 to 54 per cent.		59 to 64 per cent.		64 to 74 per cent.		Mean water requirement.	Oats.		Oats following mustard.	
	Dry matter.	Water requirement.	Dry matter.	Water requirement.	Dry matter.	Water requirement.		Dry matter.	Water requirement.	Dry matter.	Water requirement.
	Grams.		*Grams.*		*Grams.*			*Grams.*		*Grams.*	
K	40.2	290	51.2	291	47.9	302	294	62.5	291	17.5	542
N	55.2	230	67.5	243	75.5	231	235	62.4	363	36.4	343
P	38.5	268	49.9	290	54.4	283	280	72.6	255	15.3	584
KNP	49.9	225	86.7	237	95.1	232	231	90.3	258	21.2	403
Check	39.6	260	48.8	313	52.6	307	293	67.4	280	18.1	506
KN	41.3	227	65.9	225	92.9	222	225	79.3	277	31.3	350
KP	41.3	247	52.9	291	51.5	306	281	76.0	249	16.8	535
PN	46.8	236	84.0	220	108.3	216	224	91.5	254	23.3	457
Mean	......	235	......	264	......	262	......	......	278	......	465

[1] P represents 1 gram of phosphoric acid; K, 1 gram of potash; N, 1 gram of nitrogen.
[2] Harvested just before the milk stage; 20 kilograms per pot. Two pots were used in each treatment, but the data for the individual pots are not given.
[3] Eleven kilograms of earth per pot.

WILMS'S EXPERIMENTS.

Wilms (1899) conducted a somewhat more elaborate experiment with early potatoes. The results of this experiment are given in Table XXIX, the water requirement being expressed in terms of the green weight. The zinc pots in which the experiments were conducted held about 15 kilograms of soil. The surface soil was left dry throughout the experiment, water being added below the surface through Liebscher's aerating device. All tubers under 5 grams in weight were discarded and the ratio is expressed in the green weight of the remaining tubers. An analysis of the soil preparatory to the experiment showed it to be rather poor in phosphoric acid, and 1 gram of phosphoric acid (P_2O_5) was therefore added in the form of ammonium calcium phosphate to each pot. The mean water requirement for each treatment shows that the various salts reduced the water requirement very slightly. The low yield and high water requirement when potassium chlorid was used is attributed to the fact that this salt was impure, containing about 4 per cent of potassium chlorate.

TABLE XXIX.—*Effect of different fertilizers on the water requirement of potatoes,*[1] *according to Wilms (1899, pp. 288–289).*

Fertilizer.	Water content, in terms of moisture-holding capacity.						
	33 per cent.		58 per cent.		80 per cent.		Mean water requirement.
	Tubers.	Water requirement.	Tubers.	Water requirement.	Tubers.	Water requirement.	
	Grams.		*Grams.*		*Grams.*		
Check	123.5	40 ±0	178.4	48±2	196.5	57±1	48
KCL	38.7	55 ±3	47.9	88±6	41.8	138±5	94
K_2SO_4	144.7	36 ±2	190.2	47±2	246.4	52±1	45
KNO_3	215.8	37 ±1	30.4	51±1	380.5	53±0	47
K_2CO_3	137.2	35 ±2	204.1	44±1	240.9	49±0	43
NaCl	137.4	36 ±0	192.7	43±1	192.8	57±0	45
Na_2SO_4	138.5	36 ±2	179.7	44±0	181.4	62±1	47
$NaNO_3$	178.4	40 ±0	279.2	49±2	311.0	54±1	48
Na_2CO_3	134.6	39 ±0	183.3	46±0	203.7	53±1	46
$MgCl_2$	124.5	39 ±0	168.8	48±0	205.0	55±1	47
$MgSO_4$	131.2	39 ±1	185.4	47±1	206.2	57±2	48
$MgCO_3$	130.0	39 ±1	192.8	46±0	[2]193.3	61±2	49
Mean	....	39	....	50	....	62	....

[1] The water requirement, based on the green weight of the tubers only, is recalculated from the data. Two open pots containing about 17 kilograms of soil were used for each determination. The amounts of the various salts were equivalent to 3 grams of K_2O, 3 grams of Na_2O, and 3 grams of MgO. The variety used was Paulsen's July.

[2] Wilms gives 197.3, which appears to be an error.

DASZEWSKI'S EXPERIMENTS.

Daszewski (1900) determined the dry weight of some of the potatoes grown by Wilms and expressed the water requirement in terms of the dry weight of the tubers. The results are given in Table V. From these results it would appear that the use of potassium nitrate and potassium sulphate reduced the water requirement slightly.

WILFARTH AND WIMMER'S EXPERIMENTS.

Wilfarth and Wimmer (1902), using the results obtained in connection with an extensive series of fertilizer experiments, have determined the effect of varying amounts of potash and other salts upon the water requirement of various crops. The experiments were for the most part made in small, open pots, containing only a few kilograms of soil. Each experiment was duplicated, but in calculating the water requirement the results were combined as if only a single pot of double the capacity had been used. This method does not show to what extent the duplicate determinations agree. Accordingly, the water requirement for each individual pot has been recalculated by the writers and the probable error of the mean computed. One determination only was made where no probable error is given. In cases where more than two determinations were made the treatment was not exactly the same for all pots of the series. The pots received the amounts of fertilizer indicated in Table XXX and XXXI, but for a full report of the treatment the reader is referred to the original publication. These results include measurements made with potatoes, tobacco, buckwheat, mustard, chicory, and oats.

TABLE XXX.—*Effect of different amounts of potash on the water requirement of crops, according to Wilfarth and Wimmer (1902, pp. 10–15).*

Crop and period.	Soil, etc., per pot.	Fertilizer per pot. K_2O.	Fertilizer per pot. N.	Mean dry matter.	Mean water requirement.
		Grams.	*Grams.*	*Grams.*	
Potatoes:[1] 1897	Sand and turf	....	1.400	20.1	717±3
		0.094	1.400	28.7	504±27
		.188	1.400	36.7	422±11
		.940	2.388	76.9	291±4
		1.504	2.388	102.8	254±2
Apr. 29 to Sept. 8, 1897[2]	Sand, 3,760 grams; turf, 240 grams; water, 1,000 grams.	.188	1.680	35.0	453±15
		1.504	2.380	99.2	257±5
		4.700	2.800	114.0	230±15
May 2 to Sept. 13, 1898[3]	Sand, 6,670 grams; turf, 455 grams; water, 1,800 grams.	....	2.450	39.8	637±30
		.141	2.450	45.6	598±5
		.282	2.450	56.4	528±49
		.282	3.920	65.3	507±32
		.846	3.920	100.3	396±12
		1.692	3.920	128.3	339±7
May 5 to Sept. 13, 1899[3]	Sand, 6,670 grams; turf, 455 grams; water, 1,800 grams; water increased Aug. 24 to 2,010 grams.	....	1.120	33.8	1,345±55
		.282	1.120	50.5	878±72
		....	2.800	50.3	502±76
		.282	2.800	82.8	283±4
		.846	2.800	121.5	267±10
		1.800	2.800	165.1	198±5
		4.700	2.800	176.4	260±2
Apr. 25 to Sept. 15, 1900[3]	Sand, 6,670 grams; turf, 455 grams; water, 1,780 grams; water increased July 5 to 2,250, and July 18 to 2,375 grams.	3.290	2.940	199.3	232±6
		6.580	2.940	214.4	[4] 214±2
		9.400	2.940	188.8	235±14
Tobacco:[5] Apr. 6 to Aug. 20, 1897[6]	Sand, 3,760 grams; turf, 240 grams; water, 1,000 grams.	.0235	1.400	17.0	909±41
		.094	1.400	23.7	749±5
		.940	2.380	65.7	446±19
		1.410	2.380	83.9	372±2
		2.585	2.380	75.7	[7] 403±5
Apr. 21 to Sept. 17, 1898[8]	Sand, 4,445 grams; turf, 305 grams; water, 1,200 grams.	.0235	2.030	14.4	893±13
		.094	2.030	22.1	626±0
		.188	2.030	26.8	665±30
		.188	3.500	29.3	556±12
		.564	3.500	52.7	443±4
		2.115	3.500	87.0	419
		2.820	3.500	83.2	434
Apr. 24 to Oct. 5,[9] 1899[8]	Sand, 4,445 grams; turf, 305 grams; water, 1,200 grams; water increased July 13 to 1,370 grams.	.0235	1.120	20.3	696±3
		.282	1.120	52.4	457±28
		.0235	2.520	29.4	422±23
		.282	2.520	55.4	382±24
		.846	2.520	85.2	300±11
		1.880	2.520	84.5	297±5
		2.820	2.520	93.3	273±2

[1] Computed from data of Wilfarth and Wimmer (1902, pp. 10–15). Duplicate determinations were made except where probable error is not given, in which case only one determination was made. (See Wilfarth and Wimmer, 1902, pp. 8–9, form A, for a complete record of the fertilizers used with potatoes.) Tops, tubers, and roots are included. On page 13, in columns 17 and 18, are errors.

[2] Mühläuser variety used.

[3] Geheimrat Thiel variety used.

[4] Mean of eight determinations.

[5] Computed from data of Wilfarth and Wimmer (1902, pp. 44–51). Duplicate determinations were made except where no probable error is given, in which case only one determination was made. The dry matter includes roots. (See Wilfarth and Wimmer, 1902, pp. 34–35, form B, for a complete record of the fertilizers used with tobacco.)

[6] *Nicotiana rustica* variety used.

[7] Ten determinations.

[8] *Nicotiana tabacum* (Virginia) variety used.

[9] The leaves were harvested at different times and the flower buds cut off.

TABLE XXX.—*Effect of different amounts of potash on the water requirement of crops, according to Wilfarth and Wimmer (1902, pp. 10–15)*—Continued.

Crop and period.	Soil, etc., per pot.	Fertilizer per pot.		Mean dry matter.	Mean water requirement.
		K_2O.	N.		
		Grams.	*Grams.*	*Grams.*	
White mustard:[1]					
Apr. 12 to July 13, 1897	Sand, 2,350 grams; turf, 150 grams; water, 625 grams.	0.047	0.700	14.1	848±26
		.094	.700	25.6	651±6
		.188	.700	35.8	511±30
		.376	.700	37.3	498±21
Apr. 19 to July 26, 1900	Sand, 2,500 grams; turf, 160 grams; water, 665 grams.	....	.084	5.3	1,133±179
		.376	.084	4.2	1,193±8
		.047	.224	11.6	741±9
		.376	.224	12.2	718±14
		....	.700	13.4	807±8
		.047	.700	21.6	659±50
		.1175	.700	26.5	562±10
		.564	.700	29.1	500±8
Buckwheat:[2]					
Apr. 14 to July 16, 1897	Sand, 4,000 grams; water, 700 grams.	....	.700	5.1	920
		.047	.700	13.9	[3]494±12
		.141	.700	23.2	[3]417±10
Apr. 23 to July 26, 1900	do	....	.112	6.5	996±83
		.564	.112	11.2	709±3
		.047	.252	12.3	746
		.564	.252	19.2	554±25
		....	.420	8.8	950±9
		.047	.420	14.6	776±4
		.141	.420	14.6	772±0
		.564	.420	30.4	415±18
Chicory, Magdeburg:[4]					
Apr. 28 to Nov. 17, 1900	Sand, 4,465 grams; turf, 285 grams; water, 1,190 grams.	.0235	.140	14.5	698±68
		3.290	.140	12.1	790±55
		.282	.280	28.4	455±22
		3.290	.280	30.0	405±49
		.0235	1.680	16.3	679±59
		.282	1.680	52.2	331±33
		.846	1.680	77.4	254±12
		3.290	1.680	83.2	217±8
Oats:[5]					
Apr. 23 to Aug. 6, 1900	Sand, 4,000 grams; water, 700 grams.	....	.084	7.1	1,095±27
		.376	.084	8.8	948±20
		.047	.224	12.9	813±16
		.376	.224	18.8	674±6
		....	.420	7.9	1,017±26
		.047	.420	14.0	806±0
		.1175	.420	18.8	688±10
		.376	.420	22.3	615±2

[1] Computed from data of Wilfarth and Wimmer (1902, pp. 64–65). Duplicate determinations were made. The dry matter includes the roots. (See Wilfarth and Wimmer, 1902, pp. 62–63, form D, for a complete record of the fertilizers used with mustard.)

[2] Computed from data of Wilfarth and Wimmer (1902, pp. 54–55). Duplicate determinations were made except where no probable error is given, in which case only one determination was made. The dry matter includes the roots. (See Wilfarth and Wimmer, 1902, pp. 52–53, form C, for a complete record of the fertilizers used with buckwheat.)

[3] Mean of four determinations.

[4] Computed from data of Wilfarth and Wimmer (1902, pp. 74–75). Duplicate determinations were made. The dry matter includes the roots. (See Wilfarth and Wimmer, 1902, pp. 72–73, form E, for a complete record of fertilizers used with chicory.)

[5] Computed from data of Wilfarth and Wimmer (1902, pp. 82–83). Duplicate determinations were made. The dry matter includes the roots. (See Wilfarth and Wimmer, 1902, p. 81, form F, for a complete record of the fertilizers used with oats.)

The effect of different amounts of potash on potatoes is shown in Table XXX. The first series of experiments conducted in 1897 and those conducted in 1898 show without exception a reduction in the water requirement when potash is increased. The second series in 1897 is included here, but since both nitrogen and potash were increased the lower water requirement can not be attributed to potash alone. The results of 1899 and 1900 showed first a decrease and later an increase in the water requirement when the potash was increased.

In general the experiments show a consistent and decided decrease in the water requirement of potatoes when moderate amounts of potash are added, the water requirement decreasing gradually with the increase in potash until about 0.06 per cent has been added. The addition of potash in excess of this amount increases the water requirement.

The effect of different amounts of potash on the water requirement of tobacco is also shown in Table XXX. Here, as in the experiments with potatoes, the water requirement gradually decreases with the gradual increase of potash. The lowest water requirement occurs with about 0.04 per cent of potash.

The results with white mustard show a decrease in water requirement with an increase in potash. Similar results are shown for buckwheat, for Magdeburg chicory, and for oats (Table XXX).

The results of Wilfarth and Wimmer's experiments are consistent and show practically without exception a gradual decrease in the water requirement when potash is added in small amounts. If too much potash is added (more than 0.04 to 0.06 per cent) the water requirement is again slightly increased.

The effects of different amounts of nitrogen and sodium on the water requirement of potatoes, tobacco, buckwheat, mustard, chicory, and oats are shown in Table XXXI. As a rule, the addition of nitrogen lowers the water requirement of each crop considered. The exceptions show a difference so small as to be well within the limit of probable error. Except in the case of buckwheat, oats, and chicory, the addition of sodium did not consistently lower the water requirement. In some cases it seemed to increase the water requirement, as in the experiments with potatoes when potash was also added.

TABLE XXXI.—*Effect of different amounts of nitrogen and sodium on the water requirement of crops,*[1] *according to Wilfarth and Wimmer.*

Crop and period.	Soil per pot.	Fertilizer per pot.			Mean dry matter.	Mean water requirement.
		K_2O	Na_2O	N		
		Grams.	*Grams.*	*Grams.*	*Grams.*	
Potatoes: May 5 to Sept. 13, 1899.	Sand, 6,670 grams; turf, 455 grams; water, 1,800 grams; water increased Aug. 24 to 2,010 grams.	....	....	0.560	27.0	1,720
		....	....	1.120	33.8	1,345±55
		....	0.620	1.120	33.7	1,310±137
		....	....	2.800	50.3	502±76
		0.282	....	1.120	50.5	878±72
		.282	....	2.100	68.7	648±15
		.282	.620	2.100	69.5	662±2
		.282	....	2.800	82.8	283±4
		.846	....	1.820	108.3	407±11
		.846	....	2.800	121.5	267±10
		.846	1.240	2.800	105.3	453±6
Apr. 25 to Sept. 15, 1900.	Sand, 6,670 grams; turf, 455 grams; water, 1,780 grams; water increased July 5 to 2,255 grams, and July 18 to 2,375 grams.	....	....	1.750	48.6	508±25
		....	3.100	1.750	47.3	495±1
		.846	....	2.240	97.5	332±6
		.846	3.100	2.240	96.4	336±23

[1] Computed from data of Wilfarth and Wimmer (1902), as follows: Potatoes, pp. 10–15; tobacco, pp. 44–51; buckwheat, pp. 54–55; mustard, pp. 64–65; chicory, pp. 74–75; oats, pp. 82–83. Determinations were in duplicate except where no probable error is given, in which case only one determination was made.

TABLE XXXI.—*Effect of different amounts of nitrogen and sodium on the water requirement of crops, according to Wilfarth and Wimmer*—Continued.

