AGRICULTURAL METEOROLOGY

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Relation of the Weather to the Yield of Wheat in Manitoba.

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During the years 1915, 1916 and 1917, special plots of Marquis wheat were grown at the Dominion Experimental Farms for the purpose of simultaneous observations of plant-growth and weather-changes. In earlier years the Dominion Chemist (Dr. Frank T. Shutt) had maintained such special plots in pursuit of an investigation into the influence of environment upon the growth of wheat, the annual results from plots in Ontario, Quebec and the Maritime Provinces having been compared with the results from plots in the Prairie Provinces.[2]

Upon the inception of the Division of Agricultural Meteorology by the Meteorological Service, Dr. Shutt arranged that these plots should serve for both Departments. At all the farms daily observations of the meteorological instruments are made throughout the year, while upon one special plot at each farm is grown Marquis wheat from seed raised in the previous year at Indian Head, and distributed after testing by the Division of Chemistry. The plot is always as near to the meteorological instruments as is found feasible. Dates of sowing, appearance above ground, stooling, stem roots, heading, flowering, milk-stage, maturity, cutting, are carefully noted, as well as the average height of the plants every seven days. Particulars of fertilizers used, of method of cultivation, of fungous diseases, of space occupied by weeds and other details are also kept. At the close of the season the yield of grain and straw is noted, and samples are sent to Ottawa.

[1] See Influence of the Weather upon Farm Crops, Monthly Bulletin of Agricultural Statistics, March, 1918 (Vol. 11, No. 115, p. 81).

[2] See Reports of the Dominion Chemist in Annual Reports of the Dominion Experimental Farms: 1909, p. 140; 1910, p. 193 and 1911, p. 165.

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There are many related paths of investigation to be followed much further than the data we have at present accumulated will allow before we may hope to attain any conclusive results. In this introductory article some of the more striking relations, which the preliminary analysis has indicated as subsisting between yields of spring wheat in Manitoba and the weather of the growing-season, will be pointed out. Certain working hypotheses have been tentatively adopted in order to give the research a definite plan, but since these are likely to be greatly modified as the investigation progresses and new data are obtained, they will be touched upon in this article but lightly.

The first work that was done after the first year's data from the plots were available was the graphical representation of the data in the style first published by Broounoff, of the Russian Agricultural Department. These diagrams served only to emphasize the innate refractoriness of the problem. Nor did the diagrams for the second year serve at all to elucidate the difficulties, since the damage suffered from rust in that year introduced an entirely new factor whose influence cannot be measured and eliminated from the data. A large number of the plots in 1917 were free from disease or accident, and the data for that year have been charted in the same graphical manner.

The value of these diagrams will be greatly enhanced as the data are increased by the observations of succeeding years, but at present greater use has been made of the direct tabulations of the figures themselves. Various pairs of frequencies among the variates, which considerations *a priori* led one to believe correlated, were tested. Although many of these pairs yielded correlation coefficients not of negligible magnitude, yet all were to a certain extent doubtful on account of the small number of observations as yet available. In a few cases it was possible to draw a very probable curve for the function in question. Some of these preliminary findings were as follows:—

1. There appeared to be a relation between the length of the period from sowing to heading, or from appearance of the plants to heading, and the subsequent yield, the longer periods being positively related to the greater yields.

2. There appeared to be a positive correlation between the yield of straw and the length of the period from appearance to heading.

3. While from the above it should follow that there is a positive correlation between the yield of straw and the yield of grain, yet this seemed to be true only for the smaller and larger yields of grain, intermediate yields of grain varying independently of the length of straw.

4. The length of the period from appearance to heading, when plotted against the mean daily minimum temperature of the same period, gave a relation between these variables which is fairly well represented by the equation $pt = 789 + 10t + 24p$ in which $\frac{dp}{dt}$ is negative[1] and p is the period in days and t the mean minimum in degrees Fahr.

