WHEAT YIELDS FOR 50 YEARS AT SWIFT CURRENT, SASKATCHEWAN IN RELATION TO WEATHER

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Half a century of wheat yield and weather records at Swift Current in southwestern Saskatchewan were analyzed to determine the response of wheat (*Triticum aestivum* L.) to changing weather patterns. Weather at Swift Current has undergone subtle but significant changes over the past 50 yr. Earlier years had disturbed conditions: hot, dry periods alternating with cool, wet ones resulting in yield fluctuations ranging from crop failures to maximum values. More recently the weather has been quiet: dry and cool but less variable from year to year. The resulting conditions were more favorable for near-normal but less variable yields. Simple precipitation-based yield–weather models developed two decades ago no longer apply, because temperature and precipitation patterns are currently out of phase relative to earlier conditions. A factorial yield–weather model was used to explain the complex relationship. This involved the summation of the product of several quadratic functions of various weather elements. Those elements considered were precipitation, maximum and minimum temperatures, global radiation estimated from duration of bright sunshine, evaporation from a buried pan, and time as an indicator of advancing technology. One function contained a term for the antecedant crop condition. The most important elements were precipitation for the summer-fallow period and for May, June and August; maximum temperatures for June and July; and global radiation for May. Advances in technology would seem to have very little influence on wheat yield trends after weather trends were accounted for. The model accounted for 73% ($r = 0.854$) of the yield variability and provided realistic functions for explaining the curvilinear influence of individual weather elements on wheat yield. The model is of a form that is readily adaptable for assessing, at any time during the crop development period, the influence of past and current weather on future expected yield. This could be useful for interpreting weather data in terms of crop production in weather and crop condition surveillance programs.

On a analysé les rendements du blé et les relevés météorologiques d'un demi-siècle à Swift Current, dans le sud-ouest de la Saskatchewan, afin de déterminer la réaction du blé (*Triticum aestivum* L.) aux changements des conditions météorologiques. A Swift Current, le temps a subi des changements peu apparents mais tout de même importants depuis les 50 dernières années. Les premières années ont connu une phase de perturbation: des périodes chaudes et sèches alternant avec des périodes fraîches et humides ont entraîné des fluctuations de rendement allant de mauvaises récoltes à des rendements records. Plus récemment, le temps a été plus uniforme: sec et frais, mais moins variable d'une année à l'autre. Les conditions ont donc été plus favorables à des rendements presque normaux mais moins variables. Les modèles simples de rendement-climat basés sur les précipitations et élaborés il y a deux décennies, ne sont plus applicables car les conditions de température et de précipitations ne coïncident plus avec les conditions antérieures. On a utilisé un modèle factoriel rendement-climat pour expliquer leurs relations complexes. Ce modèle comprend l'addition du produit de plusieurs fonctions quadratiques de divers éléments météorologiques. Ces derniers comprenaient les précipitations, les températures maximales et minimales, le rayonnement global estimé d'après la durée de l'insolation, l'évaporation en bac enterré et le temps comme indicateur du progrès de la technique. Une des fonctions contenait un terme relatif à l'état de la culture précédente. Les éléments qui ont été reconnus comme les plus importants ont été les précipitations durant la période de jachère, et pour mai, juin et août; les températures maximales pour juin et juillet; et le rayonnement global pour mai. Les progrès techniques sembleraient très peu influer sur les tendances de rendement du blé, abstraction faite des tendances météorologiques. Le modèle a rendu compte de 73% (r = 0.854) de la variabilité du rendement et a fourni des fonctions réalistes pour expliquer l'influence curvilinéaire de chaque élément météorologique sur le rendement du blé. Le modèle est d'une forme facilement adaptable pour évaluer, à tout moment durant la période de croissance, l'influence des conditions météorologiques passées et présentes sur les rendements futurs prévus. Cela pourrait s'avérer utile pour l'interprétation des données météorologiques en termes de production dans le cadre de programmes sur la surveillance des conditions météorologiques et de l'état des cultures.

The current apparent world food shortage, together with Canada's exceptionally low wheat reserve level, has resulted in renewed interest in a system for making preharvest appraisals of crop production. Such appraisals, made as early in the season as possible, could have considerable impact on decisions regarding type and acreage of crops sown, and on the orderly and economical marketing and movement of harvested products.

Weather on a day-to-day basis both before seeding and during the growing period has a pronounced influence on the development (Robertson 1968) and growth (Baier 1973) of a crop and on its final yield. Crop condition reports have long been a means of qualitatively appraising the progress of the crop from time to time. The recent unfavorable global weather conditions for crop production and the resulting depletion of stores of grain for international trade have sparked new interest in real-time weather and crop conditions surveillance projects.

Evaluating the effects of weather on crop production has been of interest to the agricultural industry for many decades. In southwestern Saskatchewan this problem and the effects of other environmental factors on wheat yield and quality have been the major concern of research scientists since the establishment of the Canada Department of Agriculture Research Station at Swift Current in 1922 (Campbell 1971).

Early records of farm production indicate that the limited rainfall in the area was the major factor affecting wheat yield. Staple and Lehane (1954) suggested that the yield of spring wheat (*Triticum aestivum* L.) could be related to rainfall by the simple relationship that 9.3 kg/ha would be produced for each millimeter of moisture that the crop used over 140 mm. Equated, this is:

$$\hat{Y} = 9.3\ (M - 140) \qquad (1)$$

where M is the sum of moisture conserved in the soil during the 21-mo summer-fallow period prior to the growing season, and the rainfall for the three summer months of May, June and July (Staple and Lehane 1952). By measuring soil moisture in summer fallow for a number of years it was found that the conserved moisture (CM) could be related to precipitation during different seasons of the summer-fallow period by the following equation:

$$CM = .36S_1 + .33S_2 + .13S_3 + .16S_4 \qquad (2)$$

where:

S_1 is precipitation during first fall (August to October);

S_2 is precepitation during first winter (November to April);

S_3 is precepitation during first summer and second fall (May to October);

and S_4 is precipitation during second winter (November to April).

Precipitation during the summer and fall periods is usually in the form of rain, most of which evaporates, but some penetrates to deeper soil layers. During the winter, the precipitation is usually in the form of snow that lies on the frozen soil until March or April when it melts. Much of this snowmelt runs off and is lost to wheat production.

This type of relationship is still used as a ready-reckoner of yield where rainfall is the limiting factor. Williams and Robertson (1965) used a modification of this for estimating the effects of precipitation on wheat production in the Canadian Great Plains. The limitations of this simple relationship soon became apparent when used under more humid conditions. Under such conditions, Williams (1973) improved yield estimates by including a potential evapotranspiration term. Baier (1973) reviewed recent developments in empirical models for relating wheat yield to the crop's meteorological environment.

This current study was undertaken to gain a better insight into the influence of growing season weather on crop production and to develop an improved numerical model for assessing the influence of advancing weather conditions on the final yield of wheat, having in mind its ultimate use in a weather and crop condition surveillance program.

DATA SOURCE

Wheat yields were obtained in experiments at the Swift Current Research Station (lat. 50°17′ N; long. 107°45′ W; elevation 762 m) since 1922. Over the years, improved cultivars and improved cultural techniques were employed in the tests in order to obtain the best possible yields. In recent years, fertilizer (11–48–0) at rates between 30 and 45 kg/ha was used to compensate for declining fertility of the soil.

Precipitation and daily extremes of temperature were measured according to the standard procedures of the Atmospheric Environment Service which are based on recommendations of the World Meteorological Organization.

Evaporation was measured daily by means of a buried pan, 1.22 m in diameter (Robertson 1964).

ESTIMATE OF GLOBAL RADIATION

Global radiation was not measured prior to 1962 at Swift Current. However, measurements of the duration of bright sunshine as recorded by a burning-glass sunshine instrument were available for the whole period of the investigation. A mathematical model was developed for estimating average monthly global radiation values from average monthly bright sunshine.