Crop and period.	Soil per pot.	Fertilizer per pot.			Mean dry matter.	Mean water requirement.
		K_2O	Na_2O	N		
		Grams.	*Grams.*	*Grams.*	*Grams.*	
Tobacco: Apr. 6 to Aug. 20, 1897.	Sand, 3,760 grams; turf, 240 grams; water, 1,000 grams.	1.410	....	2.380	83.9	372±2
		1.410	2.790	2.380	19.8	322±5
		2.585	1.302	2.380	93.3	347±8
		2.585	1.457	2.380	87.9	358±5
Apr. 21 to Sept. 17, 1898.	Sand, 4,445 grams; turf, 305 grams; water, 1,200 grams.	.188	....	2.030	26.8	665±30
		.188	....	3.500	29.3	556±12
Apr. 24 to Oct. 5, 1899.	Sand, 4,445 grams; turf, 305 grams; water, 1,200 grams; water increased July 13 to 1,370 grams.	.0235	....	.560	18.0	709±10
		.0235	.620	.560	20.5	669±20
		.0235	....	1.120	20.3	696±3
		.0235	....	2.520	29.4	492±23
		.282	....	1.120	52.4	457±28
		.282	.620	1.120	57.2	372±8
		.282	....	2.100	57.4	363±3
		.282	....	2.520	55.4	382±24
		.846	....	1.820	82.4	288±4
		.846	.620	1.820	80.6	302±3
		.846	....	2.520	85.2	300±11
Buckwheat: Apr. 23 to July 26, 1900.	Sand, 4,000 grams; water, 700 grams.	....	....	.112	6.5	996±83
		....	....	.420	8.8	950±9
		....	.620	.420	9.8	642±29
		.047	....	.252	12.3	746
		.047	....	.420	14.6	776±4
		.047	.620	.420	12.0	575±4
		.564	....	.112	11.2	709±3
		.564	....	.252	19.2	554±25
		.564	....	.420	30.4	415±18
Mustard: Apr. 19 to July 26, 1900.	Sand, 2,500 grams; turf, 160 grams; water, 665 grams.	....	....	.084	5.3	1,133±179
		....	....	.700	13.4	807±8
		.047	....	.224	11.6	741±9
		.047	....	.700	21.6	659±50
		.376	....	.084	4.2	1,193±8
		.376	....	.224	12.2	718±14
		.564	....	.700	29.1	500±8
		.564	.744	.700	27.0	493±17
Chicory: Apr. 28 to Nov. 17, 1900.	Sand, 4,465 grams; turf, 285 grams; water, 1,190 grams.	.0235	....	.140	14.5	698±68
		.0235	....	1.680	16.3	679±59
		.0235	1.550	1.680	23.2	512±81
		.282	....	.280	28.4	455±22
		.282	....	1.680	52.2	331±33
		.282	1.550	1.680	49.7	298±0
		.846	....	1.680	77.4	254±12
		.846	1.550	1.680	77.7	232±17
		3.290	....	.140	12.1	790±55
		3.290	....	.280	30.0	405±49
		3.290	....	1.680	83.2	217±8
Oats: Apr. 23 to Aug. 6, 1900.	Sand, 4,000 grams; water, 700 grams.	....	....	.084	7.1	1,095±27
		....	....	.420	7.9	1,017±26
		....	.620	.420	9.6	949±33
		.047	....	.224	12.9	813±16
		.047	....	.420	14.0	806±0
		.047	.620	.420	22.2	586±8
		.1175	....	.420	18.8	688±10
		.1175	.620	.420	27.7	523±9
		.376	....	.084	8.8	948±20
		.376	....	.224	18.8	674±6
		.376	....	.420	22.3	615±2

VON SEELHORST AND BÜNGER'S EXPERIMENTS.

Von Seelhorst and Bünger (1907) measured the water requirement of summer wheat grown in pots containing 12 kilograms of soil. Different fertilizers were used. The results are given in Table XXXII. The experiments were conducted in open pots. It is not clear from Von Seelhorst and Bünger's description of their experiments whether the data as given in the table have been corrected for evaporation from the soil. The fertilizer scheme followed is stated to be the same as that used in one of the experiment fields at Gottingen, but details are not given. Both the increased yield and lower water requirement accompanying the use of nitrogen indicate that nitrogen is the deficient food element in the soil used in this experiment. The higher mean water requirement obtained with five plants in a pot as compared with a single plant also indicates a deficient supply of some food element.

TABLE XXXII.—*Effect of different fertilizers on the water requirement of summer wheat,*[1] *according to Von Seelhorst and Bünger (1907, p. 247).*

Fertilizer.	Low water content.				High water content.				Mean water requirement.
	One plant.		Five plants.		One plant.		Five plants.		
	Dry matter.	Water requirement.	Dry matter.	Water requirement.	Dry matter.	Water requirement.	Dry matter.	Water requirement.	
K	10.6	229	13.1	269	14.1	467	15.3	....	....
N	24.4	217	31.9	255	49.6	227	72.5	255	239
P	9.3	197	12.9	240	12.3	405	15.9	368	303
KNP	27.7	222	36.0	233	....	....	74.1	257	....
Check	10.5	217	12.5	272	13.2	309	12.5	....	....
KN	28.7	217	41.2	225	56.2	259	68.5	278	245
KP	10.8	197	13.9	261	12.5	344	16.6	362	291
PN	21.7	211	39.4	228	46.2	237	76.2	267	236
CaKNP	26.5	227	40.3	236	52.6	240	82.6	245	237
Mean	18.9	215	26.7	247	....	....	48.2	....	....
Mean water requirement for all but K, KNP, and check	....	211	....	241	....	285	....	296	....

[1] The pots contained 12 kilograms of loam soil.

OHLMER'S EXPERIMENTS.

Ohlmer (1908) measured the effect of different fertilizers on the water requirement of squarehead wheat. Open pots were used and no correction was made for evaporation from the soil. The results (Table XXXIII) show a reduction in the water requirement when nitrogen is added. The addition of phosphorus, potash, and calcium slightly increased the water requirement.

TABLE XXXIII.—*Effect of different fertilizers on the water requirement of squarehead wheat,*[1] *according to Ohlmer (1900, p. 157).*

Fertilizer.	Water content, in terms of moisture-holding capacity.			
	45 per cent.		70 per cent.	
	Dry matter.	Water requirement.	Dry matter.	Water requirement.
	Grams.		*Grams.*	
K	18.8	277	22.2	304
N	57.5	219	105.2	248
P	19.2	282	23.1	294
KNP	69.5	209	121.9	251
KN_2P	74.4	208	130.8	242
Check	19.4	274	22.8	281
KN	72.2	204	120.0	246
KP	20.5	248	21.7	328
PN	64.8	216	111.3	265
Ca	17.8	282	21.5	320
CaKNP	68.5	242	120.4	256
Mean		242		276

[1] Four pots for each determination; probably 20 kilograms of loam per pot. The fertilizer was added per pot as follows: K=1 gram K_2O as K_2CO_3; N=1.5 grams N as $NaNO_3$; N_2=1.5 grams N as $(NH_4)_2SO_4$; P=1 gram P_2O_5 as $CaH_4(PO_4)_2$; Ca=5 grams $CaCO_3$.

PREUL'S EXPERIMENTS.

Preul (1908) used a good and a poor soil in connection with an investigation of the effect of the soil-moisture content on the water requirement. The poor soil was simply a mixture of the good soil with heath sand. The results of his experiments (Table VIII, p. 19) show a consistently lower water requirement for the wheat grown in the good soil, in which the average water requirement was approximately 80 per cent of that of the wheat grown in the poor soil.

SUMMARY OF EXPERIMENTS AT GOTTINGEN, GERMANY.

Several of the experiments heretofore cited were carried on at Gottingen under comparable conditions. The results of the experiments are summarized and combined in Table XXXIV and show that, with the exception of the potash series, the unfertilized check gave the highest value. Nitrogen reduced the water requirement decidedly, whether alone or in combination with phosphorus or potash. The lowest results have been obtained by a combination of potash, nitrogen, and phosphorus. In these results the evaporation from the soil has apparently been included with the transpiration, and the water requirement calculated on the basis of the air-dry weight of the crop.

TABLE XXXIV.—*Effect of various fertilizers on the water requirement of oats and wheat at Gottingen, Germany, according to different investigators.*

Crop.	Soil.	Soil moisture.	Notes.	Water requirement with— K	N	P	KNP	Check	KN	KP	PN
	Kilograms.										
Oats[1]	Clay, 9.16	2.21 kilograms	3 pots	344±9	311±1	270±7	173±3	349±9	319±7	264±2	177±2
	Sand, 11.7	1.74 kilograms	do	313±8	194±2	307±5	178±1	332±7	192±2	299±6	192±1
Do[2]	Earth, 20	49 to 54[3]		290	230	268	225	260	227	247	236
		59 to 64[3]		291	243	290	237	313	225	291	220
		64 to 74[3]		302	231	283	232	307	222	306	216
	Earth, 11			291	363	255	258	280	277	249	254
				542	343	584	403	506	350	535	457
Wheat[4]	Loam, 12	Low water content.	1 plant per pot.	229	217	197	222	217	217	197	211
			5 plants per pot.	269	255	240	233	272	225	261	228
		High water content.	1 plant per pot.	467	227	405	......	309	259	344	237
			5 plants per pot.	......	255	368	257	......	278	362	267
Do[5]	Loam, 20 (?)	45[3]	4 pots	277	219	282	209	274	204	248	216
		70[3]	do	304	248	294	251	281	246	328	265
Mean water requirement[6]				314	259	297	238	308	246	294	243

[1] Liebscher, 1895, p. 211.
[2] Von Seelhorst, 1899, p. 372.
[3] Percentage of moisture-holding capacity.
[4] Von Seelhorst and Bünger, 1907, p. 247.
[5] Ohlmer, 1908, p. 157.
[6] Mean for all determinations except Von Seelhorst and Bünger's high water content series.

WIMMER'S EXPERIMENTS.

Wimmer (1908) published the results of extended experiments conducted by a large number of collaborators. The data on the effect of potash and nitrogen on the water requirement are given in Tables XXXV and XXXVI.

Glass pots 33 centimeters high with an upper diameter of 21 centimeters and a lower diameter of 19 centimeters were used. These pots were left open and the combined transpiration and evaporation determined. Apparently no attempt was made to correct for evaporation from the soil surface. The plants were grown to maturity. Many details of the experiment are given in the tables and need not be repeated here.

The effect of potash (Table XXXV) is much less evident than in the work of Wilfarth and Wimmer (1902), already discussed (p. 39). Even in the soils showing the lowest content of potash the addition of potash did not lower the water requirement. None of the soils were poor in potash.

The addition of nitrogen (Table XXXVI) lowered the water requirement with most plants. In Juetrichau sand the high probable error, as well as the small amount of dry matter produced, lead one to disregard these data in discussing the results as a whole.

TABLE XXXV.—*Effect of potash on the water requirement of plants,*[1] *according to Wimmer.*

Crop and period.	Soil used.				K_2O added per pot.	Soil moisture.	Mean dry matter.	Water requirement.
	Plat.	Previous fertilization.	Potash and soda by analysis.	Per pot.				
			Per cent.	*Grms.*	*Grms.*	*Per ct.*	*Grms.*	
Ray-grass:[2] June 1 to Oct. 18, 1904.	B 1	No potash, 1891 to 1904. Stable manure, 1891 to 1895. Green manure, 1901.	0.247 K_2O	6,766	......	15	66.9	302±1
			.045 Na_2O		0.155	15	63.6	301±39
					.776	15	69.9	266±3
					......	18	76.7	307±21
					.155	18	78.5	343±34
					.776	18	80.3	316±4
	B 3	None, 1891 to 1904	.251 K_2O	6,903	......	15	71.5	302±8
			.050 Na_2O		.155	15	66.3	322±22
					.776	15	68.7	324±3
					......	18	84.5	283±5
					.155	18	85.9	275±11
					.776	18	72.9	312±27
	B 5	No potash, 1891 to 1904. Stable manure, 1891 to 1895. Green manure, 1901.	.295 K_2O	6,791	......	15	57.0	365±14
			.090 Na_2O		.155	15	60.8	386±55
					.776	15	67.8	290±17
					......	18	69.4	367±1
					.155	18	66.6	376±5
					.776	18	78.4	283±11
Apr. 17 to Sept. 26, 1905.	B 3	None, 1901 to 1905	.244 K_2O	7,919	......	15	92.4	313±4
			.044 Na_2O		.155	15	93.8	306±21
					.776	15	92.5	310±7
					......	18	95.6	333±17
					.155	18	98.7	336±1
					.776	18	100.4	350±16
	F 3	....do	.239 K_2O	7,768	......	15	90.0	305±13
			.039 Na_2O		.155	15	88.4	319±32
					.776	15	90.0	312±17
					......	18	113.4	290±4
					.155	18	104.3	303±7
					.776	18	102.1	311±7
	H 3	No potash, 1902 to 1905	.221 K_2O	7,344	......	15	80.2	341±32
			.061 Na_2O		.155	15	84.7	311±11
					.776	15	96.2	262±9
					......	18	90.6	345±12
					.155	18	93.5	369±7
					.776	18	95.9	331±3
Chicory:[3] May 3 to Nov. 12, 1906.	B 5	None, 1891 to 1904. Stable manure, 1891 to 1895. Green manure, 1901.	.259 K_2O	7,000	......	18	61.2	229±17
			.068 Na_2O		.155	18	50.8	279±12
					.776	18	64.9	235±3
					1.551	18	65.4	202±7
	G 3	No potash, 1902 to 1906	....	......	......	18	64.7	218±8
					.155	18	65.4	230±10
					.776	18	60.1	228±6
					1.551	18	65.0	228±35
	F 8	Potash, 1901 to 1906	....	......	......	18	55.4	245±11
					.155	18	55.3	316±64
					.776	18	52.8	282±32
					1.551	18	66.9	211±34

[1] Computed from Wimmer's data (1908, pp. 15-37). Mean of two determinations.
[2] Each pot received 0.840 gram N and 0.284 gram P_2O_5 in 1904, and 1.120 grams N and 0.284 gram P_2O_5 in 1905.
[3] Each pot received 1.400 grams N and 0.710 gram P_2O_5.

TABLE XXXVI.—*Effect of nitrogen on the water requirement of plants,*[1] *according to Wimmer.*

Crop and period.	Soil used.			Added N.	Soil moisture.	Mean dry matter.	Water requirement.
	Plat.	Previous fertilizer.	Soil per pot.				
			Grams.	*Grams.*	*Per ct.*	*Grms.*	
Sugar beet: May 3 to Oct. 15, 1899.	Biendorf	Well manured	8,058	0.224	16	38.2	515±55
				.336	16	42.7	433±25
				1.820	16	79.1	313±3
Ray-grass: May 1 to Nov. 1, 1903.[2]	Waldau 33, 34, 35	No potash since 1902; 0.284 gram P_2O_5 per pot.	7,556	.280	12	34.1	230±20
				.700	12	43.8	254±10
				.280	15	35.4	372±32
				.700	15	52.2	232±10
				.280	18	44.0	329±38
				.700	18	53.7	322±10
	F 1, 3, 5, 7	No potash since 1902.	7,556	.280	12	33.9	323±12
				.700	12	39.6	285±8
				.280	15	44.9	302±12
				.700	15	51.7	259±4
				.280	18	48.3	319±19
				.700	18	57.7	293±7
Apr. 17 to Sept. 26, 1905.	F 3[3]	No potash since 1901.	7,768	.280	12	41.5	406±5
				1.120	12	72.2	298±6
	Waldau 87, 88, 89[4]	No potash since 1903.	8,042	.280	12	39.9	352±19
				1.120	12	45.9	387±42
	F 6[5]	Kainit since 1902	7,808	.280	12	43.0	373±35
				1.120	12	75.8	276±6
	Juetrichau sand	0.284 gram P_2O_5 per pot.	8,000	.280	9	41.6	423±6
				1.120	9	80.7	323±33
	Buhlendorf sand	do	8,000	.280	7	26.0	521±14
				1.120	7	60.7	336±31
Chicory: 1906	Buhlendorf sand[6]	do	8,000	.280	12	48.9	287±2
				1.400	12	66.6	221±13
		0.710 gram P_2O_5 per pot.	8,000	.280	12	55.8	256±13
				1.400	12	63.5	227±23
	Juetrichau sand[7]	0.284 gram P_2O_5 per pot.	8,000	.280	10	22.7	391±11
				1.400	10	10.8	676±17
		0.710 gram P_2O_5 per pot.	8,000	.280	10	20.3	380±2
				1.400	10	10.7	605±76
Carrot:[2] May 5 to Oct. 30, 1903.	Waldau 33, 34, 35	No potash since 1902; 0.284 gram P_2O_5 per pot.	7,556	.280	12	21.4	420±25
				.700	12	22.2	362±25
				.280	15	31.0	419±36
				.700	15	31.0	412±14
				.280	18	32.1	466±31
				.700	18	43.8	386±16
	F 1, 3, 5, 7	do	7,556	.280	12	19.6	458±17
				.700	12	17.3	470±46
				.280	15	31.9	352±10
				.700	15	28.5	393±14
				.280	18	32.1	442±22
				.700	18	44.2	309±15

[1] Computed from Wimmer's data (1908, pp. 89-114). Mean of two determinations.
[2] Mean of three determinations.
[3] This soil contained in 1905 0.239 per cent K_2O and 0.039 per cent Na_2O.
[4] This soil contained in 1905 0.254 per cent K_2O and 0.038 per cent Na_2O.
[5] This soil contained in 1905 0.259 per cent K_2O and 0.079 per cent Na_2O.
[6] This soil contained 0.026 per cent K_2O and 0.032 per cent Na_2O.
[7] This soil contained 0.054 per cent K_2O and 0.051 per cent Na_2O.

WIDTSOE'S EXPERIMENTS.

Widtsoe (1909) conducted during 1904 and 1905 an experiment to test the effect of manure and mineral fertilizer on the water requirement of corn. The amounts of mineral fertilizers used (Table XXXVII) were calculated upon the weight of the upper 6 inches of soil and were added at the beginning of each year. All the fertilizers used were incorporated with the surface soil to a depth of 6 inches. Two open pots of College loam were used with each fertilizer treatment, one pot being planted to corn and the other kept barren to determine the evaporation from the soil. The pots were 24 inches in diameter and 30 inches high. The results show a reduction in the water requirement following the use of fertilizers, but the results for the two seasons are widely at variance.

Widtsoe later used three different types of soil in investigating the effect of fertilizers on the water requirement of corn. The results are also given in Table XXXVII. One soil consisted of an unproductive sand from a river wash, while the other two soils were productive. The experiments were carried on for but a single year, and only single pots were used for each fertilizer. The surface of the soil was not protected, and the evaporation was assumed to be the same as from bare check pots.

The soils in the various pots used had been treated differently in experiments previous to 1905 as regards culture, crops grown, methods of irrigation, and amount of water applied, but had been exposed without crop to atmospheric agencies from 1905 to 1908. "The amount of fertilizer applied in each case was nearly five times larger than in 1904 and 1905. As a result the depressing effect of the fertilizer is observed in a number of cases."