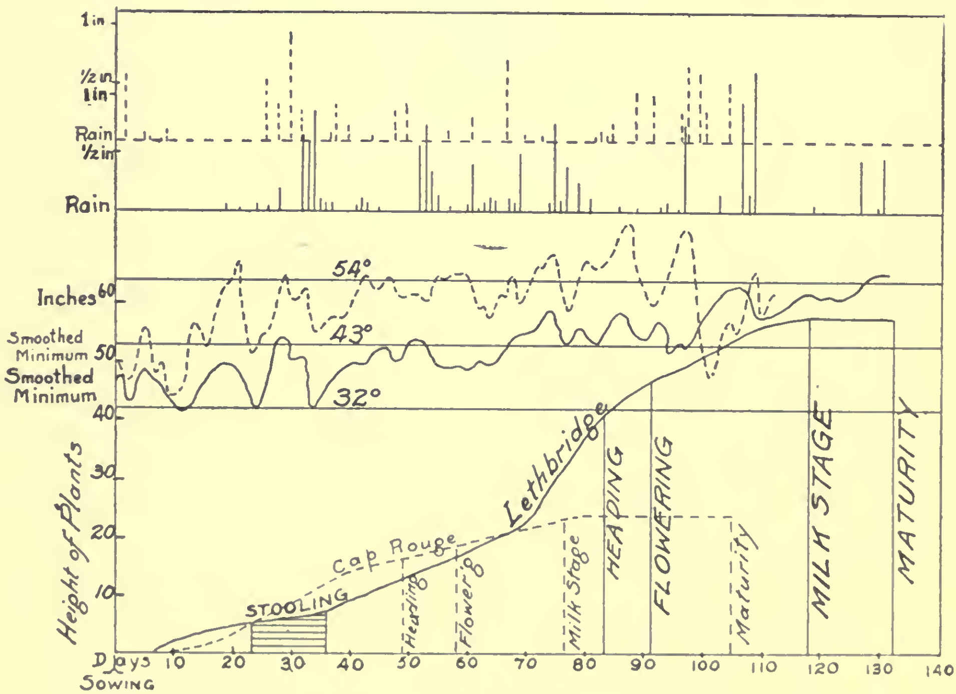
[1] i.e. p decreases as t increases.—Ed.

5. The moments of the plotted points about this last curve seemed to be correlated with the rainfall of the same period; so that p appeared in general to increase directly as the rainfall and inversely as the rise in temperature.

It will be remembered that in Broounoff's memoirs upon the growth of cereal plants, he names the period before heading, approximately ten days before, as the "critical period". In this period rain is necessary for a good yield. He wrote:

> L'inspection des autres graphiques nous amène à des conclusions analogues. On peut les formuler de la manière suivante: il existe une période particulière pour la végétation de l'avoine qu'on peut appeler critique par rapport aux précipitations atmosphériques. Leur abondance à cette époque produit un bon rendement, leur absence en détermine un mauvais. Broounoff, Les Cultures Agricoles et le Temps, Petrograd, 1912.

If this statement in regard to oats is to be assumed to hold for wheat, there immediately arises a difficulty in regard to the relations found above. These show that the time of heading is a moving point, the motion inverse to the minimum temperature, and therefore any selected period in days preceding heading, if expressed in terms of the age of the plant, is itself a variable depending on the weather since appearance. It therefore appears that the true explanation



Date of sowing at Lethbridge, April 12; at Cap Rouge, May 18. Soil at Lethbridge, chocolate loam, 18 inches deep. Soil at Cap Rouge, mellow but slightly acid, sandy loam, subsoil shale.
Note.—The broken lines refer to Cap Rouge and the unbroken lines to Lethbridge.

of the "critical period" is as follows. If in the earlier stages of the wheat's growth there be cool and rainy weather, the heading will be delayed and the subsequent yield will be heavy, but if the weather be warm and dry, heading will be hastened and the subsequent yield will be light. To illustrate this point the curves of growth for the highest and lowest yields of the 1915 plots are shown. (See diagram on p. 3.) These are, of course, extreme cases, and in the intermediate cases the growth-curves do not vary with the weather in any fashion that is at present recognizable. It is, however, manifest that the area under the growth-curve in the case where the yield is a minimum, is itself a minimum, and that also the maximum area under the growth-curve corresponds to the maximum yield. These were the plots at Cap Rouge, Quebec, and at Lethbridge, Alberta, the curves for which form the diagram. Taking numerical integrals by the planimeter in all cases and plotting against the yields, we do not, however, find any simple relation between yield and integral.