An equation of the following form was used for this purpose:

$$Q_T = Q_o\,[A\,n/N + B\,(1 - n/N)] \quad (3)$$

where Q_T is monthly average global radiation in g cal/cm^2/day;

Q_o is the extra terrestrial radiation in g cal/cm^2/day on the 15th of the month (Robertson and Russelo 1968);

N is the duration of daylight, in hours, on the 15th of the month;

n is monthly average of the daily duration of bright sunshine in hours;

A is the average monthly atmospheric transmissivity when the sky is clear ($n = 1$); and

B is the average monthly atmospheric transmissivity when the sky is overcast ($n = 0$).

The coefficients A and B vary from month to month depending on the turbidity of the atmosphere and density of the clouds. This variation is seasonal and can be represented by making these coefficients harmonic functions (Robertson 1971):

$$A = a_0 + a_1 \sin\theta + a_2 \cos\theta + a_3 \sin 2\theta + a_4 \cos 2\theta + \ldots$$

$$B = b_0 + b_1 \sin\theta + b_2 \cos\theta + b_3 \sin 2\theta + b_4 \cos 2\theta + \ldots$$

The coefficients in these harmonic functions were evaluated by multiple regression using a stepwise regression program with regression through the origin (Snedecor and Cochran 1968). Monthly data for the years 1966–1970 inclusive were used.

Monthly data for the years 1962–1965 inclusive, 1971, and 1972 were used for verifying the predictive value of the equation, and the coefficients determined from the 1966 to 1970 data.

It required only seven harmonic terms (Table 1) and nine regression coefficients to specify the annual cycle of the transmission coefficients A and B (Table 2). To determine coefficients on a monthly basis without harmonic analysis would have required 24 coefficients and a separate determination for each month. The multiple correlation coefficient (R) for the regression model was 0.996, the coefficient of determination (100 R^2) was 99.2%, and the standard error of estimate was 15.0 g cal/cm^2/day for 60 sets of values.

For the test data, 1962–1965, 1971, and 1972, the simple correlation coefficient between observed radiation and radiation calculated by the coefficients (Table 2) and equation 3 was 0.993, the coefficient of determination was 98.6%, and the standard error of estimate was 21.3 g cal/cm^2/day for 72 sets of values. These statistics indicated that either the harmonic equation or the derived monthly transmissivity values (Table 2) could be used for estimating monthly global radiation from duration of bright sunshine measurements with reasonable accuracy.

Table 1. Regression coefficients (RC) as determined by stepwise regression and the term-by-term trend in the standard error of estimate (SEE) of daily global radiation

Variable	Regression coefficient	Standard error of RC	SEE of global radiation (g cal/cm²/day)
$Q_0 \cdot \frac{n}{N}$	$a_0 =$ .793	.0295	64.7
$Q_0 \cdot \left(1 - \frac{n}{N}\right)$	$b_0 =$ .313	.0250	28.2
$Q_0 \cdot \left(1 - \frac{n}{N}\right) \cdot \sin\theta$	$b_1 =$ .0591	.0291	23.2
$Q_0 \cdot \frac{n}{N} \cdot \cos\theta$	$a_2 =$ .1144	.0172	19.7
$Q_0 \cdot \left(1 - \frac{n}{N}\right) \cdot \sin 2\theta$	$b_3 =$ .0458	.0142	18.2
$Q_0 \cdot \frac{n}{N} \cdot \sin\theta$	$a_1 =$ .0622	.0308	17.3
$Q_0 \cdot \left(1 - \frac{n}{N}\right) \cdot \cos 4\theta$	$b_8 =$ .0726	.0289	16.6
$Q_0 \cdot \frac{n}{N} \cdot \cos 4\theta$	$a_8 = -.0396$	.0279	16.2
$Q_0 \cdot \frac{n}{N} \cdot \cos 5\theta$	$a_{10} =$ .0139	.00996	16.0
$Q_0 \cdot \frac{n}{N} \cdot \cos 2\theta$	$a_4 = -.0135$†	.0154	16.1

†Not used in regression equation.

ANALYSES, RESULTS AND DISCUSSION

Trends in Weather and Yield

Before discussing the development of the yield–weather model and analyzing the influence of weather on yield, it will be advantageous to study the changes in weather and yield which have taken place over the 50-yr period of this investigation.

The variability and trend of the summer climate at Swift Current can best be depicted by a graph showing the accumulated departure from normal for rainfall (Fig. 1) and for temperature compared with rainfall (Fig. 2). The striking feature is the net accumulation of above-normal departures from 1886 to 1916 for summer rainfall, and from 1886 to 1941 for summer maximum temperature, and the rapid net accumulation of below-normal departures from these peaks to the present time. Superimposed on this general trend are shorter period trends of a few to several years duration. Another important feature is the fact that prior to 1962, dry periods were usually associated with hot summers and vice versa, whereas from 1962 to date, dry summers were accompanied by cooler temperatures.

This latter feature was more strikingly illustrated when June and July monthly averages of the daily maximum temperatures were correlated with the total growing season rainfall. For this purpose the 50-yr

Table 2. Monthly averages of the atmospheric transmissivity for clear and for overcast skies at Swift Current as determined by harmonic regression

Month	Average transmissivity: Clear sky	Average transmissivity: Overcast sky
Jan.	.931	.346
Feb.	.931	.367
Mar.	.815	.444
Apr.	.802	.288
May	.757	.266
June	.625	.385
July	.695	.286
Aug.	.695	.265
Sept.	.691	.326
Oct.	.823	.185
Nov.	.869	.207
Dec.	.882	.385

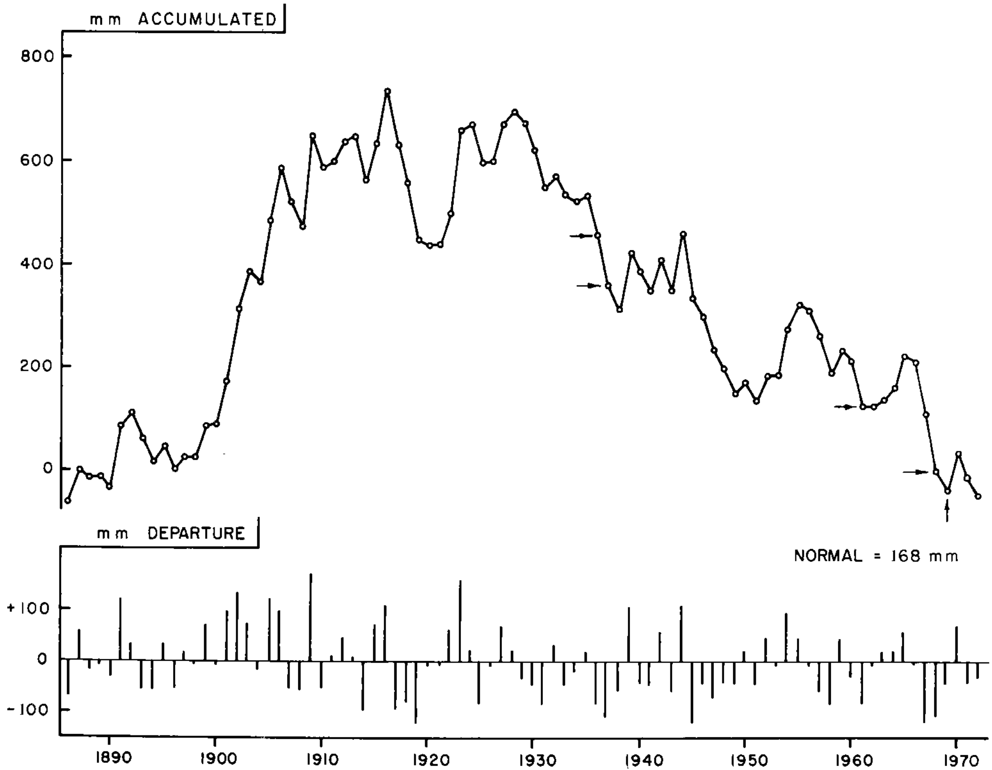

Fig. 1. Yearly departure of total rainfall from normal for May, June, and July and its accumulated departure from normal at Swift Current, 1886 to 1972. (Arrows point to drought years 1936, 1937, 1961, 1968, and 1969.)

period used in this study was divided into three subperiods: 1923–1939, 1940–1955, and 1956–1972. The simple correlations for June maximum temperatures and growing season rainfall for the three subperiods were −0.52, −0.68, and −0.15, respectively, while for July maximum temperatures and growing season rainfall they were −0.61, −0.21, and 0.04, respectively. This deterioration of the negative relationship between growing season rainfall and temperature has had a profound influence on the response of wheat yield to rainfall when considered alone during the past few years, relative to that for earlier years.