TABLE XXXVII.—*Effect of fertilizers on the water requirement of corn, according to Widtsoe (1909, pp. 49, 52).*

Year and soil.	Water requirement, using—				
	No fertilizer.	4 pounds manure.	0.1 per cent $NaNO_3$.	0.01 per cent $NaNO_3$.	0.1 per cent KCl.
1904, College loam	908	613	581	257	848
1905, College loam	....	315	151	237	431
Average	....	464	368	247	640

Year and soil.	Water requirement, using—							
	No fertilizer.	K	P	N	KN	KP	PN	KNP
1909:								
Sand	1,012	686	735	555	......	671	178	459
College loam	357	308	391	471	450	333	339	303
Sanpete clay	306	292	375	385	280	383	......	......

KIESSELBACH'S EXPERIMENTS.

Kiesselbach (1910) measured the water requirement of corn plants grown in river sand which was kept saturated with Schimpers's normal nutrient solution. Four concentrations, 0.6, 0.4, 0.2, and 0.1 per cent, were employed. Five pots, each holding about 15 kilograms and containing a single plant, were used for each concentration. The method followed is the same as that described on page 20. With the exception of the highest concentration, which reduced the growth of the plants, the results (Table XXXVIII) show a slight increase in the water requirement as the concentration of the solution is diminished.

TABLE XXXVIII.—*Influence of concentration of soil nutrient solution on the water requirement of corn, according to Kiesselbach (1910).*

Strength of solution.	Dry weight including roots.	Water requirement.
Per cent.	*Grams.*	
0.6	47.8	245±5
.4	74.9	226±5
.2	65.3	238±4
.1	73.4	260±4

LEATHER'S EXPERIMENTS.

Leather (1910, 1911) has investigated the use of nitrogen, potassium, and phosphorus as fertilizers in their relation to the water requirement of a number of crops in India. These experiments were conducted with four soils, which may be characterized as follows: The Pusa soil, where the Pusa Institute is situated, consists of Gangetic alluvium and contains a small proportion of clay. It is highly calcareous (30 to 40 per cent $CaCO_3$), low in organic matter, and very poor in available phosphate. Potash salts have no effect on the crop. The Akola soil is a typical "black cotton" soil, with a high clay content and from 1 to 3 per cent of calcium carbonate. The Shillong soil is highly ferruginous and contains much organic matter. The Palur soil is sandy in character.

The water requirements of crops grown in these soils, showing the effect of various fertilizers, are given in Table XL. Each determination refers to the mean value of the water requirement obtained from two pots, except in the case of the earlier measurements for wheat and corn, which represent the mean of the values given in Table XXXIX. The soil water content, except in the earlier determinations, was maintained as nearly as possible at 20 per cent of the saturation content. The writers have added the probable error of the mean in each case as a guide in making comparisons.[1]

[1] The probable error, when only two determinations are available, has little value other than that of serving to show how closely the duplicate determinations agree. Usually in comparing mean values to determine whether a real difference exists, a difference equal to three times the square root of the sum of the squares of the two probable errors is considered the minimum significant difference. The probable error of the probable error of the mean of two determinations is one-half that of the probable error of the mean.

These determinations include the variation in water requirement arising from seasonal differences, kind and amount of soil used, and the kind of fertilizer employed. The magnitude of the probable errors shows that there were also in many cases other disturbing factors of a serious character which were not under control. Although the water requirement for a given crop varies widely according to season, soil, and fertilizer, the results show conclusively a marked reduction in the water requirement accompanying the use of phosphate as a fertilizer for these soils. Representing the water requirement of the unmanured soil in each case by 100, the mean value when nitrogen alone was used was 97; nitrogen and phosphorus, 75; nitrogen, potassium, and phosphorus, 73. These results indicate, therefore, the necessity of an adequate supply of plant food in order to secure the most economical use of a given water supply.

TABLE XXXIX.—*Influence of fertilizers on the water requirement of wheat and corn at Pusa, India,*[1] *according to Leather (1910).*

Crop and year.	Jar capacity.	Water in soil.	Water requirement, using—					
			No fertilizer.	N	N+P	N+P+K	Mean.	Mean, omitting N+P+K.
Wheat (*Triticum sativum*):	*Kilograms.*	*Per cent.*						
1906-7	15	10	900	1,050	543	527	755	....
		15	653	944	540	515	663	....
		20	829	1,000	574	583	747	....
	22	10	941	806	593	614	739	....
		15	1,060	837	504	604	751	....
		20	955	865	515	....	[2] 726	....
Means for 1906-7	....	....	890±37	917±30	545±10	569±14	....	....
1907-8	15	10	634	[3] 523	[4] 571	....	576	....
		20	1,133	[3] 725	[4] 725	....	861	....
	29	10	696	[3] 500	[4] 446	....	547	....
		20	821	[3] 575	[4] 505	....	634	....
Means for 1907-8	....	....	821±75	581±35	562±43			
Corn (*Zea mays*) grown in Pusa soil:[5]								
1907	15	10	459	404	287	344	......	383
		15	368	377	323	322	......	356
		20	604	529	382	336	......	505
	21	10	500	645	309	....	......	485
		15	589	....	281	....	......	[6] 452
		20	381	527	295	....	......	401
	31	10	450	412	262	....	......	375
		15	421	505	286	....	......	404
		20	429	480	295	....	......	401
Means for 1907	....	....	467±19	485±21	302±7	334±7		

[1] A single open pot was used for each treatment.
[2] The mean value 569 was used for the absent term of the N+P+K series in calculating this mean.
[3] In these determinations rape cake was used, equivalent to 5 milligrams N per 100 grams of soil.
[4] In these determinations superphosphate plus phosphoric acid in rape cake was used, equivalent to 10 milligrams soluble P_2O_5 per 100 grams soil.
[5] N=$Ca(NO_3)_2$=5 milligrams N per 100 grams soil; P=superphosphate=10 milligrams soluble P_2O_5 per 100 grams soil.
[6] The mean of the N ratios was used in place of the absent term in calculating this average value.

TABLE XL.—*Water requirement of crops at Pusa, India, as modified by soils and fertilizers, according to Leather (1910, 1911).*

Crop and year.	Soil.	Weight of soil.	Water requirement, using—			
			No fertilizer.	N	N+P	N+P+K
Wheat (*Triticum sativum*):		*Kilos.*				
1906–7	Pusa	15–22	890±37	917±30	545±10	569±14
1907–8	...do	15–29	821±75	581±35	562±43	....
1908–9	...do	14	865±14	782±72	508±24	....
1909–10	...do	48	582±11	....	495±2	....
1909–10	Akola	41–45	842±6	....	....	440±16
1909–10	Shillong	43–45	526±31	....	....	580±10
Corn (*Zea mays*):						
1907	Pusa	15–31	467±19	485±25	302±7	334±7
1908	...do	14	421±21	438±35	433±9	....
1908	Akola	42.5	678±110	529±32	315±5	367±15
1908	...do	12	447±8	468±71	355±9	340±8
1908	Shillong	32	466±46	521±16	287±8	306±6
1908	...do	12	614±29	539±62	362±7	....
1908	Palur	32	412±15	261±13	363±4	375±1
Sarson (*Brassica campestris*):						
1908–9	Pusa	14	737±15	818±59	625±16	....
1909–10	...do	48	481±8	....	384±6	....
1909–10	Akola	43	603±11	....	....	479±13
Linseed (*Linum usitatissimum*):						
1908–9	Pusa	14	1,093±120	1,198±83	1,000±36	....
1909–10	...do	48	1,094±150	....	633±39	....
1909–10	Akola	42–45	1,125±89	....	....	787±8
Barley (*Hordeum vulgare*):						
1908–9	Pusa	14	678±1	429±5	482±30	....
1909–10	...do	48	448±31	....	455±3	....
Oats (*Avena sativa*):						
1908–9	...do	14	873±210	827±37	551±51	....
1909–10	...do	48	493±7	....	388±11	....
Peas (*Pisum sativum*):						
1908–9	...do	14	836±120	785±36	531±65	....
1909–10	...do	48	811±3	....	595±21	....
Gram (*Cicer arietinum*):						
1908–9	...do	14	1,427±79	1,166±120	976±130	....
1909–10	...do	48	1,216±160	....	660±11	....
Juar (*Andropogon sorghum*): 1908	...do	14	361±76	420±58	437±41	....
Rice (*Oriza sativa*): 1908	...do	14	976±130	850±97	811±11	....
Murwa (*Eleusine coracana*): 1908	...do	14	254±42	283±23	263±2	....
Kodo (*Paspalum scrobiculatum*): 1908	...do	14	326±0	266±6	312±4	....
Rahar (*Cajan indicum*): 1908	...do	14	1,109±82	1,245±100	640±31	630±21
Guar (*Cyamopsis psoralioides*): 1908	...do	14	1,082±15	1,050±140	598±5	....
Sugar cane (*Saccharum officinarum*): 1910	...do	47	388±70	312±13	212±1	....

VON SEELHORST'S LATER EXPERIMENTS.

Von Seelhorst (1910a) conducted experiments on the water requirement of rye in pots which had been previously manured for several years. This experiment was conducted in the large pots shown in figure 4 and described on page 68. The results are shown in Table XLV (p. 56). Referring to the water requirement of rye following rye, it will be seen that the lowest value was obtained by a light application of manure in the spring. The value obtained from a heavy application of manure in the fall was about 5 per cent higher, while the water requirement of the check pot, which had received no fertilizer, was about 19 per cent higher. The mean water requirement of the whole series receiving a heavy application of manure in the fall was also about 9 per cent higher than that of the series receiving a light application of manure in the spring.

MONTGOMERY AND KIESSELBACH'S EXPERIMENTS.

Montgomery and Kiesselbach (1912) measured the water requirements of corn grown in three types of soil, which they characterized as infertile, intermediate, and fertile. Each soil was used in its original condition and also with the addition of manure. Twenty-three cans were used in all, four being used for each treatment, with a single exception. The cans were 16 inches in diameter and 36 inches high. A single corn plant was grown in each can. The potometers were covered, as in their earlier experiments. Modeling clay was used to make a tight joint between the stalk of the corn and the oilcloth cover. A summary of the experiments is given in Table XLI.

The marked reduction in water requirement with the increase in soil fertility is definitely indicated. Another striking fact is the uniformity in the water requirement of corn obtained in all three soil types when manure was used. The ratios obtained in the three experiments in which manure was used differ by less than the probable error, either when based upon total dry matter or upon the dry weight of the ears.[1]

TABLE XLI.—*Water requirement of corn as influenced by soil fertility, according to Montgomery and Kiesselbach (1912, pp. 10–11).*

Soil.	Average dry weight per plant.		Water requirement based on—			
			Total dry matter.		Dry ears.	
	No manure.	Manure.	No manure.	Manure.	No manure.	Manure.
	Grams.	*Grams.*				
Infertile	113	376	550±16	350±8	2,136±436	692±45
Intermediate	184	414	479±11	341±4	1,160± 59	679±36
Fertile	270	473	392± 6	347±6	799± 39	682±18

PFEIFFER, BLANCK, AND FLÜGEL'S EXPERIMENTS.

Pfeiffer, Blanck, and Flügel (1912), experimenting with the effects of different amounts of nitrogen on the water requirement of plants, found that for the particular soil used the addition of nitrogen did not measurably lower the water requirement. The experiment is discussed in connection with the effect of soil-moisture content on the water requirement and the results are shown in Table XIII (p. 24).

CONCLUSIONS.

Almost without exception the experiments herein cited show a reduction in the water requirement accompanying the use of fertilizers. In highly productive soils this reduction amounts to only a

[1] The writers are indebted to Prof. Kiesselbach for an advance proof of this paper, and also for detailed information concerning earlier experiments, which has made the calculation of probable errors possible.

small percentage. In poor soils the water requirement may be reduced one-half or even two-thirds by the addition of fertilizers. Often the high water requirement is due to the deficiency of a single plant-food element. As the supply of such an element approaches exhaustion the rate of growth as measured by the assimilation of carbon dioxid is greatly reduced, but no corresponding change occurs in the transpiration. The result is inevitably a high water requirement.

As a whole, these experiments show clearly that transpiration is not a measure of growth, even under the same atmospheric conditions, and that the water requirement is profoundly affected by the plant food available in the soil.

Water Cultures.

woodward's experiments.

The earliest experiments conducted for the purpose of determining the water requirement of plants, so far as the writers are aware, were made by Woodward in 1699 with water cultures. Plants of known green weight were transplanted to vials. A cork stopper prevented loss of water except through the plant, and an accurate record was kept of the water consumed. The difference between the initial and final green weight was taken to represent the amount of growth.

Woodward's results, expressed in terms of green weight, are given in Table XLII. Although his experiments were made on water cultures 200 years ago, the results obtained are of fundamental importance. He found the water requirement of plants grown in spring water and in rain water to be higher than when grown in waters containing more soluble matter. Moreover, when impure water was distilled the water requirement of plants was found to be higher when grown in the distillate than when grown in the residue. This leads at once to the conclusion that the water requirement of plants is, within limits, dependent on the amount of plant food available.

Table XLII.—*Effect of pure and impure water on the water requirement of plants, according to Woodward (1699, pp. 200–206).*

Plant, water used, etc.	Year.	Increase in green weight.	Water transpired.	Water requirement, green weight.
		Grams.	*Kilograms.*	
Spearmint:				
Spring water	1691	0.97	0.165	170
Rain water	1691	1.134	.195	172
Thames water	1691	1.68	.161	96
Hyde Park conduit water	1692	8.29	.92	111
	1692	9.00	.851	95
Hyde Park conduit water and garden earth	1692	10.88	.696	64
Hyde Park conduit water and garden mold	1692	18.4	.969	53
Hyde Park conduit water, distilled	1692	2.66	.572	215
Residue	1692	6.09	.281	46
Solanum:				
Spring water	1691	3.695	.241	65
Lathyrus:				
Spring water	1691	.227	.162	715

SORAUER'S EXPERIMENTS.

Sorauer (1883) used water cultures in most of his water-requirement experiments. His results, which deal with the effect of different amounts of nutrient solution on the water requirement of rye, barley, wheat, and oats, are given in Table XLIII. The experiments were of 53 days' duration, and the water requirement was found to decrease as the concentration of the nutrient solution increased.

TABLE XLIII.—*Effect of the concentration of the nutrient solution on the water requirement of plants,*[1] *according to Sorauer (1883, pp. 90–91).*

Crop.	Concentration of the nutrient solution.									
	0.05 per cent.		0.25 per cent.		0.5 per cent.		1 per cent.		0.25 per cent nutrient+0.5 per cent calcium nitrate.	
	Number of determinations.	Water requirement.	Number of determinations.	Water requirement.	Number of determinations.	Water requirement.	Number of determinations.	Water requirement.	Number of determinations.	Water requirement.
Rye	4	495±22	4	331±22	3	267±21	4	197±20	5	235±25
Barley	4	547±39	3	432±14	4	321±11	4	289±8	....	....
Wheat	4	768±40	4	647±19	4	469±18	....	....	....	....
Oats	4	630±24	4	569±20	....	....	3	323±32	....	....
Mean	....	610	....	495	....	....	....	....	....	....
Mean for rye and barley	....	521	....	382	....	294	....	243	....	....

[1] The total dry matter produced was seldom as great as 0.5 gram per pot.

HEINRICH'S EXPERIMENTS.

Heinrich (1894) has determined the water requirements of oat plants when grown in nutrient solutions of different concentration. The nutrient solution had the following composition: 4 H_2KPO_4 + $CaCl_2$ + 5 $Ca(NO_3)_2$ + 2 $MgSO_4$ + 2 Fe. Five concentrations were used, 3 grams, 1 gram, 0.5 gram, 0.25 gram, and 0.1 gram per liter. The iron was supplied in the form of freshly precipitated suspended iron phosphate. Ten jars, each containing 3 liters of solution, were used for each of the five concentrations. Three plants were grown in each jar. An equal number of jars without plants was used to determine the evaporation taking place directly from the culture solution. The plants were grown for four months, or until ripe. The transpiration was determined by weekly weighings. The plants in the 0.3 per cent solution consumed about three-fourths of the initial water supply. The evaporation in this case was only about 2.5 per cent of the transpiration. The results are given in Table XLIV. With the exception of the weakest solution, the water requirement decreased as the concentration of the solution increased.

TABLE XLIV.—*Water requirement of oat plants grown in culture solutions of different concentrations, according to Heinrich (1894, p. 173).*

Concentration of culture solution.	Dry matter.	Grain.	Water transpired.	Water requirement based on—	
				Grain.	Dry matter.
	Grams.	*Grams.*	*Kilos.*		
3 grams per liter	134.3	5.42	69.2	12,800	515
1 gram per liter	74.4	2.71	40.9	15,100	550
0.5 gram per liter	41.5	.59	28.4	48,200	684
0.25 gram per liter	27.8	1.07	19.1	17,900	688
0.1 gram per liter	17.6	1.41	11.3	8,020	642

CONCLUSION.

The water requirement of plants grown in water cultures is increased if the solution is lacking in a sufficient amount of plant food.

EFFECT OF A PREVIOUS CROP ON THE WATER REQUIREMENT.

VON SEELHORST'S EXPERIMENTS.

The effect of a previous crop on the water requirement of rye is shown in a series of determinations made by Von Seelhorst (1910a). These determinations were made in the large pots shown in figure 4 (p. 68). The results of the determinations are given in Table XLV. The experiments were conducted with two series of pots, one series having received a light application of manure each spring from 1904 to 1907 and the other a heavy application of manure each fall during the same period. A crop was grown in each pot from 1905 to 1908. In the fall of 1908 all pots were planted to rye and the crop harvested in 1909.