It is always allowable and generally profitable to form a theory in advance in such cases in order to have a working hypothesis for further investigation. In the present instance the theory set up is that at any instant the height of the straw is a measure of the rate at which the plant is receiving or utilizing nourishment, while the integral of this rate between appearance and milky maturity is the measure of the total nutriment received. But since a portion of this nutriment is expended in producing the straw, and a part expended in the energy of the life-processes, the integral will not be directly proportional to the yield in grain. There is, therefore, to be found the relation between these integrals and the resulting yields, which will involve also the yields of straw. Only the data for 1915 and 1917 are useful for this inquiry, since the straw was badly rusted in 1916. Progress in this part of the investigation is being made; but the fact that measurements of heights are taken only every seven days, and that no count was kept of the number of plants standing upon the plot, has made interpretation of the data difficult. More detailed observations may be possible this year.

In order to test some of these findings by a totally independent set of data, there was obtained from the Census and Statistics Office a list of the annual yields of spring wheat in Manitoba since 1883. Commencing with the year 1908 the Census and Statistics Office has made a separate estimate of the yield, but prior to that year the estimates are those of the Provincial Department of Agriculture. For the years from 1908 to 1916 there are, therefore, two estimates, which differ in the case of minimum variation by 0·3 bushel, and in the case of maximum variation by 4·3 bushels per acre.

In order to make use of these figures it was necessary to obtain the dates of sowing in each year. The only method was to have recourse to the Annual Reports of the Superintendent of the Brandon Experimental Farm, who gives the date upon which sowing became general throughout the province in most of his reports, beginning with that for 1890. The data for three bad "rust-years" were first eliminated. The period after the date of sowing was divided into 30-day periods. The map of the Department of the Interior showing the spring wheat areas of Manitoba was then consulted, and several meteorological stations chosen so as to have one in each of six districts. For these stations the records since 1890 were obtained and the total rainfall for each 30-day period counted in each year from the date of sowing of wheat, was found. This was a time-consuming task, and therefore, it was decided that the mean temperature, mean maximum and minimum, and mean daily range of temperature for the same periods should be taken from Winnipeg and Minnedosa records only, the average of the two cases being regarded as the provincial mean. After the data had been put into this form the correlations between the various factors and the annual yields were found. The results were as tabulated below.

RAINFALL CORRELATIONS.

—	30-day Periods.				60-day Periods.			90-day Periods.		120-day Periods.
	I	II	III	IV	I & II	II & III	III & IV	I & II & III	II & III & IV	I, II, III, IV
Correlation coefficient...	+·28	+·15	+·42	+·10	+·26	+·50	+·41	+·55	+·52	+·57
Probable error	±·13	±·14	±·11	±·14	±·13	±·11	±·12	±·10	±·10	±·09

—	30 days before Sowing.	60 days (before & I).	90 days (before & I & II).	150 days from 30 days prior to sowing to 120 days after.
Correlation coefficient.	+·01	+·22	+·24	+·57
Probable error........	±·14	±·13	±·13	±·09

RANGE OF TEMPERATURE CORRELATIONS.

—	30-day Periods.				60-day Periods.			90-day Periods.		120-day Period.
	I	II	III	IV	I & II	II & III	III & IV	I & II & III	II & III & IV	I & II & III & IV
Coefficient.....	−·07	−·17	−·55	−·42	−·15	−·39	−·48	−·34	−·40	−·42
Probable error	±·14	±·14	±·10	±·12	±·14	±·12	±·11	±·12	±·12	±·12

MINIMUM TEMPERATURE CORRELATIONS.

—	30-day Periods.				60-day Periods.			90-day Periods.		120-day Periods.
	I	II	III	IV	I & II	II & III	III & IV	I & II & III	II & III & IV	I & II & III & IV
Coefficient.....	·00	−·23	−·40	·00	−·13	−·37	−·37	−·22	−·36	−·25
Probable error	±·14	±·14	±·12	±·14	±·14	±·12	±·12	±·13	±·12	±·13

In examining these correlation coefficients too great stress must not be laid upon the actual magnitudes, since the number of instances upon which they are based is comparatively few. It should, however, be borne in mind that the underlying data are averaged from large areas, a fact which adds weight to the final results.