These trends and anomalies in the weather are quite clear in retrospect. Analyses by harmonic and Markov chain methods, however, failed to reveal any statistically worthwhile cycles, persistence or compensation that could be used for predictive purposes. In other words, the weather events for the next month or the next season are purely random events relative to past events and cannot be predicted by statistical methods.

Wheat yield (Table 3) has increased slowly over the three subperiods and has become less variable. It will be shown that, in general, this is a result of the changing weather pattern.

As a ready-reckoner for relating wheat yield to precipitation, Staple and Lehane (1954) suggested an equation of the form (CD is the coefficient of determination = R^2 and SEE is the standard error of estimate):

$$\hat{Y} = 9.3\ (M - 140) \qquad (4)$$
$$\text{CD} = 69\%$$

where M, the available moisture for evapotranspiration, is the sum of the conserved moisture, equation 2, and the growing season rainfall.

Similar regression equations for the three subperiods mentioned above are:

1923–1939:

$$\hat{Y} = 6.8\ (M - 107) \quad (5)$$
$$CD = 58\%;\ SEE = 499\ kg/ha$$

1940–1955:

$$\hat{Y} = 10.7\ (M - 148) \quad (6)$$
$$CD = 80\%;\ SEE = 372\ kg/ha$$

1956–1972:

$$\hat{Y} = 1.8\ (M + 635) \quad (7)$$
$$CD = 7\%;\ SEE = 366\ kg/ha.$$

Staple and Lehane (1954) also showed that yield was related to growing season rainfall (GSR), and conserved moisture, by a regression equation:

$$\hat{Y} = 10.4\ (GSR + 0.68\ CM - 120) \quad (8)$$

The coefficient of CM is dimensionless and indicates that conserved moisture is only 0.68 as efficient as growing season rainfall for producing a kilogram of wheat.

Similar equations for the three subperiods of this study are:

1923–1939:

$$\hat{Y} = 3.9\ (GSR + 5.40\ CM - 461) \quad (9)$$
$$CD = 67\%;\ SEE = 456\ kg/ha$$

1940–1955:

$$\hat{Y} = 10.3\ (GSR + 1.32\ CM - 182) \quad (10)$$
$$CD = 81\%;\ SEE = 377\ kg/ha$$

1956–1972:

$$\hat{Y} = 1.6\ (GSR + 2.59\ CM + 583) \quad (11)$$
$$CD = 9\%;\ SEE = 374\ kg/ha.$$

The apparent dependence of yield on precipitation is quite strong in the two early subperiods from 1923 to 1955 as is indicated by the high values of CD. This is probably caused by two factors: firstly, the larger variability of growing season rainfall in the early years (Table 3), and secondly, the high negative correlation between growing season rainfall and June and July maximum temperatures (Table 4).

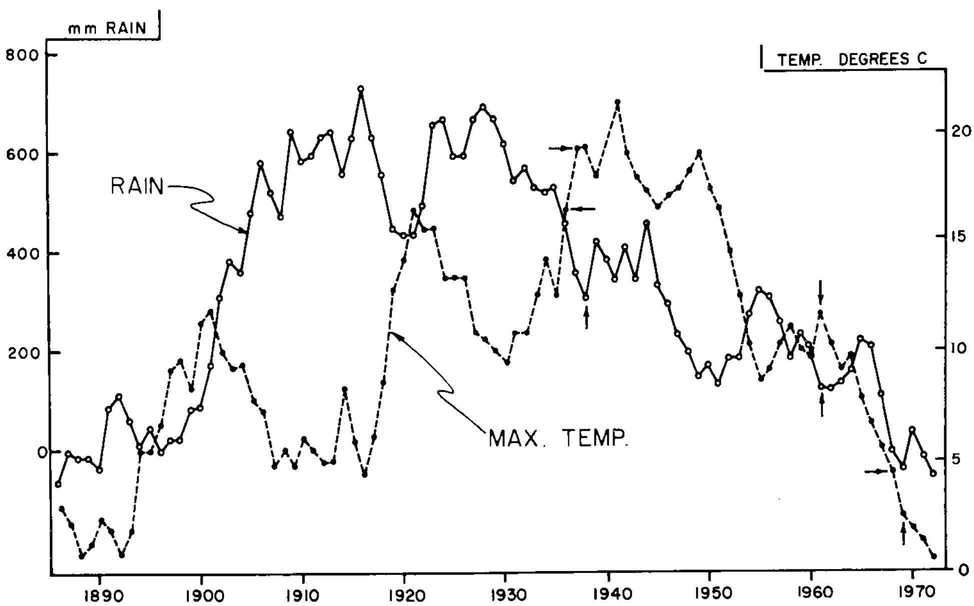

Fig. 2. Comparing the accumulated departure from normal of total rainfall and average maximum of the daily temperatures for May, June, and July at Swift Current, 1886 to 1972. (Arrows point to drought years 1936, 1937, 1961, 1968, and 1969.)

Table 3. Averages (A) and standard deviations (SD) of yield and environment factors by subperiods at Swift Current, Saskatchewan

		1923-39	1940-55	1956-72
Yield (kg/ha)	A	1116	1447	1599
	SD	746	803	368
Conserved moisture (mm)	A	109	122	114
	SD	20	23	23
Growing season rain (mm)	A	165	163	147
	SD	71	64	56
Growing season evaporation (mm)	A	488	437	460
	SD	94	69	58
May maximum temperature (C)	A	18.2	17.6	17.5
	SD	3.1	2.3	2.1
June maximum temperature (C)	A	21.7	20.8	22.1
	SD	2.3	1.7	1.9
July maximum temperature (C)	A	26.8	26.2	25.3
	SD	2.0	2.1	1.8
May minimum temperature (C)	A	4.1	3.5	4.1
	SD	2.1	1.7	.9
June minimum temperature (C)	A	8.6	8.1	8.9
	SD	1.4	1.1	1.5
July minimum temperature (C)	A	11.3	11.3	11.3
	SD	1.2	1.2	1.2
May global radiation	A	476	479	507
(g cal/cm^2/day)	SD	50	35	30
June global radiation	A	570	508	525
(g cal/cm^2/day)	SD	49	17	19
July global radiation	A	526	539	555
(g cal/cm^2/day)	SD	31	33	33

This breakdown with time in the relationship between yield and precipitation is illustrated graphically in Fig. 3. Although the total effective moisture (conserved summerfallow precipitation plus growing season rainfall) shows little change in variability with progressing years, yields have become much less variable (Table 3).

(Note: Although not included in this analysis, the weather and yield for 1973 followed the general trend set during the past decade or more (Table 18). Growing season rainfall of 50 mm was the lowest on record. Nevertheless, temperatures were about normal, which prevented high moisture and heat stress in the crop. The resulting yield (1,480 kg/ha) was surprisingly high considering the growing season rainfall.)

Another important change in the climate over the past half century was the decrease in the variability of certain weather elements to which wheat yield is sensitive. Growing season rainfall and evaporation; May, June and July maximum temperatures; and May and June global radiation have all undergone a decrease in variability over the three subperiods, as indicated by their standard deviations (Table 3). Several of the elements also show a downward trend in their absolute values.

The increasing yield with time (Table 3), in spite of decreasing growing season rainfall, was probably due to more favorable (cooler) temperatures during May and July (Campbell and Read 1968; Thorne et al. 1968) which were associated with the lower rainfall. Yield variability also decreased in the latest subperiod, probably as a result of the lower variability of the growing season rainfall and maximum temperatures. Obviously, factors other than precipitation alone must be considered when assessing the influence of seasonal weather on yield.