TABLE XLV.—*Effect of a previous crop on the water requirement of rye, according to Von Seelhorst (1910a, p. 91).*[1]

Application of manure, 1904 to 1907.	Crops, 1905 to 1908.	Rye, 1908–9.		
		Number of pots.	Yield.	Water requirement.
			Grams.	
Light, in spring	Potatoes	3	426	743±23
	Rye	2	393	759±4
	Barley	1	526	589
Mean				697
Heavy, in fall	Potatoes	3	421	748±18
	Rye	2	374	801±33
	Barley	1	482	666
Mean				738
No manure added (check)	Rye	1	339	900

[1] The water requirement includes evaporation. The soil was sandy. The results were compiled from Von Seelhorst's data. In the late summer and fall of 1906 each pot, with the exception of the unmanured set, produced a crop of lupine.

The results of this experiment show that when rye follows potatoes the yield and water requirement are not measurably different from that obtained when rye follows rye. When rye follows barley, however, the yield is increased and the water requirement is reduced, compared with rye following rye. The lower water requirement would naturally result from the increased supply of plant food in the barley pots, as indicated by the higher yields.

EFFECT OF SOIL TEMPERATURE ON THE WATER REQUIREMENT.

KING'S EXPERIMENTS.

King (1895) compared the water requirement of potatoes when grown in pots above ground with similar determinations made in pots buried in the soil. The pots above ground were protected from the direct rays of the sun by a board screen placed on the south side. Galvanized-iron pots 18 inches in diameter and 24 inches high were used. The plants were covered at night and during rains with a tent of heavy duck. It was found that the water requirement was apparently less when the pots were placed in the ground, but the difference observed can not be considered conclusive, since it is less than three times the probable error (Table XLVI). No data are given regarding the temperature fluctuations in the two series of pots. It seems probable that the more exposed position of the plants grown in the pots above ground would also affect the results.

TABLE XLVI.—*Effect of soil temperature on the water requirement of potatoes,*[1] *according to King (1895, p. 243).*

Treatment of pots.	Dry matter.	Water.	Water requirement based on dry matter.
	Grams.	*Kilograms.*	
Above ground	227.7	107.4	472
	163.0	97.4	[2]597
	246.1	112.9	458
			509±35
Sunk in potato field	232.5	100.1	430
	238.2	99.0	415
			423±6

[1] Alexander's Prolific. [2] King gives 497, which is evidently an error.

LEATHER'S EXPERIMENTS.

The pot-culture method of measuring the water requirement of plants subjects the soil to greater temperature fluctuations than occur under field conditions, owing to the exposure of the pots to the direct rays of the sun. To determine the effect of this exposure, Leather (1910) thermally insulated jars in which maize and wheat were growing by surrounding them with from 5 to 7 inches of sawdust throughout the period of growth. These were compared with jars fully exposed to the sun but otherwise similar in every respect. The results, which are given in Table XLVII, show that the effect of the exposure of the pots to the sun is within the limits of other experimental errors.

TABLE XLVII.—*Water requirement of plants as influenced by the exposure of culture pots to the sun, according to Leather (1910, p. 142).*

Crop.	Fertilizer.	Water requirement.	
		Pots protected from sun.	Pots exposed to sun.
Corn	Nitrate and phosphate	428	382
	No fertilizer	630	606
Wheat	Rape cake and phosphate	832	725
	No fertilizer	1,014	1,133
Mean		726	712

CONCLUSIONS.

From the data at hand no conclusion can be drawn concerning the effect of soil temperature on the water requirement. Leather's data indicate that the greater fluctuation in soil temperature accompanying the exposure of the pots to the sun does not materially affect the water requirement.

EFFECT OF CLIMATIC FACTORS ON THE WATER REQUIREMENT.

EFFECT OF DIFFERENT ATMOSPHERIC CONDITIONS ON THE WATER REQUIREMENT.

That atmospheric factors profoundly influence the water requirement is evident from the data of numerous investigators. The effects of temperature, light, humidity, etc., will be discussed later. Here we wish to present the results which can be considered only as due to a difference in atmospheric conditions as a whole.

FITTBOGEN'S EXPERIMENTS.

Fittbogen (1874) published the results of measurements of the water requirement made in a plant house and in the open at the south side of the plant house. The culture method was the same as that used in 1873 (p. 12). The soil-moisture content was 50 to 60 per cent of the moisture-holding capacity. The difference in the water requirement (Table XLVIII) of the plants grown inside and outside was 15 ± 6, which is without significance when the probable error is considered. The plants grown in the plant house were probably warmer, but were at the same time slightly shaded. On the other hand, the outside set received somewhat more solar radiation and was exposed to freer wind movement. It is impossible from data of this kind to draw conclusions as to the specific effect of temperature, light, or humidity upon the water requirement, since none of these factors were comparable for the two series.

TABLE XLVIII.—*Effect of different atmospheric conditions on the water requirement of oats, according to Fittbogen.*

Position.	Number of determinations.	Dry matter.	Grain.	Water requirement[1] based on—	
				Grain.	Dry matter.
		Grams.	*Grams.*		
Inside of plant house	4	13.7	7.01	777±10	398±6
Outside of plant house, on south side	4	12.7	6.46	810±3	413±1

[1] Calculated from Fittbogen's data (1874, p. 145).

HELLRIEGEL'S EXPERIMENTS.

Hellriegel (1883) determined the effect of seasonal differences upon the water requirement by a series of measurements. The results are given in Table XLIX. Red clover was used in this experiment, croppings being made at four different times during a period of two years and the water requirement of each crop determined. It will be seen from this table that the water requirement was much higher for the crops harvested in September and January than for the crops harvested in June and July, owing to variation in the climatic conditions with different periods of the year. Hellriegel also conducted a series of experiments which show the effect of different years on the water requirement. (Table LXVII, p. 75.) The water requirement of barley in 1868 was almost 40 per cent higher than in 1870. Similar results were obtained during different seasons with other crops.

TABLE XLIX.—*Effect of the period of growth on the water requirement of red clover, according to Hellriegel (1883, p. 634).*

Pot used.		Date of cropping.							
		July 17, 1872.		Sept. 14, 1872.		Jan. 8, 1873.		June 5, 1873.	
Height.	No.	Dry matter.	Water requirement.	Dry matter.	Water requirement.	Dry matter.	Water requirement.	Dry matter.	Water requirement.
		Grams.		*Grams.*		*Grams.*		*Grams.*	
15 centimeters	314 315	12.8 15.0	362 311	12.8 8.4	435 671	0.5 1.2	1,588 1,645	26.6 18.2	292 467
Mean			337±22		553±100		1,617±25		380±76
34 centimeters	346 347	26.2 14.3	349 401	Not cropped. 14.3	652	23.6 2.5	763 854	69.8 50.8	264 302
Mean			375±22				809±39		283±16
65 centimeters	348 349	30.0 21.0	293 417	25.8 21.2	439 546	10.2 5.2	451 649	111.5 98.4	256 285
Mean			355±53		493±46		545±79		271±13
96 centimeters	350 351	26.2 25.0	357 410	Not cropped. 17.4	577	52.5 11.0	680 563	168.2 157.0	243 263
Mean			384±23				622±50		253±8

KING'S EXPERIMENTS.

King (1905) measured the water requirement of corn in several different places in the United States. (Table XV, p. 27.) Different types of soil were employed, and the differences in the water requirement can not therefore be entirely attributed to varying climatic conditions.

VON SEELHORST'S EXPERIMENTS.

In his experiments with pasture and grassland plants Von Seelhorst (1910) found that the water requirement varied greatly at different periods of the year. His results (Table LIX, p. 69) show that the water requirement of the pasture crop was the lowest from April 1 to May 16; from May 16 to June 20 it was 58 per cent higher; from June 20 to July 29, 350 per cent higher; and from July 29 to September 16, 110 per cent higher. The results of the following year show the water requirement of pasture plants to be over 90 per cent higher for the period June 4 to June 28 than for the period April 6 to June 4. Similar results were obtained with the grassland pots.

BRIGGS AND SHANTZ'S EXPERIMENTS.

The writers in their work at Akron, Colo., have found that the water requirement of alfalfa (Table L) was the lowest for the period from September 18 to October 22. From May 13 to July 19 it was 94 per cent higher, and from July 19 to September 18, 160 per cent higher. With sweet clover the water requirement for the period from July 19 to September 21 was 17 per cent higher than for the period from May 13 to July 19.

TABLE L.—*Effect of the period of growth on the water requirement of crops, according to Briggs and Shantz (1913, p. 31.)*

Crop.	Period of growth.	Water requirement.	Crop.	Period of growth.	Water requirement.
Alfalfa	May 13 to July 19	1,008±26	Sweet clover	May 13 to July 19	675±5
	July 19 to Sept. 18	1,354±22		July 19 to Sept. 21	793±12
	Sept. 18 to Oct. 22	520±9			

A comparison of the writers' measurements of the water requirement of wheat and sorghum grown in northeastern Colorado and in the Panhandle of Texas during the seasons of 1910 and 1911 is given in Table LI. The results show a higher water requirement for the crops grown in Texas, but the difference is relatively much greater for wheat than for sorghum, indicating that at least one of the crops is better adapted to one region than to the other.

TABLE LI.—*Comparison of evaporation and water requirement in Colorado and Texas, according to Briggs and Shantz (1913, p. 45).*

Years and stations.	Wheat.					Sorghum.				
	Period of growth.	Evaporation.		Water requirement.		Period of growth.	Evaporation.		Water requirement.	
		Actual.	Relative.	Actual.	Relative.		Actual.	Relative.	Actual.	Relative.
1910.										
Akron, Colo...	Apr. 18 to Aug. 2..	27.7	100	664	100	May 25 to Sept. 28.	33.0	100	356	100
Amarillo, Tex.	Apr. 5 to July 19..	34.0	122	853	128	May 10 to Aug. 28.	37.7	114	359	101
1911.										
Akron, Colo...	May 13 to Aug. 2..	24.8	100	468	100	May 12 to Sept. 4..	35.0	100	298	100
Dalhart, Tex..	Apr. 25 to July 18.	28.5	115	673	143	May 14 to Sept. 12.	41.9	120	313	105

CONCLUSIONS.

The data here presented show clearly that the water requirement is profoundly affected by atmospheric conditions. Measurements of the water requirement conducted during different periods of the year show great differences. Experiments conducted at different places during the same period, using the same variety, give different values for the water requirement, owing to differences in the climatic conditions. Even though the methods and soil conditions are the same for two different years, profound differences are often recorded in the water requirement.

EFFECT OF AIR TEMPERATURE ON THE WATER REQUIREMENT.

The effect of temperature on the water requirement of plants does not appear ever to have been investigated under control conditions. Seasonal changes in temperature are accompanied by changes in the saturation deficit, so that the differences observed in the water requirement of plants resulting from the march of the seasons can not be attributed to temperature alone. The investigations which have so far been made on this subject have only a qualitative bearing. See Fittbogen (1874), Table XLVIII (p. 59); Hellriegel (1883), Table XLIX (p. 59); King (1905), Table XV (p. 27); Von Seelhorst (1910), Table LIX (p. 69); and Briggs and Shantz (1913), Table L (p. 60) and Table LI (p. 61).

EFFECT OF SHADE ON THE WATER REQUIREMENT.

It is well recognized that sunlight is an important factor in increasing transpiration. It is also known that in ordinary sunlight more solar energy is received by the plants than is necessary for photosynthesis. It seems evident, therefore, that an increase in solar intensity would cause an increase in the rate of loss of water from the plant without changing the rate of carbon fixation. Under such conditions increased sunlight would, of course, increase the water requirement.

On the other hand, the use of shade might be expected to lower the water requirement, so long as photosynthesis is not interfered with. If the shading is carried so far as to prevent carbon fixation at the normal rate, then the water requirement would again increase.

SORAUER'S EXPERIMENTS.

Sorauer (1880, p. 463) determined the water requirement of bean plants in the dark and in the light. The plants were grown for 20 days under bell jars, four pots being used in each experiment. The water requirement of plants grown in the dark was 21 ± 3, and of plants in the light, 47 ± 1. This experiment does not really afford any evidence with respect to the effect of light upon the water requirement, since no elaboration of carbohydrates is possible in the dark. Furthermore, no correction was made for the initial weight of the seedling plants, and the apparently low water requirement of plants grown in the dark is due to this. This experiment illustrates the possibility of securing misleading results from the use of seedlings in water-requirement measurements.

HELLRIEGEL'S EXPERIMENTS.

The experiments of Hellriegel (1883) are more conclusive. The results are given in Table LII. The water requirement was found to be lowest when the plants were grown in full light, and increased with increasing shade. The actual light reduction resulting from the use of the different screens is not stated. The "medium" screen increased the water requirement of the barley approximately 50 per cent and of the peas about 75 per cent.

TABLE LII.—*Effect of different light intensities on the water requirement of barley and peas,[1] according to Hellriegel (1883, p. 633).*

Plant.	Size of pot.	Full light.		Shade.					
				Wide screen.		Medium screen.		Close screen.	
		Dry matter.	Water requirement.	Dry matter.	Water requirement.	Dry matter.	Water requirement.	Dry matter.	Water requirement.
		Grams.		*Grams.*		*Grams.*		*Grams.*	
Barley	65 by 67 centimeters	57.3	360	15.3	498	10.8	510	7.7	609
	34 by 35 centimeters	28.0	338	12.2	468	11.8	528	6.5	542
Mean			349±9		483±13		519±8		576±29
Peas	34 by 35 centimeters	38.4	343						
		37.1	364			11.4	624		
Mean			354±9						

[1] Garden soil was used. The amount of soil did not affect the water requirement. Evaporation was prevented by waxed-board covers. Each given determination of water requirement is the mean value of two measurements, except that the one for shaded pea is a single measurement.

PFEIFFER, BLANCK, AND FLÜGEL'S EXPERIMENTS.

Pfeiffer, Blanck, and Flügel (1912) obtained a slight increase in the water requirement of oats, due to shade. Unfortunately, however, no idea is given of the light reduction resulting from the use of the shade. Their results are given in Table XIII (p. 24). The difference in the water requirement of the shaded series and the series in full light was 20±3, which corresponds to an increase of about 5 per cent due to shading.

CONCLUSIONS.

The intensity of the sunlight or the extent to which it was reduced by the various shades used is not stated in any of the above investigations, so that it is not possible to draw specific conclusions from the data here presented. All of these data, however, indicate that shading produces an increase in the water requirement. It seems probable that in these experiments the shade was so dense as to reduce photosynthesis. This would in turn decrease the rate of growth and so increase the water requirement.

EFFECT OF AIR HUMIDITY ON THE WATER REQUIREMENT.

SORAUER'S EXPERIMENTS.

Sorauer (1880) investigated the effect of humidity on the water requirement by growing a number of woody plants in moist air and in dry air. (Table LIII.) The water requirement in moist air averaged about 80 per cent of the water requirement in dry air.

TABLE LIII.—*Effect of dry and moist air on the water requirement of woody plants, according to Sorauer (1880, p. 435).*

Plants.	Duration.	Moist air.		Dry air.	
		Number of determinations.	Water requirement.	Number of determinations.	Water requirement.
	Days.				
Pyrus communis	39	1	284	1	353
Pyrus malus	39	3	146±3	2	233±27
Vitis vinifera	39	2	113±8	2	220±47
Ailanthus glandulosa	39	1	497	1	467
Robinia pseudoacacia	39	1	331	1	441
Mean			274		343

HEINRICH'S EXPERIMENTS.

Heinrich (1894) grew oats in damp air and in air dried by calcium chlorid. (Table LIV.) The plants were grown in glass pots, only one pot being used in each experiment. The relative humidity of the air is not given in either experiment. The results are very striking, the water requirement of the plants grown in dry air being over five times that of the plants grown in moist air.

TABLE LIV.—*Effect of dry and moist air on the water requirement of oats,*[1] *according to Heinrich (1894, pp. 170–171).*

Treatment.	Dry matter.	Water.	Water requirement on basis of dry matter.
	Grams.	*Kilograms.*	
Moist air	5.444	0.6549	[2] 120
Dry air	8.995	5.5567	618

[1] Duration of experiment, May 14 to July 29; 3 plants per pot.
[2] Heinrich gives 102, which is evidently an error.

MONTGOMERY AND KIESSELBACH'S EXPERIMENTS.

The most conclusive experiments on this subject are those of Montgomery and Kiesselbach (1912) with corn. Two greenhouses were used, one of which was ventilated and the other kept as humid as possible by wetting the floors and by using atomizers on the water system. The experiments were conducted in June and July. Apparently 4 large, covered pots, each containing 2 corn plants, were used in each house. Self-registering thermometers and hygrometers were used to record the temperature and humidity in each house and the evaporation from a free water surface (36 square inches) was also measured.

Montgomery and Kiesselbach's summary of the conditions in the two houses and the resulting water requirement is given in Table LV.

TABLE LV.—*Relation of humidity and other factors to the water requirement of corn, according to Montgomery and Kiesselbach (1912, p. 4).*

	Dry greenhouse.	Humid greenhouse.	Ratio, humid to dry.
Mean temperature:			
12 hours of night ° F.	80	75	....
12 hours of day ° F.	91	88	....
Mean relative humidity:			
12 hours of night per cent.	48	72	....
12 hours of day do.	37	58	....
Total weight of 8 plants grams.	670.36	861.77	....
Average leaf area per plant square inches.	1,079	1,070	....
Total water used kilograms.	227.785	184.230	....
Water requirement:			
Based on dry weight grams.	340	191	1.56
Based on square inches of leaf area do.	27.3	19.2	1.70
Water evaporated from 36 square inches of free-water surface do.	3,891	2,187	1.56

Table LV shows that the corn grown in the dry house had a water requirement 56 per cent higher than that in the humid house. It is of special interest to note that the evaporation from a free water surface in the dry house exceeded that in the humid house by the same amount, 56 per cent.

Another point of interest in connection with the above data which was not brought out by Montgomery and Kiesselbach arises from the consideration of the relative humidity of the two houses. Other things being equal, the rate of evaporation would be proportional to the saturation deficit. This can, furthermore, be limited to the saturation deficit during the day, since the transpiration at night is so small that it can be disregarded.