In regard to rainfall there appears that (1) the effect of the rainfall of the 30 days preceding sowing had, in the long run, no effect upon the subsequent yield; (2) in each of the 30-day periods after sowing, and in all combinations of them, the effect of increased rainfall was to increase the yield, except, perhaps, the fourth; (3) the rainfall of the third 30 days after sowing was the most potent in increasing the yield; (4) that the rainfall effect was cumulative, the correlation coefficient for the 120 days being the largest.

In regard to mean daily range of temperature there appears (1) that in all the 30-day periods succeeding sowing the coefficient was negative, indicating that the yield was increased by a lowered range; (2) that in the case of the first period after sowing the coefficient is negligible; (3) that in the case of the third period the coefficient is largest, five and one-half times the probable error; (4) that any combination of other periods with the third produces a smaller coefficient than that for the third alone.

In regard to mean daily minimum temperature, we have that (1) the effect of this factor in the first and fourth periods after sowing is zero; (2) in the second and third periods the coefficient is negative, indicating that the yield is increased by a lowered temperature; (3) in the case of the third 30 days after sowing, the coefficient is greatest; (4) combinations of other periods with the third produce a smaller coefficient.

Summarized in the most general terms, the foregoing statements may be reduced to the assertion that the wheat plant demands moisture and coolness prior to the 91st day after sowing, and the subsequent yield is most reduced by large ranges of temperature during the third thirty-days after sowing. There is a general concordance between the conclusions reached from the two independent sets of data: that from the experimental plots, and that from the annual provincial averages; the latter set, however, has brought out the paramount importance of the daily range of temperature.

From the results so far attained it is not educible that there is a critical period of short duration. The coefficients for the third 30 days after sowing are the largest, but this division into 30-day periods was arbitrarily chosen, and there is nothing to show that a larger or smaller period, if chosen, might not have revealed still larger coefficients. From the two sets of data, together, without more detailed treatment, we may assert with fair justification, that the first 90 days after sowing are very important with regard to moisture and coolness, but that ordinarily there is sufficient moisture in the soil in the first 60 days for the young plants, and ow enough ranges of temperatures to prevent evaporation to a harmful extent. During the latter part of the 90-day period, however, there will ordinarily obtain midsummer weather with increased probability of heat and drought, and in this regard the last part of the 90 days after sowing may be said to be a "critical period". If in this "critical" time the weather be warm, dry, with great temperature range, the wheat-plants will head early and the harvest will be light, but if the cool and moist conditions continue, heading will be postponed and the yield increased. Now the average date of sowing of wheat in Manitoba since 1890 is approximately April 25, which will fix the average time of the "critical period" as the last week of June and the first three weeks of July. Hence the variability of early July weather may be regarded as the "critical factor" in wheat-production in Manitoba.

Over this variability there is no control, except in so far as methods of cultivation can lessen its ill effect, or in so far as a change in the time of sowing might serve to throw the variable weather period later than the 90th day. The investigation of this latter possibility is scarcely worth while in regard to Manitoba, since it would appear that in general the very earliest sowing is the best and this is the method in practice. In Ontario and the eastern provinces, however, the curves of growth from the experimental plots show that the comparatively late sowing of spring wheat does not assure the plants that cool, moist weather during the first 90 days which appears to be demanded.

The other method of control, namely, that of cultivation, was investigated in a preliminary way by choosing data from the Reports of the Experimental Farm at Brandon, so that a series of yields from fields which had been summer-fallowed was obtained. A similar method of analysis of 30-day periods was carried out and the correlation coefficients formed. Later, an attempt was made to separate these data into two series, one for summer-fallow on heavy soil, and one for summer-fallow on light soil. While these last two series suffer from the fewness of items, which increases the probable error, some interesting results were obtained. On the summer-fallowed plots the coefficient of the rainfall in the third 30 days is negligible, while that for the full 120 days is much reduced. The coefficient of the range for the same 30 days is reduced from 0·55, as given in the provincial table, to 0·35, while that for the minimum becomes practically zero. On light soil which had been summer-fallowed, rainfall and minimum temperature coefficients were very small, but that for range of temperature was increased to 0·60, which may be interpreted to mean only that light soil, whether fallowed or not in the previous season, is very subject to loss of moisture from large temperature ranges, or it may be interpreted to mean that fallowing light soil increases this tendency. The question needs two series to be analysed, one from light soil not fallowed, one from light soil previously fallowed. Such series are not yet available. For heavy soils which had been summer-fallowed the sign of the coefficient is reversed for range of temperature, while that for the rainfall of the whole season becomes very small. It would appear, therefore, as far as our short records can be relied upon, that a clayey soil summer-fallowed in the previous year has the best chance of carrying a wheat crop through heat and drought: but that any soil, save perhaps the very lightest, summer-fallowed, carries good assurance against failure.