Table 4. Simple correlation coefficient between yield and crop sensitive atmospheric environmental elements by periods at Swift Current

		(1)	(2)	(3)	(4)	(5)	(6)	(7)
				1923-1939				
Yield	(1)	1.00						
Conserved moisture	(2)	0.76**	1.00					
Growing season rainfall	(3)	0.69**	0.59**	1.00				
Growing season evaporation	(4)	−0.82**	0.59**	−0.73**	1.00			
May maximum temperature	(5)	−0.16	−0.04	−0.20	0.52*	1.00		
June maximum temperature	(6)	−0.76**	−0.42	−0.52*	0.65**	0.07	1.00	
July maximum temperature	(7)	−0.63**	−0.34	−0.61**	0.68**	0.23	0.32	1.00
				1940-1955				
Yield	(1)	1.00						
Conserved moisture	(2)	0.38	1.00					
Growing season rainfall	(3)	0.80**	0.03	1.00				
Growing season evaporation	(4)	−0.71**	−0.49*	−0.48*	1.00			
May maximum temperature	(5)	−0.22	−0.05	−0.19	0.62**	1.00		
June maximum temperature	(6)	−0.49*	−0.39	−0.21	0.59**	0.42	1.00	
July maximum temperature	(7)	−0.69*	−0.17	−0.68**	0.39	−0.04	0.15	
				1956-1972				
Yield	(1)	1.00						
Conserved moisture	(2)	0.21	1.00					
Growing season rainfall	(3)	0.18	−0.20	1.00				
Growing season evaporation	(4)	−0.27	−0.19	0.59**	1.00			
May maximum temperature	(5)	0.18	−0.06	−0.37	0.37	1.00		
June maximum temperature	(6)	−0.27	−0.08	0.04	0.30	0.04	1.00	
July maximum temperature	(7)	−0.23	0.20	−0.15	0.51*	−0.09	−0.13	

*,**Correlation coefficient statistically significant at 5 and 1% levels, respectively.

Monthly Statistics and Simple Correlations

A better understanding of the relative importance of various weather elements that influence the yield of spring wheat can be obtained by studying certain statistics for the elements used in the regression analyses together with their interactions as determined by simple correlation analysis (Tables 5-8). June was the month of highest rainfall and rainfall variability, whereas May was the driest month. July was the warmest month, but May had the greatest temperature variability. Global radiation was highest in July, although daylength was longest and noontime sun was at its highest elevation about 22 June. Global radiation was most variable in May, and least in June.

The correlation of −0.71 between yield and July pan evaporation was the highest

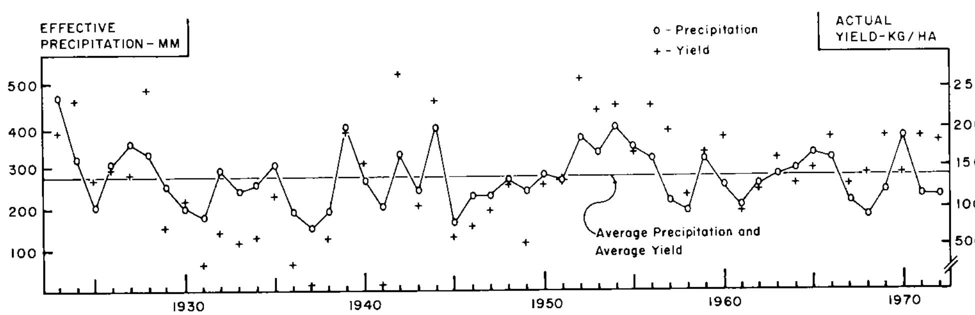

Fig. 3. The trend of the effective precipitation (conserved moisture on fallow plus May, June and July rainfall) and the yield of spring wheat at Swift Current, 1923 to 1972.

Table 5. Simple correlation coefficients and other statistical data for *May* weather elements, Swift Current, 1923–1972

		(1)	(2)	(3)	(4)	(5)	(6)	(7)
				Correlation				
Yield	(1)	1.00						
Previous yield estimate, Y_{CR}	(2)	0.52**	1.00					
Total monthly rainfall	(3)	0.32**	0.14	1.00				
Avg daily maximum temp.	(4)	−0.16	−0.07	−0.41**	1.00			
Avg daily minimum temp.	(5)	−0.14	−0.19	−0.07	0.71**	1.00		
Total pan evaporation	(6)	−0.33*	−0.37**	−0.53**	0.81**	0.56**	1.00	
Avg daily global radiation	(7)	0.06	0.15	−0.53**	−0.08	0.37**	0.56**	1.00
				Other statistics				
	Units:	kg/ha	kg/ha	mm	C	C	mm	g cal/ cm^2/day
Average		1386	1386	36	17.8	3.9	135	487
Standard deviation		683	351	27	2.5	1.6	34	41
Range: Low		0	869	3	12.2	−0.3	60	354
High		2677	2097	140	23.4	7.8	219	562

*·**Correlation coefficient statistically significant at 5 and 1% levels, respectively.

simple correlation between yield and any single weather element. Next highest correlation was −0.61 with July maximum temperature, followed by −0.55 for June pan evaporation, −0.50 for June maximum temperature, and +0.43 for June rainfall. Rainfall was negatively correlated with maximum temperature, pan evaporation and global radiation in all 4 mo.

Pan evaporation was related negatively to rainfall and positively to maximum temperatures during all 4 mo. Yield has a correlation with rainfall and maximum temperature that is opposite to that of pan evaporation. This probably explains the large simple correlation between yield and pan evaporation.

Table 6. Simple correlation coefficients and other statistical data for *June* weather elements, Swift Current, 1923–1972

		(1)	(2)	(3)	(4)	(5)	(6)	(7)
				Correlation				
Yield	(1)	1.00						
Previous yield estimate, $\hat{Y}_5$	(2)	0.61**	1.00					
Total monthly rainfall	(3)	0.43**	0.11	1.00				
Avg daily maximum temp.	(4)	−0.50**	−0.39**	−0.24	1.00			
Avg daily minimum temp.	(5)	−0.24	−0.25	0.14	0.76**	1.00		
Total pan evaporation	(6)	−0.55**	−0.45**	−0.38**	0.80**	0.40**	1.00	
Avg daily global radiation	(7)	−0.16	−0.03	−0.22	0.66**	0.48**	0.60**	1.00
				Other statistics				
	Units:	kg/ha	kg/ha	mm	C	C	mm	g cal/ cm^2/day
Average		1386	1321	75	21.6	8.5	146	513
Standard deviation		683	391	43	2.1	1.3	32	19
Range: low		0	569	16	16.9	5.6	93	473
high		2677	2229	186	27.1	11.9	223	574

**Correlation coefficient statistically significant at 1% level.

Table 7. Simple correlation coefficients and other statistical data for *July* weather elements, Swift Current, 1923–1972

		(1)	(2)	(3)	(4)	(5)	(6)	(7)
				Correlation				
Yield	(1)	1.00						
Previous yield estimate, $\hat{Y}_6$	(2)	0.76**	1.00					
Total monthly rainfall	(3)	0.30*	0.13	1.00				
Avg daily maximum temp.	(4)	−0.61**	−0.38	−0.46**	1.00			
Avg daily minimum temp.	(5)	−0.34*	−0.14	−0.12	0.61**	1.00		
Total pan evaporation	(6)	−0.71**	−0.61**	−0.51**	0.81**	0.36**	1.00	
Avg daily global radiation	(7)	−0.12	0.03	−0.30*	0.30*	0.60**	0.36**	1.00
				Other statistics				
	Units:	kg/ha	kg/ha	mm	C	C	mm	g cal/ cm^2/day
Average		1386	1355	47	26.1	11.3	181	540
Standard deviation		683	495	29	2.1	1.1	34	34
Range: low		0	351	5	21.6	9.3	119	464
high		2677	2465	122	32.1	14.2	265	608

*,**Correlation coefficient statistically significant at 5 and 1% levels, respectively.