The pressure of aqueous vapor in saturated air at the mean day temperatures of the dry and humid houses is 31.67 and 31.11 millimeters, respectively. The corresponding saturation deficits expressed in terms of vapor pressure would then be

$$31.67 \times (1.00-0.37) = 19.95 \text{ millimeters,}$$
$$\text{and } 31.11 \times (1.00-0.58) = 13.05 \text{ millimeters.}$$

The ratio of these saturation deficits is 1.53, as compared with 1.56 obtained experimentally as the ratio of the water requirements. The linear relationship which is thus indicated between the saturation deficit and the water requirement must, of course, be considered only as tentative until its validity shall have been determined through further experiments. It affords, however, a possible method of determining indirectly from the mean relative humidity the relative water requirement of crops in different sections of the country, provided the temperature and the other climatic factors are equally favorable for growth.

CONCLUSIONS.

All of the investigations that have been made relative to the effect of humidity on the water requirement of plants show conclusively that the water requirement is greater in dry than in moist air.

Montgomery and Kiesselbach have found that the water requirement of corn is proportional to the evaporation from a small free water surface. From their data the writers have shown that the water requirement is also approximately proportional to the saturation deficit.

EFFECT OF THE CARBON-DIOXID CONTENT OF THE AIR ON THE WATER REQUIREMENT.

SORAUER'S EXPERIMENTS.

Sorauer (1880) measured the effect of the carbon-dioxid content of the atmosphere upon the water requirement (Table LVI). Rape was grown in free air and also under two bell jars. In one of the bell jars a solution of potassium hydrate was kept to reduce the carbon dioxid of the air. The results indicate that the water requirement is greatly increased by reducing the carbon-dioxid content of the atmosphere.

97991°—Bul. 285—13——5

TABLE LVI.—*Effect of insufficient carbon dioxid in the air on the water requirement of rape, according to Sorauer (1880, p. 467).*

Duration.	In free air.		Under bell jar.		Under bell jar, with potassium hydrate.	
	Number of determinations.	Water requirement.	Number of determinations.	Water requirement.	Number of determinations.	Water requirement.
Days. 20	4	282±11	3	243±5	2	355±5

CONCLUSIONS.

The effect of the carbon-dioxid content of the atmosphere upon the water requirement appears to have been investigated only by Sorauer. He found the water requirement to increase when the carbon-dioxid content was diminished. This is in accord with what is now known regarding the rôle of carbon dioxid in photosynthesis.

EFFECT OF PARASITES ON THE WATER REQUIREMENT.

WIMMER'S EXPERIMENTS.

Wimmer (1908) reported a series of experiments to show the effect of nematode-infested soil on the water requirement of sugar beets and celery. The results (Table LVII) show without exception an increase in the water requirement due to the action of the parasitic worms. This is probably due to the fact that infested plants grow much more slowly than those not infested, as is indicated by the weight of dry matter produced in each case.

TABLE LVII.—*Effect of nematodes[1] on the water requirement of sugar beets and celery, according to Wimmer.*

Crop and plat.	Weight of soil per pot.	Nematodes.	Fertilizer per pot.			Soil-moisture content.	Mean of dry matter.	Water requirement.
			K_2O	N	P_2O_5			
Sugar beets:	*Grams.*		*Grams.*	*Grams.*	*Grams.*	*Per cent.*	*Grams.*	
A7n	8,106	Dead	....	0.224	0.355	16	47.8	419±4
		Alive	....	.224	.355	16	19.1	933±118
	8,106	Dead	....	1.820	.355	16	75.9	336±11
		Alive	....	1.820	.355	16	36.8	567±85
	8,106	Dead	....	.700	.355	12	45.4	395±14
		Alive	....	.700	.355	12	34.4	474±26
A8n	8,202	Dead	0.705	....	.355	16	21.9	710±41
		Alive	.705	....	.355	16	6.6	2,083±57
Celery:								
A7n	8,106	Dead	.705	.224	.335	14 to 15	52.2	269±49
		Alive	.705	.224	.335	14 to 15	33.5	368±15[2]
A8n	8,202	Dead	.705	....	.335	14 to 18	40.5	422±20[3]
		Alive	.705	....	.335	14 to 18	23.7	521±4

[1] The nematodes were killed by carbon-bisulphid treatment. Computed from Wimmer's data (1908, pp. 142-143, 154-155). A7n is the mean of two determinations, A8n the mean of three, except as noted.
[2] Mean of four determinations.
[3] Mean of two determinations.

OTHER FACTORS INFLUENCING THE WATER REQUIREMENT.

THE EFFECT OF RELATIVE LEAF AREA ON THE WATER REQUIREMENT.

MONTGOMERY'S EXPERIMENTS.

Montgomery (1911) has investigated the influence of the leaf area of corn on its water requirement, using for this purpose selected strains having a high leaf area and a low leaf area, respectively. The plants were grown in large potometers of two sizes, one containing 1,000 pounds and the other 350 pounds of soil. The larger potometers contained two plants each, the smaller ones a single plant. The results of the experiments, which cover a period of three years, are given in Table LVIII, and show that, with an average difference in relative leafiness of 14 per cent, the more leafy type had a water requirement 7 per cent higher than the less leafy strain. The leafy plants required 16 per cent more water to produce an equal weight of ear.

TABLE LVIII.—*Effect of relative leaf area on the water requirement of corn, according to Montgomery (1911, p. 150).*

Year.	Ratio of leaf area to dry weight.		Ratio of high to low.	Water requirement.		Ratio of high to low.
	Low leaf area.	High leaf area.		Low leaf.	High leaf.	
1907	2.31	2.65	1.14	220	242	1.10
1909	2.33	2.73	1.17	263	287	1.09
1910	2.10	2.36	1.12	236	240	1.02
Mean			1.14±.01			1.07±.02

The transpiration per unit area of leaf was higher in the less leafy types, the ratio of low to high leaf area for the three years being 1.04, 1.07, 1.10. But some transpiration takes place also from the stalk, which would be relatively greater in the type with low leaf area, and the effect of this would be to make the transpiration of the low leaf-area strain per unit area appear higher than it really is. This effect is not sufficient, however, to account for the differences found between high leaf-area and low leaf-area types. From a computation made by the writers it appears that, in order to account for the observed differences in transpiration per unit area of leaf, the stalk would have to possess an area which is the equivalent as regards transpiration of 20 to 40 per cent of the total leaf area.

Montgomery's results indicate that the transpiration loss of corn in proportion to the growth made is decreased by a decreased leaf area. It is possible, however, that the narrow-leaved type developed through selection possessed also a varietal efficiency in the use of water independent of its leaf area. Further experimentation, using strains of other plants with high and low leaf areas, is desirable in this connection.

EFFECT OF FREQUENT CUTTING ON THE WATER REQUIREMENT.

VON SEELHORST'S EXPERIMENTS.

Von Seelhorst (1910) conducted an experiment to determine the water requirement of grassland and pasture. The pots used by Von Seelhorst (1902, p. 276) had a surface 1 square meter in area, a depth of 1.3 meters, and were mounted upon trucks in a trench running east and west, which was provided with cement walls and floor

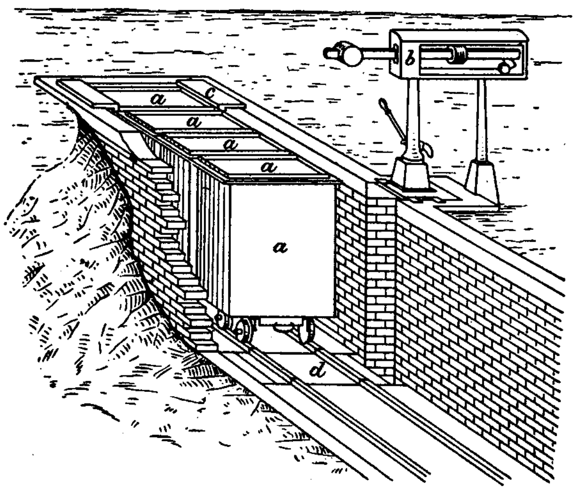

FIG. 4.—Apparatus used by Von Seelhorst (1902) in his later measurements of the water requirement of plants.

(fig. 4). The bottom of the pot (*a*) was so constructed as to permit free drainage. The scales (*b*) for weighing the trucks were built in as a part of the trench (*d*). The rainfall was determined from the rain-gauge measurements or directly by weighing, and the drainage water was also collected. No correction was made for evaporation. The pots which represented pasture were cropped more often than those which represented grassland. This was apparently the only difference in treatment. Ordinary grassland and pasture grasses were grown. The results of two years' work are shown in Table LIX, from which it will be seen that the water requirement was higher under pasture-land conditions than under grassland conditions. From these results, one would conclude that the frequent and continued cropping as the result of pasturing increases the water requirement per unit of dry matter produced, and that grassland can produce dry matter more economically when allowed to continue its growth uncropped for a longer period.

TABLE LIX.—*Relative water requirement of pasture and grassland, according to Von Seelhorst (1910, pp. 84–87).*[1]

Period of growth.	Pasture.		Grassland.	
	Dry matter.	Water requirement.	Dry matter.	Water requirement.
1908.	*Grams.*		*Grams.*	
Apr. 1 to May 16	150.6	248		
Apr. 1 to June 13			512.5	370
May 16 to June 20	156.0	715		
June 13 to July 29			253.7	733
June 20 to July 29	100.5	1,130		
July 29 to Sept. 16	135.0	546	206.3	513
Whole period, Apr. 1 to Sept. 16	542.1	620	972.5	495
1909.				
Apr. 6 to June 4	325.1	429		
Apr. 6 to June 28			584	451
June 4 to June 28	56.0	845		
Whole period, Apr. 6 to June 28	381.1	490	584	451

[1] Determinations were made in large pots, shown in figure 4 and described by Von Seelhorst (1902). Ordinary grassland and pasture plants were used. The experiment was continued until Sept. 27, 1909, but no comparable data are given after June 28, 1909.

EFFECT OF DEFOLIATION ON THE WATER REQUIREMENT.

SORAUER'S EXPERIMENTS.

Sorauer (1880) determined the effect of defoliation upon the water requirement of a grapevine grown in distilled water. The experiment was continued from July 14 to September 14. The results (Table LXIX) indicate that the removal of the leaves at the beginning of the experiment increased the water requirement over 50 per cent.

TABLE LX.—*Effect of defoliation on the water requirement of a grapevine, according to Sorauer (1880, p. 461).*

Plant.	In leaf.		Defoliated at start.	
	Number of determinations.	Water requirement.	Number of determinations.	Water requirement.
Vitis vinifera (Jaques)	2	122±13	2	186±8

EFFECT OF THE AMOUNT OF GROWTH OR NUMBER OF PLANTS PER UNIT OF SOIL MASS ON THE WATER REQUIREMENT.[1]

VON SEELHORST AND BÜNGER'S EXPERIMENTS.

Von Seelhorst and Bünger (1907) measured the water requirement of summer wheat when five plants were grown in each pot and when single plants were used. The experiments were carried out in pots containing 12 kilograms of soil. The results are given in Table XXXII (p. 44). In 14 out of 15 trials a higher water requirement was obtained when five plants were grown in a pot than when single plants were used. The increase in the water requirement was, however, small, averaging about 15 per cent for the low water-content series, and about 4 per cent for the high water-content series. It will be noted that the amount of dry matter produced varied greatly according to the treatment, and that in every case a single plant produced more than one-half as much dry matter as five plants taken together. As already suggested (p. 44), this indicates a deficiency of plant food in the small pots containing the five plants.

EFFECT OF THE AGE OF THE PLANT ON THE WATER REQUIREMENT.

VON SEELHORST'S EXPERIMENTS.

Von Seelhorst (1908a) experimented with lupine to determine the effect of duration of growth on the water requirement. The experiments were started on August 2, and the plants in eight pots were

[1] Von Seelhorst (1910a, p. 91) in presenting the data used in compiling Table XLV (p. 56) arranged the pots without respect to previous treatment or previous crop, in the order of decreasing yields, as follows:

Dry matter.		Water requirement, including evaporation.	
Actual.	Mean.	Actual.	Mean.
Grams.	*Grams.*	*Grams.*	*Grams.*
526.0		389	
482.3		685	
482.1		666	
458.5		720	
414.8		731	
399.4		777	
397.4		761	
395.5	394.4	768	769
393.5		754	
390.6		763	
390.0		793	
350.5		840	
339.0		900	

From these results he concludes that the water requirement increases as the production of dry matter decreases. The amount of growth was, however, greatly influenced by the fact that some pots contained more plant food than others, due to differences in the previous treatment. The unfertilized pot produced a light crop, and, as already shown in the section dealing with the effect of fertilizers on the water requirement, a deficiency in the plant-food supply greatly increases the water requirement.

It does not necessarily follow from this experiment, therefore, that the water requirement is inversely proportional to the amount of growth. These data are of value rather in showing the effect of fertilizer and of the previous crop upon the water requirement, and have been thus considered by the writers.

harvested October 8. The plants in the remaining four pots were harvested December 7. The water requirement of the pots last harvested was about 40 per cent higher than those first harvested.

These results (Table LXI) indicate that the water requirement during the later period of growth was greater than that during the earlier period of growth. Climatic conditions influence the water requirement so profoundly that it is unsafe to draw conclusions from this experiment.

TABLE LXI.—*Effect of length of the growth period on the water requirement of lupine, according to Von Seelhorst (1908a, pp. 199–201).*[1]

Period.	Number of determinations.	Dry matter.	Water requirement.
		Grams.	
Aug. 2 to Oct. 8	8	310±8	216±5
Aug. 2 to Dec. 7	4	264±7	306±10

[1] For correction of data, see Von Seelhorst (1909). An error occurs in Von Seelhorst's paper where the water requirement for pot 5 is given as 613 instead of 316.

A uniform correction is applied for evaporation based upon the evaporation from a bare check pot, but only 70 per cent of the evaporation loss from the check pot is deducted.

The probable error includes differences due to previous treatment. One half of the pots for each period of growth were fertilized lightly in the spring and the other half heavily in the fall. Half of the pots for the short period had previously produced rye and half, potatoes. The same is true for the long-period pots, except that barley and potatoes were the previous crops. The experiment was conducted in the larger pots described on page 68.

FEST'S EXPERIMENTS.

Fest (1908) determined the water requirement of the bush bean at different times during its growth, using 72 pots, each containing 20 kilograms of soil. Ten beans were planted in each of 70 of the pots and 2 were left as checks. Shade was provided for the check pots as the crop developed. The shade was a disk of roofing paper cut radially inward from the circumference into narrow strips to a depth of 10 centimeters. Alternate strips were bent inward more or less to obtain the shade desired. Each pot was given 1 gram each of potassium, nitrogen, and phosphorus, and 2 grams of calcium carbonate. The pots were kept in the plant house during the experiment. The results (Table LXII) indicate a higher water requirement during the later periods of growth. This may be due to the period of growth, but no check was provided against a change in climatic conditions during the progress of the experiment. The later part of the experiment was conducted during the warmest months of the year and this would increase the water requirement. For this reason the experiment as conducted does not seem to the writers to be conclusive as regards the relative water requirement at different stages of growth.

TABLE LXII.—*Effect of duration of growth on the water requirement of the bush bean at Gottingen, according to Fest (1908, p. 34).*[1]

Period of growth.	Condition at harvest.	Number of plants harvested.	Dry matter.	Water requirement.
			Grams.	
May 28 to June 19	Third leaf formed	350	255.8	134
June 20 to July 1	Beginning of bloom	229	450.8	211
July 2 to July 10	End of bloom	150	438.4	192
July 11 to July 25	Fruit formed	104	681.3	261
July 26 to Aug. 18	Ripe	25	497.8	304

[1] Twenty kilograms of soil per pot; water content, 70 per cent of moisture-holding capacity.

VON SEELHORST'S LATER EXPERIMENTS.

The results obtained by Von Seelhorst in 1910, already given in Table LIX (p. 69), lead to the conclusion that the older growth on grassland consumes less water in proportion to the dry matter produced than does the younger growth or that following cutting. This would indicate that the results previously recorded in this section were largely an expression of climatic differences.

CONCLUSIONS.

Most of the evidence presented regarding the effect of the age of the plant on the water requirement does not seem to be conclusive, since the changes in climatic conditions have not been eliminated. Von Seelhorst's later work indicates that a nearly matured plant has a lower water requirement than a young plant.

WATER REQUIREMENT OF DIFFERENT KINDS OF PLANTS.

WOODWARD'S EXPERIMENTS.

Woodward (1699) was the first to show that different kinds of plants do not have the same water requirement. His experiments with culture solutions (p. 54) included also the determination of the water requirement of different plants grown in spring water. His results, which are based on green weight, are summarized in Table LXIII.

TABLE LXIII.—*Water requirement of plants in England, according to Woodward (1699, pp. 200–201).*

Plant.	Culture.	Number of determinations.	Green weight produced.	Water requirement based on green weight.
			Grams.	
Spearmint	Spring water	1	0.97	170
Solanum	do	1	3.695	65
Lathyrus	do	1	.227	715

The results are of interest chiefly because of the early date at which they were obtained. It is evident that Lathyrus made very little growth but continued to transpire, thus increasing its water requirement.

LAWES'S EXPERIMENTS.

Lawes (1850) was the first to make a careful comparison of the water requirement of crop plants. The results of his experiments have been discussed and are given in Table XXI (p. 31). The water requirement of the different plants measured is summarized in Table LXIV.

TABLE LXIV.—*Water requirement of crop plants in England, according to Lawes (1850, p. 54).*

Crop.	Culture.	Number of determinations.	Mean dry matter.	Water requirement.	Remarks.
			Grams.		
Wheat	Soil	3	25.3	225	Comparable.
Barley	do	3	27.6	262	
Clover	do	3	11.4	216	
Wheat	do	2	29.1	235	Do.
Barley	do	2	31.3	258	
Beans	do	2	34.8	214	
Peas	do	2	28.5	235	
Clover	do	2	14.2	251	

No probable error can be applied to these results, since three series of determinations were made, one with manured soil, one with unmanured soil, and one with soil containing mineral manure. The wheat, barley, and clover were treated in the same way and the results are directly comparable. The results show but little difference in the water requirement of the different crops. In the order of increasing water requirement the crops are beans, peas, wheat, clover, and barley. These results agree with those of the writers in placing the water requirement of barley above that of wheat.