In view of the relatively large magnitudes of the correlation coefficients for the third 30 days in Manitoba, it appeared to be possible to express the resulting yields of grain as a function of the weather of the third period. The usual method of forming a regression-equation did not seem to me to be applicable here since that would involve the average weather of the third period. Now the earliest date of sowing in Manitoba has been April 1 and the latest May 10. The third period may therefore begin early in June or late in July according to the sowing, whether early or late. The average weather of the third period would therefore be scarcely an intelligible quantity to use as a constant in an equation. The three variables used were the rainfall, mean daily minimum temperature and mean daily range of temperature, all of the third 30 days after sowing, and it was found that these are to some extent inter-correlated. The minimum is slightly and the rainfall to a much greater degree correlated with the range, both negatively, while there is no relation between the minimum and the rain. Since the rainfall is related positively and the other factors negatively to the yield of wheat, the quotient $\frac{\text{Rain}}{\text{range} \times \text{minimum}}$ should be related positively. The plotting of these quotients against the yields led to the following equation:

If Y be the yield in bushels per acre,
m the mean minimum temperature,
p the total precipitation for the 30 days,
r the mean daily range,
m′ be (m–40),

$$\text{then } Y = .434 \left(m - \frac{r}{2}\right) \log \frac{1000\,p}{rm'}$$

If the mean daily temperature be denoted by t, then the quantity $\left(m - \frac{r}{2}\right)$ may be written (t-r).[1]

[1]It is probable that closer approximation might be obtained by least-square treatment of (m–40), the constant 40 being slightly changed.

The calculated values of Y and values from the Provincial Government's estimate are given below. As noted before, the provincial and federal estimates have differed by as much as 4.3 bushels per acre. In 18 out of 23 the difference between the calculated yield and the provincial estimate is less than this; while in 17 instances the difference is less than 3 bushels. The importance of the weather of this third 30 days after sowing in Manitoba is thus emphasized.

Year.	Provincial estimate.	Calculated.	Difference.	Year.	Provincial estimate.	Calculated	Difference.
1890	19·7	19·5	−0·2	1903	16·4	15·4	− 1·0
1891	25·3	23·8	+ 1·5	1905	21·1	23·1	+ 2·0
1892	16·5	18·5	+ 2·1	1907	14·2	13·8	− 0·4
1893	15·6	12·5	− 3·1	1908	17·3	16·0	− 1·3
1894	17·0	18·3	+ 1·3	1909	17·3	15·5	− 1·8
1895	27·9	19·6	− 8·3[1]	1910	13·5	15·6	+ 2·1
1897	14·1	21·1	+ 7·0[2]	1911	18·3	18·3	0·0
1898	17·0	23·1	+ 6·1[3]	1912	20·7	21·7	+ 1·0
1899	17·1	17·2	+ 0·1	1913	20·0	19·3	− 0·7
1900	8·9	10·4	+ 1·5	1914	15·5	15·2	− 0·3
1901	25·1	24·8	− 0·3	1915	26·4	20·7	− 5·7[5]
1902	26·0	14·5	−11·5[4]				

[1] Unaccounted for. [2] Damaged in 2nd 30 days. [3] Damaged in 2nd and 1st 30 days. [4] Very wet 2nd period; rainfall of 3rd period insufficient to express soil moisture. [5] Extraordinary fall-ploughing in 1914.