The Factorial Yield–Weather Model

Robertson (1968) showed how photoperiod, maximum temperature and minimum temperature could be used in one integrated equation combining the addition and multiplication of individual weather elements for evaluating their influence on the rate of wheat development. Baier (1973) used a modification of this product or factorial model in a study of the influence of various weather elements on wheat yield. For the purpose of this paper a simplified version of Baier's model was used. The model called the factorial yield–weather model (FYWM) was:

$$\hat{Y}_t = V(\hat{Y}_{t-1}, P_t) \times V_2(T_1)_t \times V_3(T_2)_t \times V_4(Q)_t \quad (12)$$

where $\hat{Y}_t$ is the yield (or really the condition of the crop in terms of the

Table 8. Simple correlation coefficients and other statistical data for *August* weather elements, Swift Current, 1923–1972

		(1)	(2)	(3)	(4)	(5)	(6)	(7)
				Correlation				
Yield	(1)	1.00						
Previous yield estimate, $\hat{Y}_7$	(2)	0.83**	1.00					
Total monthly rainfall	(3)	−0.17	−0.06	1.00				
Avg daily maximum temp.	(4)	−0.23	−0.27*	−0.60**	1.00			
Avg daily minimum temp.	(5)	−0.16	−0.20	−0.06	0.63**	1.00		
Total pan evaporation	(6)	−0.34*	−0.40**	−0.63**	0.87**	0.48**	1.00	
Avg daily global radiation	(7)	0.17	0.15	−0.54**	0.61**	0.43**	0.55**	1.00
				Other statistics				
	Units:	kg/ha	kg/ha	mm	C	C	mm	g cal/ cm^2/day
Average		1386	1374	41	25.2	9.9	166	445
Standard deviation		683	566	27	2.1	1.4	35	33
Range: low		0	287	3	21.6	7.1	96	367
high		2677	2897	115	30.1	13.2	230	518

*,**Correlation coefficient statistically significant at 5 and 1% levels, respectively.

yield that it will support) estimated at the time, t, of a given crop stage;

$\hat{Y}_{t-1}$ is the yield estimated at the end of the previous stage (antecedent crop condition);

P_t is the total precipitation between stages;

T_1 is the average of the daily maximum temperatures during the period between stages;

T_2 is the average of the daily minimum temperatures during the period between stages;

Q is the average daily global radiation during the period between stages;

and where the functions, V_1, etc., are:

$$V_1(\hat{Y}_{t-1}, P_t) = b_0 + b_1\hat{Y}_{t-1} + b_2P_t \quad (13)$$

$$V_2(T_1) = p_0 + p_1T_1 + p_2T_1^2 \quad (14)$$

$$V_3(T_2) = q_0 + q_1T_2 + q_2T_2^2 \quad (15)$$

$$V_4(Q) = r_0 + r_1Q + r_2Q^2 \quad (16)$$

where b, p, q and r are regression coefficients to be evaluated for each crop period. The quadratic functions permit an evaluation of the optimum values, as well as possible values of the lower and upper critical limits, for the temperatures and for global radiation.

This FYWM contains some desirable characteristics which others neglect. As well as making use of readily available weather data, it uses these in realistic combinations to emphasize the modifying influence, particularly of temperature and radiation. For example, some simple models use linear multiple regression equations in which several elements for different months are all additive. The general form of such an equation is:

$$\hat{Y} = a_0 + a_1X_1 + a_2X_2 + a_3X_3 + \ldots \quad (17)$$

In this type of model it is inherently assumed that one element (e.g., June temperature) can replace another (e.g., July rainfall) at an earlier or later date. Furthermore, such an equation contains no provision for limiting factors (threshold values). A zero rainfall or a threshold temperature does not result in zero growth of the crop since some other factor in the expression replaces the limiting ones.

It appears more logical to consider certain weather elements (temperature and radiation) as modifiers of yield and other elements (rain and evaporation) as a budget process which add to, or take away from, yield. Thus the general form of the equation used here is to add rainfall to the previous estimate of yield and modify this sum by functions of temperature and radiation (equations 13-16). The process should be integrated over short periods, but the practical period used here was a month. This provides a unique method for modifying the expected yield at the end of the last period by the favorable or unfavorable temperature and radiation conditions of the current period. This unique built-in feature permits a step-by-step monitoring of the progressive crop condition and its changes in response to the progressive changes in the weather elements. Theoretically, the steps can be made as short as possible, but there is a practical limit dictated by economy and accuracy achieved in the results.

At Swift Current, the development and growth of spring wheat planted on summer fallow follows a monthly pattern (Robertson 1968). Sowing takes place in late April or early May. By mid-May the crop has usually emerged and by the end of the month it has reached the fifth-leaf or beginning of internode elongation stage. During June, the crop passes through the period of grand growth and is usually headed out by the end of the month. Early in July, anthesis takes place followed by kernel development. Soft dough is reached by the end of the month. August is the month of ripening and the crop is ready for harvest about mid-month. Since the calendar months coincide with the natural major crop stages, it was appropriate to consider only monthly crop periods as well as monthly averages of weather elements in this study at Swift Current.

One advantage of this form of the equation is that it permits the evaluation of the influence on expected yield, $\hat{Y}_t$, of weather factors up to a certain specific time, t. The earliest practical evaluation of the expected yield is at the end of April, using the moisture conserved during the 21-mo summer-fallow period. This estimation was used as the initial value of $\hat{Y}_t$, i.e., for $\hat{Y}_{t-1}$ in equation 12.

The evaluation of the regression coefficients in equations 13–16 was accomplished by progressively setting:

$$Y_0 = b_0W_1 + b_1W_1\hat{Y}_{t-1} + b_2W_1P_t \quad (18)$$

$$Y_0 = p_0W_2 + p_1W_2T_1 + p_2W_2T_1^2 \quad (19)$$

$$Y_0 = q_0W_3 + q_1W_3T_2 + q_2W_3T_2^2 \quad (20)$$

$$Y_0 = r_0W_4 + r_1W_4Q + r_2W_4Q^2 \quad (21)$$

where Y_0, the dependent variable, is the observed yield and

$$W_1 = V_2V_3V_4$$

$$W_2 = V_1V_3V_4$$

$$W_3 = V_1V_2V_4$$

$$W_4 = V_1V_2V_3$$

The independent variables then are either the W's alone or the product of the W's and their accompanying yield or weather elements.

Each of these equations is of the general form of a multiple regression equation, and the coefficients can be determined by regression analysis for the situation where the Y_0-intercept is assumed to pass through the origin (Snedecor and Cochran 1968). It was necessary to use an iterative technique on the four equations 18 to 21, similar to the procedure described by Robertson (1968), Baier (1973) and Amores-Vergara (1973). Initially the values of W_1, W_2, W_3, and W_4 were set to unity. This procedure was repeated for each crop period or month starting with May. Once stable values were obtained for all regression coefficients, the whole procedure was repeated in turn for June, July and August weather elements. In each case, the value for $\hat{Y}_{t-1}$ (equation 12) was the estimated value, calculated by means of the final regression equation determined for the previous month.

At each step in the iteration procedure, the coefficients in the functions V_2, V_3, etc. were normalized in such a manner that when the long-term average or normal value of the weather element was used in the regression equation, the functions $V_2 = V_3 = V_4 = 1$. The normalized regression coefficients were determined by multiplying each regression coefficient in equations 18-21 by the ratio of the average actual yield to the average yield estimated by using the equation in question and the average values of the variables involved.

Likewise, the coefficients in the function V_1 were normalized so that when the average values of rainfall and of the yield for the previous period were introduced, the function V_1 = average yield. This normalization was necessary in order that the individual regression coefficients would converge regularly to a stable value.

Earliest Yield Estimate

The first step in evaluating the coefficients in the factorial weather model, equation 12,

Table 9. Simple correlation coefficients and other statistical data for the summer fallow period Swift Current — 1923–72

		(1)	(2)	(3)	(4)	(5)
			Correlation			
Yield	(1)	1.00				
First fall precipitation	(2)	0.18	1.00			
First winter precipitation	(3)	0.29	−0.11	1.00		
First summer precipitation	(4)	0.34*	0.14	0.06	1.00	
Second winter precipitation	(5)	0.26	0.20	−0.03	0.08	1.00
			Other statistics			
	Units	kg/ha	mm	mm	mm	mm
Average		1386	93	99	250	99
Standard deviation		683	40	33	73	33
Range: low		0	24	36	125	36
high		2677	196	181	429	181

*,**Correlation coefficient significant at 5 and 1%.

was to consider the influence of the precipitation during the summer-fallow period. The simple correlation between yield and seasonal precipitation during the summer-fallow period was low (Table 9). The highest correlation coefficient, and only significant one, was 0.34 for the precipitation during the first summer, S_3. Nevertheless, sufficient experimental evidence exists to indicate that precipitation during other seasons makes important contributions to stored moisture and should not be ignored (Staple and Lehane 1952).