WOLLNY'S EXPERIMENTS.

Wollny (1877) determined the water requirement of a number of plants. He grew the plants in small zinc cylinders of two sizes, 20 centimeters in height and either 22 or 13 centimeters in diameter. Each cylinder was provided with a cover, in the center of which a tube 2.5 centimeters long and 3 or 4 centimeters in diameter was soldered. The seeds were planted directly below the tube. The cylinders were kept on the west side of a house provided with an overhanging roof to protect them from the rain. They were weighed every three days, and the water lost was replaced. A correction was made for the water lost through evaporation from the soil by weighing pots provided with similar covers but containing no plants.

Wollny apparently used but a single pot in the case of each crop. His experiments extended through approximately four months. No determinations are given regarding the amount of grain produced. The ratio of the water transpired to the dry matter [1] produced in Wollny's experiments is given in Table LXV.

TABLE LXV.—*Water requirement of crop plants in Munich, Germany, according to Wollny (1877, p. 125).*

Crop.	Dry matter.	Water requirement.	Crop.	Dry matter.	Water requirement.
	Grams.			*Grams.*	
Corn	48.1	233	Peas	9.8	416
Barley	6.4	774	Rape	4.9	912
Oats	10.7	665	Mustard	5.9	843
Millet	5.3	447	Sunflower	27.8	490
Buckwheat	6.4	646			

SORAUER'S EXPERIMENTS.

The data presented by Sorauer (1883) which bear on the water requirement of different crop plants are given in Table LXVI.

TABLE LXVI.—*Water requirement of crop plants in Germany, according to Sorauer (1883, pp. 90–91).*

Plant.	Culture.	Duration.	Number of determinations.	Dry matter.	Water requirement.
		Days.			
Rye	Water culture	53	8	0.144	413
Barley	do	53	7	.327	490
Wheat	do	53	8	.088	708
Oats	do	53	8	.104	600

These data are taken from Table XLIII (p. 55), and include the two series grown in a weak nutrient solution. The results are not in accord either with our results for the four crops or with those of Lawes for barley and wheat or with Wollny for oats and barley. This may be due to the fact that the plants did not reach maturity.

HELLRIEGEL'S EXPERIMENTS.

Hellriegel (1883) conducted a series of water-requirement experiments extending over a period of seven years and including a number of crop plants. By a series of ratios Hellriegel has also compared the relative water requirement of the crops not grown simultaneously. His results for each year are given in Table LXVII and the mean values are given in the last column.

[1] It is not clear from Wollny's description whether the term refers to air-dried or oven-dried material.

TABLE LXVII.—*Water requirement of plants at Dahme, Germany, according to Hellriegel (1883, pp. 641–661).*[1]

Crop.	1867		1868		1869		1870		1871		1872		1873		Summary.		Relative water requirement compared with barley.[2]					
	Number of determinations.	Water requirement.	Number of determinations.	Water requirement.	Number of determinations.	Water requirement.	Number of determinations.	Water requirement.	Number of determinations.	Water requirement.	Number of determinations.	Water requirement.	Number of determinations.	Water requirement.	Number of determinations.	Mean water requirement.	1867	1868	1871	1872	1873	Mean.
Barley	13	295±5	25	366±3	5	305±7	13	263±4	6	[2]286±7	6	318±10	6	347±6	74	297	100	100	100	100	100	100
Oats	24	339±5	16	464±4	...	...	...	...	...	...	...	...	...	...	40	401	115	127	...	...	...	121
Summer wheat	26	328±5	15	390±5	...	...	...	...	...	...	...	...	...	...	41	359	111	107	...	...	...	109
Summer rye	26	315±4	15	438±7	...	...	...	...	...	...	...	...	...	...	41	377	107	120	...	...	...	114
Horse beans	...	...	...	...	...	...	...	...	3	261±4	6	264± 9	...	...	9	263	...	...	91	83	...	87
Yellow lupine	...	...	...	...	...	...	...	...	3	319±11	8	427± 4	...	...	11	378	...	...	112	134	...	123
Peas	...	...	...	...	...	...	...	...	...	...	8	231± 4	2	353± 9	10	292	...	...	...	73	102	88
Red clover	...	...	...	...	...	...	...	...	...	...	8	363±12	8	297±14	16	330	...	...	...	114	86	100
Buckwheat	...	...	...	...	...	...	...	...	...	...	7	371± 3	...	...	7	371	...	...	...	117	...	117
Summer rape	...	...	...	...	...	...	...	...	...	...	3	337± 9	...	...	3	337	...	...	...	106	...	106

[1] The evaporation was estimated by check pots from 1867 to 1870; from 1871 to 1873 the pots were covered to prevent evaporation; 4 kilograms of sand per pot were used.

[2] In the summary given by Hellriegel (1883, p. 662) the water requirement of barley for 1871 is erroneously given as 264 instead of 286. Because of this error his summary does not conform exactly to the summary of his results here given.

Previous to 1871 the experiments were conducted in open jars containing about 4 kilograms of sand. Check pots were used to estimate the loss by evaporation. In 1871 and during succeeding years the soil was covered with a board infiltrated with a wax and paraffin mixture, which greatly reduced the direct evaporation. The crops grown during the year 1867, arranged in the order of increasing water requirement, are barley, rye, wheat, and oats. During the year 1868 the water requirement of all the crops was higher than in 1867. In 1871 the horse bean had the lowest requirement, followed by barley and yellow lupine in order. The order of these crops was the same in 1872. The crops grown in 1872 arranged in order of increasing water requirement are pea, horse bean, barley, rape, red clover, buckwheat, and yellow lupine. The results in 1873 as compared with those of the same crops grown during 1872 shows the order to be exactly reversed. The differences are small in most cases, when the probable error is considered.

A comparison of the results in the last column of Table LXVII shows the water requirement of barley and of red clover to be the same, wheat 9 per cent higher, rye 14 per cent higher, and oats 21 per cent higher than barley. Of the other crops, the horse bean and pea have the lowest water requirement, while the remaining crops exceed the water requirement of barley.

KING'S EXPERIMENTS.

During the years 1891 to 1894 King (1892 to 1895) conducted a series of experiments dealing largely with the relative water requirements of different crops. Correction was made for rainfall, but not for evaporation. King does not give the results of his duplicate determinations except for corn, the other results being expressed as mean values. The comparable results are shown in Table LXVIII.

TABLE LXVIII.—*Water requirement of crop plants in Wisconsin, according to King (1889 to 1895).*[1]

Crop.	1891		1892		1893		1894		Summary.		Relative water requirement compared with oats.			
	Number of pots.	Water requirement.	Number of pots.	Water requirement.	Number of pots.	Water requirement.	Number of pots.	Water requirement.	Number of pots.	Mean water requirement.	Crop.	1891	1892	1894
Dent corn[2]	2	305±5	2	318±68	...	...	...	...	4	310	Oats	100	100	100
Flint corn	...	...	...	...	2	[3]390±91	...	...	2	390	Barley	80	71	...
Oats	2	502±6	2	[4]526	...	...	4	594±25	8	541	Dent corn[2]	61	60	...
Barley	2	401±2	2	[4]375	...	...	...	...	4	388	Field pea	...	91	...
Field peas	...	...	2	[4]477	...	...	...	...	2	477	Red clover	...	107	...
Red clover	...	...	2	[4]564	2	[4]398	...	...	2	481	Potatoes	...	...	71
Potatoes	...	...	...	...	...	...	2	423±6	2	423	...	...	...	...

[1] In this table the writers have endeavored to eliminate errors in comparison. Consequently, they have omitted the determinations which were specially fertilized and have not used a weighted mean in the summary. The experiments in 1891 were made in 50-gallon barrels, painted and sunk level with the surface of the ground. In 1892 galvanized cans 18 by 40 inches were used in place of the barrels. In 1894 the plants and pots were protected from rain by a temporary cover of heavy duck. The potato cans were 18 by 24 inches.

[2] Pride of the North variety used.

[3] For an error in King's data in connection with this value, see Table XXV (p. 35).

[4] There were two pots, but the results are given only as a mean.

From these results it would appear that the water requirements of oats, clover, and field peas are about the same. Potatoes and barley have a somewhat lower water requirement, and dent corn requires about 40 per cent less water than oats for the production of an equal amount of dry matter.

VON SEELHORST'S EXPERIMENTS.

Most of the experiments conducted by Von Seelhorst were for the purpose of determining the effect of various environmental factors on the water requirement. In his experiments, published in 1906 and 1908, different crops were grown simultaneously under comparable conditions, as shown in Table LXIX. The experiments with rye, barley, and potatoes were conducted in the large pots described on page 68.

TABLE LXIX.—*Water requirement of crop plants at Gottingen, Germany, according to Von Seelhorst (1906, 1908, and 1908a).*[1]

Series, date of publication, and page reference.	Crop.	Soil type.	Number of determinations.	Dry matter.	Water requirement.	Period of growth.
				Grams.		
	Wheat	Loam	1	942	333	Oct. 8, 1904, to Aug. 2, 1905.
First series, 1906, p. 329	Rye	do	1	700	375	Oct. 8, 1904, to Aug. 3, 1905.
	Potatoes	do	1	1,173	[2] 268	Apr. 26 to Oct. 10, 1905.
	Rye	Sand	2	364	480	Aug. 10, 1904, to Aug. 2, 1905.
Second series, 1906, pp. 340–342	Barley	do	1	457	454	Mar. 29 to Aug. 2, 1905.
	Potatoes	do	3	[3] 1,685	[3] 60	Apr. 26 to Aug. 3, 1905.
	Rye	Loam	1	883	307	Oct. 17, 1906, to Aug. 12, 1907.
Third series, 1908, pp. 195–197	Barley	do	1	827	346	Mar. 30 to Aug. 12, 1907.
	Beets	do	1	823	268	May 11 to Nov. 5, 1907.
	Potatoes	Sand	6	286	294	Apr. 24 to Aug. 7, 1907.
Fourth series, 1908a, pp. 203–207	Rye	do	4	343	383	Oct. 12, 1906, to Aug. 7, 1907.
	Barley	do	2	457	295	Mar. 30 to Aug. 7, 1907.

[1] The experiments were mainly conducted in square-meter pots (p. 68). The data in each group are comparable, but the different groups can not be intercompared. In the last series half of the determination for each crop is from pots that received heavy fertilizer in the fall and half that received light fertilizer in the spring. (See Table XLV, p. 74.) Each pot produced a crop of lupine in the late summer and fall of 1906. The probable error is therefore not given. The second series, rye, barley, and potatoes, grown in 1905, were all in pots which were given a light application of manure in the spring.
[2] Water requirement based on green weight, 66.
[3] Green weight or based on green weight.

TABLE LXIX.—*Water requirement of crop plants at Gottingen, Germany, according to Von Seelhorst (1906, 1908, and 1908a)*—Continued.

RELATIVE WATER REQUIREMENT COMPARED WITH RYE.

Crop.	First series.	Second series.	Third series.	Fourth series.
Rye	100	100	100	100
Barley	....	95	112	77
Potatoes	72	....	....	77
Wheat	89	....	....	....
Beets	....	....	87	....

According to the above figures, rye and barley have about the same water requirement. Potatoes have a water requirement three-fourths that of rye, while wheat and beets are intermediate.

WIDTSOE'S EXPERIMENTS.

Widtsoe (1909) gives the average water requirement found for each of the crops used during the 4-year period covered by his experiments. (Table XVII, p. 28.) The results obtained using "College loam" soil may be considered as representing the water requirement of crops at Logan, Utah, when grown in productive soils. Widtsoe gives the following values for the water requirement of crops in this soil: Corn, 386; wheat, 546; sugar beets, 497; and peas, 843. These results are in agreement with those obtained by the writers in northeastern Colorado, with the exception of sugar beets, the water requirement of which is 32 per cent higher than the ratio obtained there.

LEATHER'S EXPERIMENTS.

Leather (1910, 1911) has measured the water requirement of a number of crops at Pusa, India. His experiments were carried on in glazed stone jars of various sizes, 9 or 12 inches in diameter and from 12 to 22 inches in depth, ranging in capacity from 12 to 48 kilograms of soil. The jars were not covered, the loss of water from the soil being estimated by the use of check jars in which no plants were grown. When a number of crops were grown in the same soil, four blank jars, two of which contained manured soil, were used, and the arithmetical mean of the losses taking place from the four jars was assumed to represent the amount of water which evaporated directly from the soil during the experiment.[1]

[1] Leather cites in illustration four blank jars which lost 9.93, 10.68, 13.03, and 14.11 kilograms, respectively, during the growing period. He states that the differences are not attributable to the presence of manure. The probable error of a single determination as calculated from the above figures is 1.6 kilograms. The water transpired by juar with different treatments during the period covered by the above figures is as follows: Unfertilized, 3.4 and 6.7 kilograms; with nitrogen, 6.2 and 7.1 kilograms; with nitrogen and phosphoric acid, 36.1 and 28.1 kilograms. The probable error of the evaporation correction thus amounts to about 5 per cent of the total transpiration in the case of the thrifty plants. With the unfertilized plants it is 47 and 24 per cent, respectively. This uncertainty arises from the differences in the evaporation from blank jars even when they are treated alike. A further error which can not be estimated results from the fact that the soil in the culture pots is shaded and dried by the plants growing in it.

The jars were supported on small cars, which ran on tracks extending to the culture house from an inclosure covered with wire netting. During the day when the weather was good the jars occupied the screened inclosure. At night and during wet weather they were brought under cover.

The jars were weighed each morning, which was accomplished by a large beam scale sensitive to 5 grams with a maximum load of 100 kilograms. By means of a cross track, jars from any track could be brought under the balance for weighing.

Water was added through unglazed earthenware cylinders about 5 centimeters in diameter and from 15 to 20 centimeters deep, provided with small holes in the bottom and the lower part of the sides. These cylinders were fixed in position in the center of the jar, so that the upper edge coincided approximately with that of the sides of the jar. By watering through these cylinders the surface soil remained loose, friable, and nearly air-dry, and cracking was avoided. The direct loss of water from the soil was also much reduced, being only about one-third as much as when the water is added to the surface o the soil. The roots were not found to be unusually abundant about the cylinders. Clean well water was used for watering the plants.

Fertilizers, when used, were added either in the dry state to the air-dried soil or were dissolved in the water used for dampening the soil before filling the pots. The weight of the plants after drying at about 100° C. was used in the final calculation of the water requirements. A summary of Leather's results is given in Table LXX.

TABLE LXX.—*Relative water requirement of crop plants at Pusa, India, based on results of soils fertilized with N+P and N+P+K, according to Leather (1910 and 1911).*

Crop.	Total number pots used in tests.	Mean water requirement.	Crop.	Total number pots used in tests.	Mean water requirement.
Cold-weather crops:			Monsoon crops—Continued.		
Wheat (*Triticum sativum*).	23	544±10	Juar (*Andropogon sorghum*)	2	437±41
Barley (*Hordeum vulgare*).	4	468±12	Murwa (Ragi millet, *Eleusine coracana*)	2	263± 2
Oats (*Avena sativa*)	4	469±40	Kodo (Kodo millet, *Paspalum scrobiculatum*)		312± 4
Linseed (*Linum usitatissimum*)	6	807±49	Rahar (pigeon-pea, *Cajan indicum*)	4	635±15
Sarson (kali, *Brassica campestris*)	6	496±32	Guar (*Cyamopsis psoralioides, C. tetragonoloba*).	2	598± 5
Pea (*Pisum sativum*)	4	563±28	Rice (*Oryza sativa*)	2	811±11
Gram (chick-pea, *Cicer arietinum*)	4	818±77	Sugar cane (*Saccharum officinarum*)	2	212± 1
Monsoon crops:					
Maize (*Zea mays*)	31	337± 5			

The cold-weather crops have a higher average water requirement than the monsoon crops. Barley and oats have the same water requirement, while wheat is about 16 per cent higher. Chick-peas, rice, and linseed have the highest water requirement, which is nearly four times that of the lowest, sugar cane. Next in efficiency to the sugar cane are millet, corn, and sorghum.

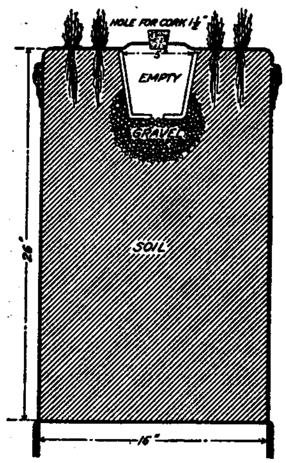

FIG. 5.—Pot used by Briggs and Shantz (1913) in measuring the water requirement of plants.

BRIGGS AND SHANTZ'S EXPERIMENTS.

The writers (1913) have measured the water requirement of plants in the Great Plains at Akron, Colo., and at Dalhart and Amarillo, Tex. For a comparison of the results at Akron and the Texas stations the reader is referred to Table LI (p. 61).

The plants were grown in large galvanized-iron cans containing about 115 kilograms of soil. All direct evaporation from the soil was practically eliminated by tight covers and by sealing the openings around the stems of the plants with wax (fig. 5). The method of watering is shown in figure 6. In order to determine the probable error of the results, six pots were used in each determination. Over 200 cans were employed in the experiments at Akron in 1911, including tests with 30 varieties of crop plants. The results are summarized in Table LXXI.

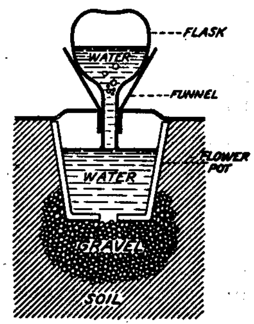

FIG. 6.—Sketch showing the device used by Briggs and Shantz (1913) in adding water to the pots.