In the case of the yield for 1915 I have been inclined to attribute the increase in the yield over that calculated to the extraordinary amount of fall-ploughing which is mentioned on page 143 of the Canada Year Book for 1915[1]. This explanation is based on the belief that ordinarily a considerable amount of wheat is sown in the spring on wheat-stubble very lightly worked, while an extraordinary amount of fall-ploughing might have resulted in a larger area of better prepared soil.

In the case of 1897 and in that of 1898 early droughts and drying winds evidently set the plants back to an extent that subsequent good weather could not remedy. In the case of 1902, the extremely wet second period seemed to have supplied such a quantity of moisture as offset the very scanty rainfall of the third period. In 1895 the provincial estimate shows a very high yield which the weather of the whole season does not seem to justify, if one assumes that there was no systematic improvement in the methods of cultivation in the province during that year.

Concerning the variation in the chemical composition of the wheat-kernels and its possible dependence on weather changes, not sufficient progress in the investigation has been made to warrant lengthy notice here. The meteorologist is sadly handicapped in such inquiry

[1] See also Census and Statistics Monthly for November 1914, pp. 276 and 278 and for January 1916, p. 1.

because of the fact that little or nothing can be gleaned from plant-physiologists in explanation of the processes of formation of starches, proteids, glucosides, etc., which would serve to give him a clear idea of the mode of conversion of the products of assimilation. The problem as it stands from the standpoint of the agricultural meteorologist is to relate the variations in the products of an unknown process to the simultaneous weather-changes. These variations are most familiarly known as the changes in the relative " hardness " of the wheat and have a great practical importance because of the corresponding changes in the quality of the resulting flours.

The Dominion Chemist has supplied the Meteorological Office each year with the results of the analysis of kernels from each of the experimental plots. The first attempts were directed to finding a relation between nitrogen-content and the weather of various periods, attempts which have been unsuccessful up to the present at least. Quite lately, I have changed the direction of the investigation. In view of the frank admissions of plant-physiologists as to inability to explain the conversion processes in plants, I took the liberty of forming a tentative theory regarding the variations in the chemical content of wheat, which, based upon what evidence was available, is purely hypothetical and is intended to serve as a plan of investigation only. This theory or supposition rests upon the fact that when the protein-content of the grain falls the starch content, in general, rises. It seemed better therefore, to relate the variation in starch-content to the weather-changes, which led to the hypothesis that the total starch-content of the grain varies directly as the amount of water transpired by the plant from heading to maturity. To show this from the experimental plots, or to disprove it, is that which is at present being attempted. No method of measuring the transpiration has yet been devised for the field, but it is hoped that supplementary observations in future years may supply approximate information. If this hypothesis be found true it will explain such results as that of Thatcher (Agr. Exp. St. Pullman, Wash.) in 1906 and 1908, who found that after growing wheat under the shade of 16 ounce duck canvas, the average percentage of crude protein was 2.26 (dry-matter basis) in favour of the shaded portions of the plots. The table he gives shows that the starch-content in favour of the unshaded portions varies by 4.5 to 7.2 for the four plots of which the starch-content is given. It seems natural to suppose that the transpiration from the plants continuously under the shade of 16 ounce duck should be much less than from plants unshaded.

Upon the same hypothesis we must assume that the factors favourable to starchy grain are a moist soil with bright sunshine, low humidity, high temperature and drying winds. Since these last concomitants are inimical to the maintenance of the soil in a moist condition, the rate of transpiration would rapidly fall on account of exhaustion of soil-moisture unless the moisture were continuously renewed. This might be done by irrigation or in nature by frequent showers alternating with bright, hot, dry weather. The factors favourable to decreased starch-content, and therefore, by implication, to increased nitrogen-content, are those which tend to keep in check the transpiration of water by the plants, such as high atmospheric humidity, cloudiness, absence of winds, low moisture-content of the soil. Conditions which we have already seen will reduce the yield of wheat (viz., high minimum temperatures, increased ranges of temperature combined with lack of soil-moisture, which bring on early maturity) will also make it impossible for the plant to continue the transpiration of water in any great volume. We may, therefore, suppose that in general light yields of wheat tend to be "harder" in quality than large yields. Further investigation into these matters may either confirm or deny these hypotheses.