A simple regression of observed yield and calculated conserved moisture, equation 2, using data for 50 yr revealed that:

$$\hat{Y}_{CM} = -247 + 14.3\ CM \qquad (22)$$

$$\text{CD} = 22\%;\ \text{SEE} = 610\ \text{kg/ha.}$$

By substituting the expression for CM (equation 2), in equation 22 a new equation and a new set of coefficients were determined, thus:

$$\hat{Y}_{CM} = -247 + 5.1\ S_1 + 4.7\ S_2 + 1.9\ S_3 + 2.3\ S_4 \qquad (23)$$

The coefficients in equation 2 were determined by actual measurements of soil moisture during the period 1939–1950 (Staple and Lehane 1952). To test the usefulness of these coefficients during the longer period used in the current study (1923–1972), a multiple regression analysis was performed relating yield to the different seasons of the summer-fallow period. The resulting regression equation was:

$$\hat{Y}_{CR} = -543 + 2.2\ S_1 + 6.1\ S_2 + 2.7\ S_3 + 4.6\ S_4 \qquad (24)$$

$$\text{CD} = 26.5\%;\ \text{SEE} = 592\ \text{kg/ha.}$$

The coefficients in equation 24 differ somewhat from those in equation 23. In view of the fact that the coefficients of S_2, S_3, and S_4 are statistically significant (Table 10), it was decided to use equation 24 as the best estimate of the yields at the end of April for input to equation 12 as the initial value of $\hat{Y}_{t-1}$.

Evaluating the Coefficients in the Factorial Yield–Weather Model

The coefficients in the model were evaluated by using equations 18 to 21 and an iterative procedure described by Robertson (1968), Baier (1973) and Amores-Vergara (1973). As none of the equations 18 to 21 contains a coefficient for intercept, regression was assumed to pass through the origin (Snedecor and Cochran 1968). The iterative regression technique was performed by relating yield to weather elements for each month independently, starting with May and working through to August. Thus, the weather data for each month were treated as independent from those for any other month. For the 4 mo of the growing period of the crop, there were some 52 coefficients to be evaluated with only 50 sets (years) of data. This was readily accomplished with the factorial model, since each regression analysis of each interaction involved only three independent variables and the evaluation of only three regression coefficients at one time. This apparent paradox was accomplished by progressively calculating a new set of independent variables for each new regression calculation. Statistically nonsignificant regression coefficients as determined by the t-test were set to zero and nonsignificant; whole functions, as determined by the reduction in the standard error of estimate, were set to unity.

The final regression coefficients and their standard errors are shown in Table 10. Although several of these coefficients have large standard errors, their inclusion in the equation did improve the yield estimate as measured by the standard error of estimate and the coefficient of determination between the observed yield, Y_0, and the estimated yield, $\hat{Y}_t$. (Note: The subscript t, of $\hat{Y}_t$ indicates the number of the month for which the yield is estimated, e.g., $\hat{Y}_8$ is the estimated yield at the end of August.)

During the iteration and regression analysis, some elements did not improve the regression and these were eliminated during the process. Those so eliminated were minimum temperatures for May and June, the square terms for May, July and August

Table 10. Final normalized regression coefficients (RC), intercepts (IRCT) and their standard errors (SE)

For weather element	IRCT	RC	SE
Summer-fallow period:	−543		359
First fall		2.23	2.24
First winter		6.11	2.65
First summer		2.65	1.21
Second winter		4.63	2.71
May:	−75		330
Yield estimate at end of April		0.796	0.224
Rainfall		9.85	3.22
Max. temp.	−1.01		1.32
Max. temp.		0.236	0.265
Max. temp. squared		−0.00693	0.00759
Global radiation	−0.200		0.582
Global radiation		0.00246	0.00124
Global radiation squared		-	
June:	−287		248
Yield estimate at end of May		0.904	0.163
Rainfall		6.44	1.52
Max. temp.	−6.40		2.39
Max. temp.		0.717	0.252
Max. temp. squared		−0.0173	0.00596
Global radiation	41.26		29.3
Global radiation		−0.1565	0.115
Global radiation squared		0.000152	0.000112
July:	134		194
Yield estimate at end of June		.869	0.110
Rain fall		1.60	1.80
Max. temp.	−2.017		2.82
Max. temp.		0.290	0.915
Max. temp. squared		−0.00668	0.00691
Global radiation	1.396		0.507
Global radiation		−0.000733	0.000940
Global radiation squared		-	
Min. temp.	1.533		0.649
Min. temp.		−0.0471	0.0428
Min. temp. squared		-	
August:	243		148
Yield estimate at end of July		1.000	0.0910
Rainfall		−5.66	1.89
Max. temp.	1.55		0.522
Max. temp.		−0.0217	0.0147
Max. temp. squared		-	
Global radiation	1.53		0.425
Global radiation		−0.001185	0.000962
Global radiation squared		-	
Min. temp.	0.684		3.97
Min. temp.		0.0320	0.0243
Min. temp. squared		-	

global radiation, and the square term for July minimum temperature.

Pan evaporation was introduced as a fifth function,

$$V_5\ (E) = s_0 + s_1E + s_2E^2,$$

and tested for contribution to the regression. To test whether or not it might contribute to the moisture balance, it was also introduced in the model as a term in $V_1 = b_0 + b_1\hat{Y}_{t-1} + b_2P_t + b_3E_t$ (equation 13).

In neither position did pan evaporation contribute to improvement of the regression.

June rainfall is quite variable and sometimes may be more than the soil can absorb or the crop use (Table 6). In order to take into account a possible decreasing effect of higher June rainfalls, a square term was introduced in $V_1 = b_0 + b_1\hat{Y}_5 + b_2P_6 + b_3P_6^2$ (equation 13).

This square term did not improve the regression at that stage, so the term was omitted.

Finally, time as a measure of technology, t_Y, was introduced in two places in the model:

(1) as an additive, non-linear correction to the estimated yield at the end of August:

$$Y_0 = p_0 + p_1\hat{Y}_8 + p_2t_Y + p_3t_Y^2 \quad (25)$$

(2) as a non-linear factorial correction applied to the yield estimate at the end of August:

$$Y_0 = \hat{Y}_8\ (q_0 + q_1t_Y + q_2t_Y^2) \quad (26)$$

Only the square term, t_Y^2, in equation 25 improved the regression and this only slightly:

$$Y_0 = -25 + 0.971\ \hat{Y}_8 + 0.0865\ t_Y^2$$

SE of RC = 0.089 0.068

CD = 72.9 73.8 (%)

SEE = 355 kg/ha.

Over the 50-yr period this amounts to an increase of only 216 kg/ha. It is quite possible that technology contributed more to the yield trend than is indicated here. Much of the improvement due to technology, however, has probably been offset by soil deterioration, both physical and chemical, over the period.

Table 11. Month-by-month improvement in the estimated yield as indicated by the coefficient of determination (CD = 100 R^2) and the standard error of estimate (SEE)

Regression to the end of		CD (%)	SEE (kg/ha)
April	$\hat{Y}_{CR}$	26.5	592
May	$\hat{Y}_5$	37.1	545
June	$\hat{Y}_6$	57.7	451
July	$\hat{Y}_7$	70.2	377
August	$\hat{Y}_8$	72.9	355

The month-by-month improvement in the yield estimate is shown in Table 11. Regression to the end of April, that is, using only precipitation during the summer-fallow period, accounted for 26.5% reduction in the error variance of the estimated yield. On this date, the standard error of estimate was 592 kg/ha. After taking into account, in the regression, all weather elements during the growing season, these statistics improved to 72.9% and 355 kg/ha. The greatest improvement was achieved by adding in the weather elements during June, when crop growth was more sensitive to weather phenomena (i.e., rainfall and maximum temperature).