ABLE LXXI.—*Summary of water-requirement measurements of varieties and crops at Akron, Colo., 1911, according to Briggs and Shantz (1913, p. 47).*

BASED ON WEIGHT OF DRY MATTER PRODUCED.

Crop.	Variety.	Water requirement: Variety.	Water requirement: Crop.	Water requirement: Relative, compared with wheat.
Alfalfa	Grimm	1068±16	1,068	211
Peas	Canada	800±17	800	158
Artemisia frigida		765±24	765	151
Rye	Spring	724±7	724	143
Sweet clover		709±9	709	140
Oats	Burt	639±7	614	122
	Swedish Select	615±7		
	Sixty-Day	605±5		
	Canadian	598±14		
Buckwheat		578±13	578	114
Barley	Beardless	544±9	539	106
	Beldi	543±2		
	White Hull-less	542±3		
	Hannchen	527±8		
Wheat	Emmer	534±14	507	100
	Bluestem	531±5		
	Spring Ghirka	506±3		
	Galgalos	496±4		
	Kubanka	468±8		
Potatoes	Irish Cobbler	448±11	448	88
Rape		441±12	441	87
Sugar beets	Kleinwanzleben	377±8	377	74
Corn	Iowa Silvermine	420±3	369	73
	Northwestern Dent	368±10		
	Esperanza	319±5		
Weeds	Amaranthus retroflexus	356±4	322	63
	Salsola pestifer	336±5		
	Amaranthus graecizans	275±7		
Sorghum	Dwarf milo	333±3	306	60
	White durra	321±2		
	Brown kaoliang	301±3		
	Red amber	298±4		
	Blackhull kafir	278±5		
Millet	Kursk	287±2	275	54
	German	263±15		

BASED ON WEIGHT OF GRAIN PRODUCED.

Crop.	Variety.	Water requirement: Variety.	Water requirement: Crop.	Water requirement: Relative, compared with wheat.
Peas	Canada	2218±100	2,218	163
Rye	Spring	2215±37	2,215	163
Oats	Canadian	2204±140	1,680	124
	Swedish Select	1632±35		
	Burt	1500±57		
	Sixty-Day	1383±30		
Wheat	Bluestem	1786±60	1,357	100
	Spring Ghirka	1382±43		
	Galgalos	1245±13		
	Kubanka	1191±14		
	Emmer	1180±42		
Barley	White Hull-less	1475±40	1,244	92
	Beardless	1210±38		
	Beldi	1155±18		
	Hannchen	1134±27		
Buckwheat		1037±33	1,037	76
Millet	Kursk	923±40	923	68
Sorghum	Dwarf milo	1123±57	790	58
	White durra	806±12		
	Blackhull kafir	803±26		
	Brown kaoliang	726±12		

Of the crops tested, those most efficient in the use of water are the millets, the sorghums, and the corns, their water requirement ranging from 275 to 370. The legumes, alfalfa, sweet clover, and Canada pea, have the highest water requirement, ranging from 710 to 1,070, while the small grains, wheat, barley, oats, and rye, have a water requirement ranging from 510 to 700. Potatoes and sugar beets are intermediate between the small grains and the corns. The efficiency of the grain sorghums and millet is again apparent in grain production. Spring rye and Canada peas are least efficient, while oats, wheat, barley, and buckwheat are intermediate. Varieties of barley, wheat, oats, and sorghum show great differences in the water requirement for grain production.

In the investigations which have been discussed heretofore the determinations of the water requirement have been limited to different crops. In this investigation the water requirement of different varieties of the same crop was also determined, and measurable differences were found. These varietal differences suggest not only the superiority of certain strains but also the desirability of applying water-requirement measurements in the selection of varieties for semiarid regions.

CONCLUSIONS.

In comparing the results obtained by different investigators relative to the water requirement of different species of plants, two points should be kept in mind: (1) A real difference in the results is to be expected if the climatic conditions differ at the places where the experiments were conducted. From this point of view the observed differences in the water requirement may be looked upon as a measure of the climatic differences. (2) Differences due to the method of experiment, to the use of different varieties, to the amount of plant food available, to the period during which the crop was grown, and to other similar factors must be classed as experimental errors in a comparison of this kind. The summary of the results of different investigators as presented in Table LXXII should then be considered with the points mentioned above in mind. Often the results are not strictly comparable, even when forming part of the same investigation, owing to differences in the duration or period of growth, and the more detailed statement given elsewhere in the bulletin should be referred to in this connection.

TABLE LXXII.—*Summary of water requirement determinations for different crops as influenced by climate.*[1]

Crop.	Lawes, 1850, Rothamsted, England.	Wollny, 1876, Munich, Germany.	Hellriegel, 1883, Dahme, Germany.	King, 1892–1895, Madison, Wis.	Von Seelhorst, 1896–1898, Gottingen, Germany.	Widtsoe, 1909, Logan, Utah.	Leather, 1910–11, Pusa, India.	Briggs and Shantz, 1913, Akron, Colo.
Wheat	235		359		333	546	554	507
Oats		665	401	541			469	614
Barley	258	774	297	388	365		468	539
Rye			377		386			724
Corn		233		350		386	337	369
Sorghum							437	306
Millet		447						275
Beans	214							
Peas	235	416	292	477		843	563	800
Clover (red)	251		330	481				
Clover (sweet)								709
Alfalfa								1,068
Horse beans			263					
Lupine			373					
Chick-peas							818	
Buckwheat		646	371					578
Rape		912	337					441
Mustard		843					496	
Sunflower		490						
Potatoes				423	281			448
Linseed							807	
Eleusine							263	
Paspalum							312	
Cajanna							635	
Cyamopsis							598	
Rice							811	
Sugar cane							212	
Sugar beets						497		377
Salsola								336
Amaranthus								303
Artemisia								765

[1] Summarized with respect to crops without respect to varieties. Includes only crops grown to maturity. The data are not strictly comparable, even in the case of a single investigation. The reader should consult the detailed discussion of each investigation in the earlier portions of this bulletin.

Lawes, working in England, obtained a lower value for the water requirement than any other investigator. Hellriegel and Von Seelhorst, in Germany, both obtained comparatively low values, while Wollny's results are comparatively high. King, working in Wisconsin, obtained lower values than the writers obtained in northeastern Colorado. Widtsoe's results at Logan, Utah, agree closely with those of the writers, being from 4 to 7 per cent higher for all crops except the sugar beet, which was 32 per cent higher. Leather, at Pusa, India, obtained lower values for oats, barley, corn, and peas, but higher values for wheat and sorghum than did the writers. Wollny's results are higher than the writers' in every case where the same crop was grown, with the single exception of corn.

The relative positions of the different crops vary greatly in the different investigations. Wheat and barley alternate, wheat having the higher water requirement in Hellriegel's and Leather's determinations and barley ranking higher in Lawes's, Von Seelhorst's, and the writers' measurements. Rye has a higher water requirement than wheat or barley in every case. The water requirement of oats is higher than barley in all cases except in Wollny's determinations. Peas gave a water requirement lower than barley in all cases except Leather's and the writers'. The water requirement of potatoes was lower than barley in all cases except in King's determination.

DETERMINATION OF THE WATER REQUIREMENT OF CROPS UNDER FIELD CONDITIONS.

CROPS GROWN WITH IRRIGATION.

WIDTSOE'S EXPERIMENTS.

Widtsoe (1912) conducted an extensive field experiment for the purpose of determining the effect of different amounts of irrigation water upon the water requirement. A number of crops were employed in the investigations. The results are given in Table LXXIII, the amount of irrigation water applied being given in the first column of the table. In addition to this irrigation water, there was available to each crop the rainfall of the season, which amounted to about 5 inches, and also the water which was stored in the soil at the beginning of the season as the result of the winter rains. From earlier measurements Widtsoe has calculated the average amount of stored water removed from the soil by each of the crops tested. The sum of the rainfall and the stored moisture used by each crop, according to Widtsoe's calculations, is given at the bottom of the table. This sum was added to each amount of irrigation water applied in calculating the water requirement of the crop. This procedure assumes that the soil-moisture content was the same at the end of the season in all of the plats devoted to a given crop without reference to the amount of irrigation water which had been applied during the season and which varied from 4 to 70 inches. It is unfortunate that moisture determinations were not made in each plat at the beginning and at the end of the season in order to avoid the uncertainty arising from this assumption.

TABLE LXXIII.—*Effect of different amounts of irrigation water on the water requirement of crops under field conditions, according to Widtsoe (1912, pp. 55–57).*

Water applied.	Water requirement, including evaporation, for—									
	Wheat.	Oats.	Barley.	Corn.	Alfalfa.	Sugar beets.	Carrots.	Potatoes.	Cabbage.	Onions.
Irrigation water added, in acre-inches:										
3.75							423			
5	856	596				569		1,136		
7.5	869		513	276			557	1,136		
10	948	872		275	621	571		1,255		
12.5									2,214	
15	1,038	845	695	356	977	663	572	1,411		2,170
20		897		416	946	682		1,466	3,128	2,628
25	1,317		998	474	1,052		760		4,248	
30				527	1,253	889		2,242		2,485
35	1,530						880			
39.5			1,263							
40									5,058	
45		1,566						3,060		
50	1,809				1,480	1,186				
55				1,087						
60							1,071	3,292		
65										4,689
70									7,419	
Soil water and rainfall used by crop in addition to irrigation:										
Inches	13.74	9.66	9.66	5.54	14.91	10.25	10.25	6.17	5.54	5.54

Widtsoe's results show clearly the great increase in the water requirement, which includes the evaporation as well, when the quantity of irrigation water applied is increased, the largest amounts of water applied resulting in a water requirement of about three times that observed when small quantities of irrigation water were used.

CROPS GROWN WITHOUT IRRIGATION.

LEATHER'S EXPERIMENTS.

Leather (1911) also measured the water requirements of a number of crops under field conditions. The land selected for the purpose was kept fallow during the rainy (monsoon) season, and the crops were sown at the beginning of the dry season. Moisture determinations were made in each plat soon after the plants were above ground and again at harvest. The difference in the amount of water in the soil at the time of these two measurements plus the water added through rainfall represented the total loss of water. The rainfall during the experimental period was very low, being only 0.4 inch at Pusa in 1908–9 and 0.2 inch in 1909–10, making the conditions exceptionally favorable for an experiment of this kind. Moisture determinations at seeding time and at harvest were also made in a part of the field which was kept fallow throughout the experiment. The difference in these determinations gave the loss due to evaporation from the fallow plat. The evaporation loss from the cropped plats was assumed to be the same as from the fallow plat. The difference between the total amount of water lost and that lost through evaporation was ascribed to the transpiration of the crop. This, divided by the dry matter produced, gave the water requirement. The crops grown were heavy, amounting to 5,000 pounds or more per acre in the case of the cereals. About 50 square feet were harvested for determining the dry matter produced. The area of this sample included the point where the initial moisture determination was taken. Moisture samples were taken to a depth of 9 feet. Table LXXIV shows the results of Leather's field determinations of the moisture requirement and includes also some determinations of the water requirement of wheat grown under irrigation at Cawnpore, India.

TABLE LXXIV.—*Water requirement of crops in India grown under field conditions, according to Leather (1911, pp. 234–279).*

Crop.	Station.	Year.	Rainfall during experiment.	Water requirement.	
				No manure.	Manure.
			Inches.		
Wheat	Pusa	1908–9	0.38	....	415
	....do	1909–10	.22	237	313
Wheat (irrigated)	Cawnpore	1908–9	.25	442	....
	....do	1908–9	.25	550	....
	....do	1909–10	1.81	407	....
	....do	1909–10	1.81	302	....
Barley	Pusa	1908–9	.38	430	341
Oats	....do	1907–8	2.8	411	....
	....do	1908–9	.38	331	230
	....do	1909–10	.22	....	282
Linseed	....do	1908–9	.38	693	718
	....do	1909–10	.22	706	940
Peas	....do	1908–9	.38	314	505
Mustard	....do	1908–9	.32	471	298
	....do	1909–10	.16	477	614

Unfortunately, Leather's experiments were, for the most part, conducted upon a single plat in each case. It is consequently not possible to form any definite conception of the probable error of the experiments. Results from duplicate plats are, however, available in the case of the irrigated wheat grown at Cawnpore, and the probable error for a single determination is, in the case of these results, 12 per cent and 17 per cent, respectively, of the observed water requirement. It is therefore evident that a relatively large observational error is to be expected in this method of determining the water requirement. Some of the anomalies appearing in the results, notably the higher water requirement obtained in some cases when manure is used, are probably to be ascribed to experimental error. From investigations now in progress regarding the loss of water from fallow lands in the Great Plains, the writers are inclined to believe that the direct evaporation from the soil of the fallow land is considerably greater than the corresponding loss from the soil of the cropped plats. The soil of the cropped plats is not only shaded by the growing crop, but is also considerably protected from wind, so that the humidity of the air is relatively higher immediately above the soil surface than over the fallow land. The crop in its early stages also dries out the surface soil, so that the water content of the upper layers of the cropped plat is materially lower than the fallow land. This would tend to reduce the evaporation loss from the cropped plat. It would consequently appear that the correction term for the evaporation loss from the cropped plats is somewhat too large, which would tend to give too low a value for the water requirement under field conditions. It will be noted that the values obtained in the field experiments are, almost without exception, below the mean water requirement obtained from the pot experiments. (Table XL, p. 52.) Leather calls attention, however, to the fact that in the latter determinations small pots were used in a part of the experiments, which tend to give too high a value for the water requirement. He also suggests as a possible source of error the capillary rise of water from below the 9-foot level in the field experiments, but believes the error due to an unmeasured water supply from this source to be very small. The field experiments of the writers fully support him in this conclusion.

BRIGGS AND SHANTZ'S EXPERIMENTS.

The writers' measurements of the water requirement of wheat under field conditions at Akron, Colo., were based upon the water removed by the crop as shown by the difference between the initial and final water content combined with the rainfall entering the soil, determined by daily sampling. No correction for evaporation was attempted. The results are summarized in Table LXXV. The water requirement of wheat grown in the field was found by this procedure to be higher than that obtained in the pot measurements. However, when the rainfall during the growth of the crop was not considered, the water requirement of the wheat grown under field conditions agreed closely with that obtained in the pot cultures. The writers attribute this to the fact that the wheat was drawing its supply of moisture from the subsoil at the time of these rains, and failed to develop a surface root system in time to absorb the rainfall before it evaporated.

TABLE LXXV.—*Comparison of water requirement of Kubanka wheat crops grown under field conditions, 1910 and 1911, according to Briggs and Shantz (1913, p. 41).*

Character of experiments.	Water requirement.			
	Including rainfall during growth.		Excluding rainfall.	
	Based on dry matter.	Based on grain.	Based on dry matter.	Based on grain.
Field experiments, 1910	700	2,315	486	1,780
Field experiments, 1911	862	2,380	466	1,614
Pot experiments, 1911			468±8	1,196±15

CONCLUSIONS.

The measurement of the water requirement under field conditions is uncertain, owing to the difficulty of determining what proportion of the rainfall during the growing season is actually used by the crop. This uncertainty arises from a lack of knowledge regarding the amount of run-off and the amount of rainfall that is evaporated from the soil surface without becoming available to the crop. The production of the crop upon water stored in the subsoil during a period without rain, as in Leather's experiments, is an ideal condition for field measurements of this kind. Under these conditions Leather obtained a lower water requirement in the field experiments than in the pot cultures. The writers found that the water requirement was higher under field conditions than in pot cultures if the rainfall during the growing period was taken into consideration, but that the determinations agreed closely if the light rainfall that occurred during the growing season was ignored.

SUMMARY.

The term "water requirement" is used in this paper to indicate the ratio of the weight of water absorbed by a plant during its growth to the dry matter produced.

The experiments made in connection with the effect of soil-moisture content on the water requirement show, as a rule, an increase in the water requirement when the soil-moisture content approaches either extreme. Many of these experiments were conducted in open pots and the direct evaporation estimated from check pots without plants. Owing to the uncertainty of this method when a wide range in soil-moisture content is employed and to the difficulty of securing a uniform distribution of soil moisture when the soil is maintained at a low water content, it would appear that the direct effect of soil-moisture content on the water requirement is still an open question.

Many investigations have been made regarding the effect of fertilizers on the water requirement, and with few exceptions the experiments show a reduction in the water requirement accompanying the use of fertilizers. In highly productive soils this reduction is slight. In poor soils the water requirement may be reduced one-half, or even two-thirds, by the use of fertilizers. Often a high water requirement is due to a deficiency of a single plant-food element. As the supply of such an element approaches exhaustion, growth practically ceases, while the transpiration continues, which leads to a high water requirement. This emphasizes the importance of maintaining the fertility of the soils of the semiarid regions if the most effective use is to be made of the limited water supply.

As a whole, the investigations relative to the effect of fertilizers on the water requirement show clearly that transpiration is not a measure of growth, even under the same atmospheric conditions, since the water requirement is profoundly affected by the plant food available in the soil.

The type of soil used may affect the water requirement in so far as it determines the amount of plant food available to the crop. There is no indication that the texture of the soil, independently of the plant food it contains, affects the water requirement of plants.

The water requirement is influenced by limiting the amount of soil available to the roots of the plants, the water requirement decreasing within limits as the amount of soil is increased. This would follow as a result of an inadequate supply of plant food. In some cases the water requirement has been increased as a result of previous cropping. This would follow from the reduction of the available supply of plant food by the previous crop.

No direct measurements have been made of the effect of soil temperature on the water requirement. Leather found, however, that an increase in the soil temperature due to the sun shining on the pots did not materially affect the water requirement.

The water requirement has been shown to be profoundly affected by the atmospheric conditions. The water requirement of the same crop varies greatly according to the period of the year in which it is grown. Similarly, the same crop will give a widely differing water requirement when grown in different regions during the same period.

All of the investigations which have so far been made indicate that shading increases the water requirement. This would follow if the shade were so dense as to reduce photosynthesis.

The water requirement is greater in dry than in moist air. Montgomery and Kiesselbach have found the water requirement of corn to be proportional to the evaporation from a small free water surface. From their data the writers have shown that the water requirement was approximately proportional to the saturation deficit of the air.

Sorauer found the water requirement to increase when the carbon-dioxid content of the air was diminished, which is analogous to a deficiency in mineral plant food.

Wimmer has shown that the water requirement of sugar beets and celery is increased by the attacks of parasitic nematodes. The infested plants grow more slowly, which would account for the increase in the water requirement.

Montgomery has compared the water requirement of narrow-leaf and broad-leaf types of corn, and found that the narrow-leaf strain had a lower water requirement. It is, however, possible that this difference may have been due to a superior varietal efficiency of the narrow-leaf type independent of its leaf area.

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Von Seelhorst's experiments on the effect of frequent cutting indicate that grassland can produce dry matter more efficiently than pasture land. In other words, the water requirement of the grasses is apparently higher during the earlier stages of growth than at any other time. These experiments, however, include the loss due to direct evaporation from the soil, which might be greater during the earlier stages of the crop.

A summary of the water-requirement measurements which have been made with different crops is given in Table LXXVI. The variation in the water requirement of the same crop as determined by different investigators is due largely to soil and climatic conditions, but probably in part also to the use of different varieties as well as to experimental errors. The data given in the same investigation are not always strictly comparable, since the crops were not all grown during the same period.

TABLE LXXVI.—*Summary of the water-requirement measurements for various crops, as determined by different investigators.*

Crop.	Lawes, 1850, Rothamsted, England.	Wollny, 1886, Munich, Germany.	Hellriegel, 1883, Dahme, Germany.	King, 1892 to 1895, Madison, Wis.	Von Seelhorst, 1896 to 1898, Gottingen, Germany.	Widtsoe, 1909, Logan, Utah.	Leather, 1910–11, Pusa, India.	Briggs and Shantz, 1913, Akron, Colo.
Wheat	235		359		333	546	554	507
Oats		665	401	541			469	614
Barley	258	774	297	388	365		468	539
Rye			377		386			724
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Sorghum							437	306
Millet		447						275
Beans	214							
Peas	235	416	292	477		843	563	800
Clover (red)	251		330	481				
Clover (sweet)								709
Alfalfa								1,068
Horse beans			263					
Lupine			373					
Chick-peas							818	
Buckwheat		646	371					578
Rape		912	337					441
Mustard		843					496	
Sunflower		490						
Potatoes				423	281			448
Linseed							807	
Eleusine							263	
Paspalum							312	
Cajanna							635	
Cyamopsis							598	
Rice							811	
Sugar cane							212	
Sugar beets						497		377
Salsola								336
Amaranthus								303
Artemisia								765

One of the most striking features of water-requirement measurements is the marked difference in efficiency exhibited by different plants in the use of water. The millet, sorghum, and corn groups have been found the most efficient, while alfalfa and sweet clover are the least efficient in producing dry matter with a given amount of water. The small-grain crops have a water requirement intermediate between the legumes and corn. Measurable differences in the water requirement also exist between different varieties of the same crop, and this suggests the possibility of developing through selection strains which are still more efficient in the use of water.

Leather found that the water requirement of a crop grown under field conditions was, as a rule, lower than the water requirement of the same crop determined from pot experiments. The writers' measurements of the water requirement of wheat under field conditions gave a higher value than the corresponding pot determinations. If, however, the calculations were based upon the amount of stored moisture removed by the crop without reference to the rainfall received during the growing season, the field results were in close agreement with the pot experiments.

LITERATURE CITED.

Cited in this bulletin on page—

BRIGGS, L. J., and SHANTZ, H. L.
1913. The water requirement of plants. I.—Investigations in the Great Plains in 1910 and 1911. U. S. Department of Agriculture, Bureau of Plant Industry, Bulletin 284, p. 49 .... 60, 61, 80, 87

BURGERSTEIN, ALFRED.
1904. Die Transpiration der Pflanzen. Jena, pp. 154–158.................... 11

DASZEWSKI, A. VON.
1900. Der Einfluss des Wassers und der Düngung auf die Zusammensetzung der Asche der Kartoffelpflanze. Journal für Landwirtschaft, Bd. 48, Heft 3, pp. 223–249.................... 15, 39

DEHÉRAIN, P. P.
1892. La transpiration des végétaux et l'emploi des engrais. Annales Agronomiques, t. 18, pp. 465–486.................... 34

FEST, FRANZ.
1908. Über den zeitlichen Verlauf der Nährstoffaufnahme und Trockensubstanzproduktion bei der Buschbohne unter verschiedenen Düngungs- und Witterungsverhältnissen. Journal für Landwirtschaft, Bd. 56, Heft 1, p. 1–47, 1 fig., pl. 1–5.................... 71

FITTBOGEN, J.
1873. Untersuchungen über das für eine normale Produktion der Haferpflanze nothwendige Minimum von Bodenfeuchtigkeit, sowie über die Aufnahme von Bestandtheilen des Bodens bei verschiedenem Wassergehalt desselben. Landwirtschaftliche Jahrbücher, Bd. 2, pp. 353–371, 1 fig.................... 12
1874. Ueber die Wasserverdunstung der Haferpflanze unter verschiedenen Wärme-, Licht- und Luftfeuchtigkeits-Verhältnissen. Landwirtschaftliche Jahrbücher, Bd. 3, pp. 141–157.................... 58, 61

FORTIER, SAMUEL.
1903. Soil moisture in relation to crop yield. Montana Agricultural Experiment Station, 9th Annual Report, 1902, p. 107.................... 15

HEINRICH, REINHOLD.
1894. Ueber die Wassermengen, welche die Haferpflanze aus verschiedenen Nährstoff-Concentrationen während ihrer Vegetationszeit verbraucht. Zweiter Bericht über die Verhältnisse und Wirksamkeit der Landwirtschaftlichen Versuchs-Station, Rostock, pp. 170–174.................... 55, 63

HELLRIEGEL, F. H.
1883. Verhältnis zwischen Produktion und Verdunstung.—Wie viel Wasser verbraucht eine Pflanze während der Erzeugung von einem Gramm Trockensubstanz durchschnittlich? *In his* Beiträge zu den Naturwissenschaftlichen Grundlagen des Ackerbaus. Braunschweig, pp. 622–664 .... 13, 30, 33, 59, 61, 62, 74

HÖHNEL, FRANZ, RITTER VON.
1881. Ueber den Wasserverbrauch der Holzgewächse mit Beziehung auf die meteorologischen Factoren. Forschungen auf dem Gebiete der Agrikultur-Physik, Bd. 4, pp. 435–445.................... 10

IL'ENKOV, P. A.
1865. Einige Versuche zur Bestimmung des Einflusses, welchen die Bodenfeuchtigkeit auf die Vegetation ausübt. Annalen der Chemie und Pharmacie, Bd. 136 (n. R., Bd. 60), Heft 2, p. 162.................... 12

KIESSELBACH, T. A.
1910. Transpiration experiments with the corn plant. Nebraska Agricultural Experiment Station, 23d Annual Report [1909], pp. 125–139, 2 figs.................... 20, 50

Cited in this bulletin on page—

KIESSELBACH, T. A., and MONTGOMERY, E. G.
1911. The relation of climatic factors to the water used by the corn plant. Nebraska Agricultural Experiment Station, 24th Annual Report [1910], pp. 91–107, 2 figs. 21

KING, F. H.
1889. Amount of water consumed by plants. Wisconsin Agricultural Experiment Station, 6th Annual Report [1888]/1889, pp. 191–192 76
1892. The amount of water required to produce a pound of barley, oats and corn in Wisconsin. Wisconsin Agricultural Experiment Station, 8th Annual Report [1890]/1891, pp. 124–131, figs. 4 76
1893. The amount of water required to produce a pound of dry matter in barley, oats, corn, clover, and peas in Wisconsin. Wisconsin Agricultural Experiment Station, 9th Annual Report [1891]/1892, pp. 94–100 76
1894. The amount of water required to produce a pound of dry matter in Wisconsin. Wisconsin Agricultural Experiment Station, 10th Annual Report [1892]/1893, pp. 152–159, figs. 15 .... 34, 76
1895. The number of inches of water required for a ton of dry matter in Wisconsin. Wisconsin Agricultural Experiment Station, 11th Annual Report [1893]/1894, pp. 240–248 .... 57, 76
1905. Relative rates of evaporation at stations in four States from soil surfaces staturated by capillarity, and from corn. *In his* Investigations in soil management. U. S. Department of Agriculture, Bureau of Soils, Bulletin 26, pp. 192–198 .... 26, 60, 61

KOLKUNOV, V.
1905. K Voprosu O V′ĭrabotkie V′inosliv′ĭkh K Zasukham Rass Kul′turn′ĭkh Rasteniĭ. Anatomo-Fiziologicheskiia I Biometricheskiia Izsliedovaniia. Kiev′, 82 pp., 3 pls .... (1)

LAWES, J. B.
1850. Experimental investigation into the amount of water given off by plants during their growth; especially in relation to the fixation and source of their various constituents. Journal, Horticultural Society, London, v. 5, pp. 38–63, illus 11, 31, 73

LEATHER, J. W.
1910. Water requirements of crops in India. Memoirs, Department of Agriculture, India. Chemical Series, v. 1, no. 8, pp. 133–184, pls. 3–19 .... 20, 28, 30, 50, 57, 78
1911. Water requirements of crops in India.—II. Memoirs, Department of Agriculutre, India. Chemical Series, v. 1, no. 10, pp. 205–281, illus 28, 50, 78, 85

LE CLERC, J. A., and BREAZEALE, J. F.
1911. Translocation of plant food and elaboration of organic plant material in wheat seedlings. U. S. Department of Agriculture, Bureau of Chemistry, Bulletin 138, p. 10 10

LIEBSCHER, GEORG.
1895. Untersuchungen über die Bestimmung des Düngerbedürfnisses der Ackerböden und Kulturpflanzen. Journal für Landwirtschaft, Bd. 43, Heft. 1/2, pp. 49–216 .... 26, 35

MAERCKER, MAX.
1896. Über die Wirkung der Kalisalze auf Sandboden. Arbeiten, Deutsche Landwirtschafts-Gesellschaft, Heft 20, pp. 7–30 .... 13, 36

[1] The writers are indebted to Prof. T. A. Kiesselbach for the reference to this paper, which contains data on the effect of the kind of plant and of soil-moisture content on the water requirement. It was received too late to be reviewed in this bulletin.

Cited in this bulletin on page—

MAERCKER, MAX—Continued.

1896a. Versuche über die Beeinflussung des Wasserverbrauchs der Pflanzen durch die Kalirohsalze. Jahrbuch, Agrikultur-Chemische Versuchsstation der Landwirtschaftskammer der Provinz Sachsen zu Halle a/S., 1895, pp. 15–16 .... 13, 36

MARIÉ-DAVY, E. H.

1874. Note sur la quantité d'eau consommée par le froment pendant sa croissance. Comptes Rendus, Académie des Sciences [Paris], t. 79, pp. 208–212 33

1875. Évaporation du sol et des plantes. Annuaire Météorologique et Agricole de l'Observatoire, Montsouris, pp. 290–321 .... 25, 32

1876. Évaporation, transpiration. Annuaire Météorologique et Agricole de l'Observatoire, Montsouris, pp. 374–388 25

MONTGOMERY, E. G.

1911. Correlation studies of corn. Nebraska Agricultural Experiment Station, 24th Annual Report [1910], pp. 108–159, illus 67

1912. Methods of determining the water requirements of crops. Proceedings, American Society of Agronomy, v. 3, 1911, pp. 261–283, figs. 37–48, pls. 3–4 .... 11, 53

——— and KIESSELBACH, T. A.

1912. Studies in water requirements of corn. Nebraska Agricultural Experiment Station, Bulletin 128, 15 pp 64

OHLMER, W.

1908. Über den Einfluss der Düngung und der Bodenfeuchtigkeit bei gleichem Standraum auf die Anlage und Ausbildung der Ähre und die Ausbildung der Kolbenform beim Göttinger begrannten Squarehead-Winterweizen. Journal für Landwirtschaft, Bd. 56, Heft 2, pp. 153–171, pls. 7–10 .... 16, 44

PFEIFFER, THEODOR; BLANCK, EDWIN; and FLÜGEL, M.

1912. Wasser und Licht als Vegetationsfaktoren und ihre Beziehungen zum Gesetze vom Minimum. Die Landwirtschaftlichen Versuchs-Stationen, Bd. 76, Heft 3/6, pp. 169–236 .... 22, 53, 63

PREUL, FRANZ.

1908. Untersuchungen über den Einfluss verschiedenen hohen Wassergehaltes des Bodens in den einzelnen Vegetationsstadien bei verschiedenem Bodenreichtum auf die Entwickelung der Sommerweizenpflanze, Göttingen. Inaugural Dissertation. Abstract in Journal für Landwirtschaft, Bd. 56, Heft 3, pp. 229–271 .... 18, 45

SCHROEDER, M. R.

1896. Razvitie i isparenie iachmeaea pri razlichnoĭ vlazhnosti i pitatelnosti substrata. Izvíestiia Moskoskago sel Skokhoziaĭstvennago Instituta, god 2, kniga 1 (Annales, Institut Agronomique, Moscou, ann. 2, livr. 1), pp. 188–226 .... 14, 37

SEELHORST, CONRAD VON.

1899. Über den Wasserverbrauch der Haferpflanze bei verschiedenem Wassergehalt und bei verschiedener Düngung des Bodens. Journal für Landwirtschaft, Bd. 47, Heft 4, pp. 369–378 .... 14, 37

1902. Vegetationskästen zum Studium des Wasserhaushaltes im Boden. Journal für Landwirtschaft, Bd. 50, pp. 277–280, pls. 9 68

1906. Über den Wasserverbrauch von Roggen, Gerste, Weizen und Kartoffeln. I. Mitteilung. Journal für Landwirtschaft, Bd. 54, Heft 4, pp. 316–342, pls. 18 .... 27, 77

1908. Über den Wasserverbrauch von Lupinen im Herbst 1906 und von Kartoffeln, Sommergerste und Roggen im Sommer 1907 auf einem Sandboden. Journal für Landwirtschaft, Bd. 56, Heft 2, pp. 199–207 77

Cited in this bulletin on page—

SEELHORST, CONRAD VON—Continued.
1908a. Über den Wasserverbrauch von Rüben, Roggen, und Gerste auf einem Lehmboden im Jahre 1907. Journal für Landwirtschaft, Bd. 56, Heft 2, pp. 195–198, pls. 12 .... 70, 77
1909. Berichtigung zu dem Aufsatz: über den Wasserverbrauch von Lupinen im Herbst 1906 usw. im Journal für Landwirtschaft 1908, S. 199 u. ff. Journal für Landwirtschaft, Bd. 57, pp. 111–112 77
1910. Der Wasserverbrauch von Wiese und Weide. Journal für Landwirtschaft, Bd. 58, Heft 1, pp. 83–88 .... 60, 61, 68, 72
1910a. Wasserverbrauch von Roggen auf Sandboden 1908/09. Journal für Landwirtschaft, Bd. 58, Heft 1, pp. 89–92 .... 52, 56, 70

——— and BÜNGER, J.
1907. Versuche mit Sommerweizen. Journal für Landwirtschaft, Bd. 55, Heft 3, pp. 246–260, pls. 4–5 .... 16, 44, 70

SLĚSKIN, P.
1908. K'voprosu ŏ raskhodie vody sakharnoï soekloĭ. Zhurnal Opytnoi Agronomu (Russisches Journal für Experimentelle Landwirtschaft), t. 9, pp. 474–482 28

SORAUER, PAUL.
1880. Studien über Verdunstung. Forschungen auf dem Gebiete der Agrikultur-Physik, Bd. 3, pp. 351–490 .... 62, 63, 65, 69
1883. Nachtrag zu den Studien über Verdunstung. Forschungen auf dem Gebiete der Agrikultur-Physik, Bd. 6, pp. 79–96 .... 55, 74

WIDTSOE, J. A.
1909. Irrigation investigations. Factors influencing evaporation and transpiration. Utah Agricultural Experiment Station, Bulletin 105, 64 p., 7 figs., pp. 49, 52 .... 19, 27, 29, 49, 78
1912. The production of dry matter with different quantities of irrigation water. Utah Agricultural Experiment Station, Bulletin 116, 64 pp., illus 84

WILFARTH, HERMANN, and WIMMER, G.
1902. Die Wirkung des Kaliums auf das Pflanzenleben nach Vegetationsversuchen mit Kartoffeln, Tabak, Buchweizen, Senf, Zichorien und Hafer. Berlin, 106 pp., illus. (Arbeiten, Deutsche Landwirtschafts-Gesellschaft, Heft 68) 39

WILMS, JOHANN.
1899. Einfluss des Wassergehalts und Nährstoffreichtums des Bodens auf die Lebensthätigkeit und Ausbildung der Kartoffelpflanze. Journal für Landwirtschaft, Bd. 47, Heft 3, pp. 251–292, pls. 3–5 .... 15, 38

WIMMER, G.
1908. Nach welchen Gesetzen erfolgt die Kaliaufnahme der Pflanzen aus dem Boden? Bearbeitet von H. Wilfarth, W. Krüger, H. Roemer, G. Wimmer, G. Geisthoff, O. Ringleben, J. Storck. Berlin, 169 p. (Arbeiten, Deutsche Landwirtschafts-Gesellschaft, Heft 143) ... 16, 46, 66

WOLLNY, EWALD.
1877. Einfluss der Pflanzendecke und der Beschattung auf den Wassergehalt des Bodens. *In his* Der Einfluss der Pflanzendecke und Beschattung auf die physikalischen Eigenschaften und die Fruchtbarkeit des Bodens. Berlin, pp. 105–135 73

WOODWARD, JOHN.
1699. Some thoughts and experiments concerning vegetation. Philosophical Transactions, [Royal Society, London], v. 21, no. 253, pp. 193–227 .... 11, 54, 72

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