The Influence of Individual Weather Elements

The relative importance of weather elements was evaluated by the following unique method. Using the final regression equation and coefficients for August, each element in turn was substituted by its normal or average value for the 50 yr of the study. This normalizing technique removed the variation of that particular element and its effect on the estimated yield, without passing this effect on through some other related element. The resulting estimated yield was correlated with actual yield using data for the 50-yr period. The resulting coefficients of determination were subtracted from the overall coefficient of determination when no weather element was normalized. This difference was used as a relative measure of the contribution of that element to the overall total. For reasons that are not readily apparent, the total of these differences for all normalized elements involved did not equal the overall coefficient

Table 12. Reduction in the coefficient of determination (CD) for yield as calculated by the factorial yield weather model when each weather element in turn was set equal to its normal value (normalized)

Element normalized	Reduction in CD (%)	Order of importance
None	0	
Preseason precipitation	14.0	2
May		
Rainfall	7.9	4
Maximum temperature	.8	11
Global radiation	4.0	7
June		
Rainfall	17.3	1
Maximum temperature	8.7	3
Global radiation	.4	14
July		
Rainfall	.8	11
Maximum temperature	7.0	5
Minimum temperature	.8	11
Global radiation	.1	15
August		
Rainfall	6.8	6
Maximum temperature	1.6	8
Minimum	1.3	9
Global radiation	1.1	10
Total	72.9	

of determination for the case when none of the elements was normalized, 72.9 (Table 11). These differences were, therefore, all adjusted on a pro rata basis to make them total 72.9 for comparative purposes (Table 12).

The seven most important elements (Table 12) in order were: June rainfall, preseason precipitation, June maximum temperature, May rainfall, July maximum temperature, August rainfall, and May global radiation. Some elements contributed less than 1% each to the total reduction in the coefficient of determination and possibly could have been omitted, although collectively they accounted for an overall reduction of nearly 3%. These include May maximum temperature, June global radiation, July rainfall, July minimum temperature, and July global radiation.

Rainfall during May, June and July had a positive influence on yield. Each millimeter of rain contributed 9.85, 6.44 and 1.60 kg/ha, respectively, for the 3 mo assuming that other weather elements were normal (Table 10).

July rainfall is often considered critical for the production of a high yield. Therefore its relatively small contribution (11th in order of importance, Table 12) to the reduction of the total coefficient of determination for yield is surprising and needs further comment. The wheat crop has usually passed the heading stage by the first of July (Robertson 1968). By this time, root penetration has usually stopped (Hurd 1964). Soil moisture reserves in the upper 30 cm at least are usually depleted by this time. Rainfall during the month is light, averaging 47 mm with a standard deviation of 29 mm (Table 7). Seldom is the rainfall during a single storm in July sufficiently heavy to penetrate the soil to any appreciable depth. This means that the rainfall usually wets only the upper few millimeters of soil and is lost by evaporation, while very little contributes to the evapotranspiration process. The largest contribution to this process comes from stored moisture, which was conserved during the summer-fallow period and which is now available to the fully developed root system. This stored moisture is used more efficiently by the crop if the weather is cool and cloudy. Such conditions accompany rainfall in July (Table 7) and would appear to be at least as effective as July rainfall per se in increasing yield, if not more so.

August rainfall was sixth in order of importance regarding its contribution to the total coefficient of determination for yield (Table 12). August is the month of ripening and harvest. By this time it is too late for rainfall to contribute to the growth and increase the crop yield. Instead, its contribution was negative, each millimeter reducing the yield by 5.66 kg/ha (Table 10). It is a well known fact that alternately wetting and drying ripe grain that is still in the swath causes brittle straw and glumes, resulting in harvesting losses due to excessive shattering. Also, since wet weather delays harvest, there may be losses due to damage caused by birds and rodents, and by sprouting. Thompson (1962) noted similar negative effects of rainfall on wheat yield at harvest time in the Great Plains of the U.S.A.

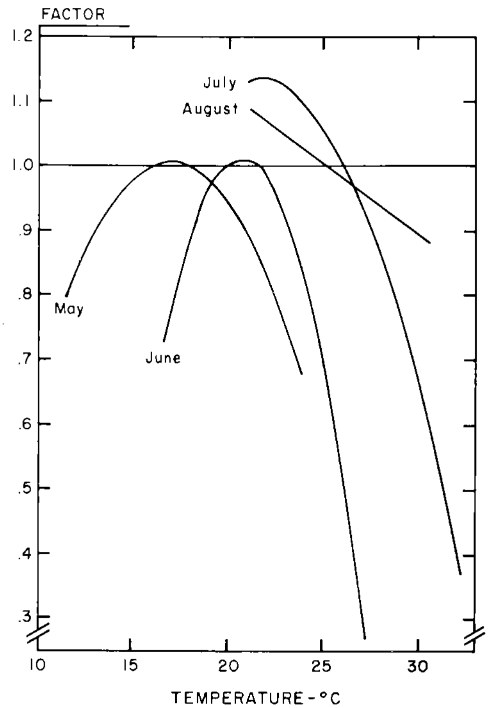

Fig. 4. The yield correction factors for the monthly means of the daily maximum temperatures.

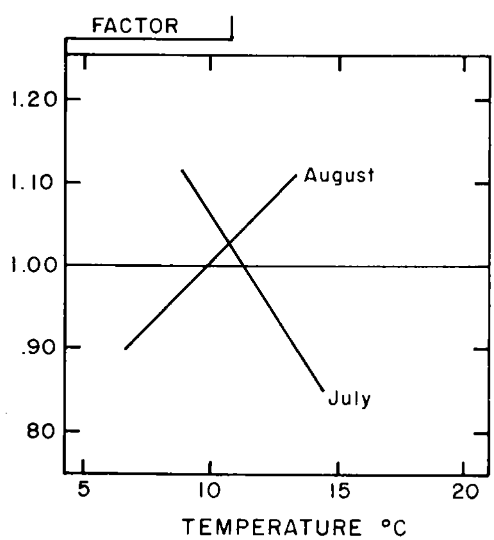

Fig. 5. The yield correction factors for the monthly mean of the daily minimum temperatures.

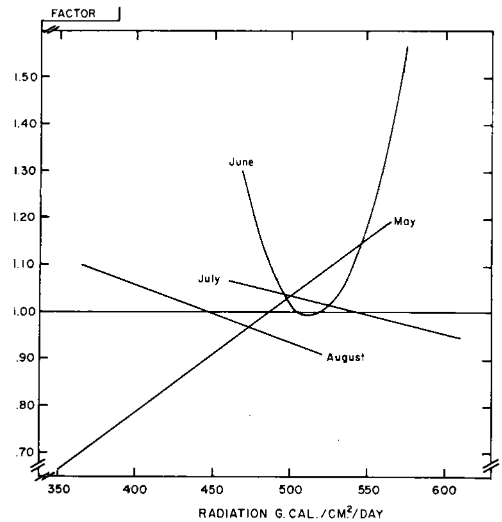

Fig. 6. The yield correction factors for the monthly mean of the daily global radiation.

These conclusions for July and August rainfall are in accord with findings by Baier (1973).

Another advantage of the factorial yield–weather model is that it permits an independent evaluation of the yield influence function for each modifying weather element (Fig. 4, 5 and 6). The equations for the curves in these figures have been adjusted by normalizing the regression coefficients, as explained previously, so that the influence on yield is unity for the normal value of the element involved. Departures from normal, therefore, become ratio modifications to the yield as determined by antecedent conditions during the past month plus current monthly rainfall (equation 13).

The curves for maximum temperature, in particular (Fig. 4), reflect the characteristic biological response of plants to environmental elements, showing the optimum value and indicating possible lower and upper critical limits. The range of monthly values over the 50 yr of the study did not permit evaluation of the full extent of these curves, which were terminated at the actual range limits.

The optimum maximum temperatures increase from 17 C in May to 20.5 C in June and 22 C in July. Temperatures above these values are devastating to the crop, particularly in June and July when the hottest months could reduce yields to less than 30% of that expected in June and less than 40% of that expected in July. These reductions are possibly due to heat and moisture stress in the plant, causing high respiration rates in the whole plant, chlorosis, early senescence and desiccation, particularly of the lower leaves, and ultimately their death (Friend et al. 1962; Asana and Williams 1965).

These curves are not unlike those obtained by Baier (1973). Similar curvilinear relationships for temperatures around heading and filling stages, for wheat with high temperatures depressing yields, were reported by Thompson (1962) for the wheat states of central U.S.A.

The deleterious effects of increasing maximum temperatures in August are possibly due to rapid ripening resulting in improper filling, light kernels and shattering during harvest. This element has a weak effect, coming eighth in order of importance (Table 12).

According to the analysis, minimum temperatures during May and June had no influence on the final yield. The responses of yield to July and August minimum temperatures were weak, being 11th and 9th, respectively, in order of importance (Table 12). The negative effect of the July minimum temperature (Fig. 5) is possibly due to an increasing respiration rate with higher nighttime temperature (Asana and Williams 1965). The positive effect of the August minimum temperature might be associated with a decrease in shattering losses during harvesting. It is a well known meteorological fact that moisture content of the atmosphere and the nighttime minimum temperature are positively correlated. Higher moisture content of the air could mean tougher glumes, and therefore less shattering. These opposing effects of August maximum and minimum temperatures indicate the power of the model and of the analytical procedure to isolate independent responses to factors that are highly correlated, $r = 0.63$ (Table 8).

Global radiation could have influences on the growth of wheat through several processes: photosynthesis, raising the tissue temperature above ambient air temperature, increasing the transpiration rate if water is not limiting and increasing moisture stress, where water is limiting, causing wilting and a decrease in photosynthesis.

The response curves for radiation (Fig. 6) are somewhat confused, but nevertheless they follow a logical pattern. The order of importance of radiation was not high, being 7th and 8th for May and August, respectively, and only 14th and 15th for June and July, respectively (Table 12). May is the month during which the soil is warming up. High radiation will speed the process, promoting early seeding, seed germination, and seedling development. An early start helps the wheat crop to avoid the higher temperatures of July, during a physiological period when the plant's optimum temperature requirement is low (Fig. 4). The negative response to low radiation values in June may be due to increased transpiration and plant tissue temperature, both of which may reach a saturation point for these processes before maximum radiation values are reached. Higher radiation values penetrate the leaf canopy and help increase photosynthesis in the lower leaves. This all takes place during the period of grand growth when soil moisture may still be abundant and lower leaves are photosynthetically active.

During July, soil moisture is usually nearing depletion and moisture stress may develop in the plants. Lower leaves, which were photosynthetically active in June, reach senescence and become inactive.

Increasing radiation may increase the tissue temperature (Robertson 1953) as well as internal plant water stress. These negative influences more than offset the positive influence of photosynthesis, resulting in a negative crop yield response to July radiation, which incidentally is at its peak, on the average, in July (Campbell et al. 1969).

August is the harvest month, and any process that increases the risk of shattering may cause yield losses. High radiation values usually occur during periods of clear skies and low humidities. These conditions all contribute to the formation of dry, brittle glumes and may explain the negative correlation between yield and August global radiation.

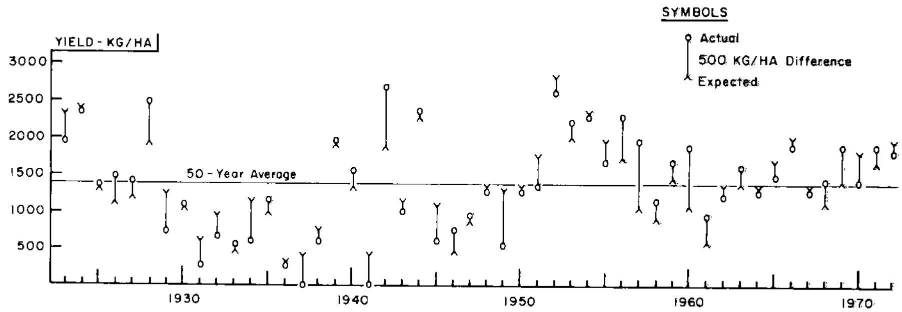

Fig. 7. Time trend of the observed yields and the weather-based estimates of yields at the end of August ($\hat{Y}_8$) showing also the trend of their differences, Swift Current, 1923 to 1972.

Although pan evaporation during June and July had high, simple correlations with yield (Tables 6, 7), it did not appear as an important factor in the final analysis. Evaporation is positively correlated with maximum temperature and radiation, and negatively correlated with rainfall. These correlations are the opposite for wheat yield on all three counts. Therefore pan evaporation is one of the best single weather elements for use as an indicator of yield. However, when introduced in a weather model along with rainfall, radiation and maximum temperatures considered separately, these latter factors contribute more to the yield variation than does evaporation. Had evaporation been used in a soil moisture budget model (Baier and Robertson 1966), and the estimated soil moisture used in the yield model (Baier and Robertson 1968), then evaporation might have made a definite contribution to yield estimates. As it was used, evaporation made no contribution either as a modifying factor, equation 13, or as an additive element to the rainfall function (V_1 and equation 14).

Model Performance over the 50 Yr of the Study

Since the climate at Swift Current has undergone changes over the past 50 yr (Table 3; Fig. 1 and 2), a test was made to determine how the estimated yields ($\hat{Y}_8$) agreed with observed yields. The differences between estimated and actual yields appeared to be randomly distributed by years over the whole period (Fig. 7), except for the 6 consecutive yr from 1956 to 1961, when observed yields were higher than the weather-based estimates (Table 13). A further study of the agreement of actual and estimated yields was made by breaking the 50-yr period into three subperiods: 1923–1939, 1940–1955, and 1956–1972. Simple correlation

Table 13. Correlation analysis of observed wheat yield and yield estimated ($\hat{Y}_8$) by the factorial yield-weather model by periods for Swift Current

	1923-39	1940-55	1956-72	1956-61	1962-72
Coefficient of determination ($100R^2$) (%)	84	80	29	68	34
Standard error of estimate of yield (kg/ha)	304	373	320	333	237
Regression coefficient	1.06	1.06	0.53	1.05	0.58
Standard error of RC	0.12	0.14	0.21	0.36	0.27
Intercept (kg/ha)	−152	−166	850	442	662
Average observed yield (kg/ha)	1116	1447	1599	1658	1568
Standard deviation (kg/ha)	746	803	368	522	277
Average estimated yield (kg/ha)	1196	1526	1418	1291	1561
Standard deviation (kg/ha)	647	679	375	408	280

analysis was applied to each of these three periods.

The estimated yields compare favorably with the observed yields during the two earlier subperiods. Over 80% of the variability in yield was explained by the weather model. Also, the regression coefficients were approximately equal to unity while the intercepts were near zero, indicating little bias in the estimated yields.

Agreement during the last subperiod (1956–1972) was not so good. Only 29% of the variability in yield was explained by the weather model, although the standard error of estimate was comparable to that for the two earlier subperiods. The average yield was higher than during the previous two subperiods and 181 kg/ha greater than estimated. The yield variability, 368 kg/ha, was considerably less than during the two earlier subperiods. The variability of the integrated weather influences on yield, as measured by the standard deviation of the estimated yield, was also low, being 375 kg/ha compared with 647 and 679 kg/ha for the earlier subperiods.

During the first 6 yr of the last subperiod, the actual yield averaged 1,658 kg/ha, considerably higher than the estimated yield of 1,291 kg/ha (Table 13). In spite of this, the weather model accounted for 68% of the yield variability. The regression coefficient was not much greater than unity, about the same as for the first two subperiods. The intercept was large, however, amounting to 442 kg/ha, indicating a large negative bias in the estimated yield, although the standard error of estimate of 333 kg/ha was comparable to values for the earlier subperiods.

The high yields relative to the weather-based estimates during these 6 yr might be due to a carryover of the effect of exceptionally favorable weather conditions during the previous 6 yr (1950–1955), when yields were near, or much above, the 50-yr average (Fig. 7). During this period, the annual precipitation averaged 440 mm, 77 mm above normal. Other weather factors were also favor-

Table 14. Progressive contribution of *normal* weather to final yield as estimated by the crop–weather model for Swift Current

Factor	Value	Contribution	Total (kg/ha)
Preseason precipitation	541 (mm)	1385 (kg/ha)	1385
May			
No rainfall	0	−356 (kg/ha)	
Rainfall	36 (mm)	356 (kg/ha)	
Max. correction	17.8 (C)	1.00	
Rad. correction	487 (g cal/cm^2/day)	1.00	1385
June			
No rainfall	0	−424	
Rainfall	74	484	
Max. correction	21.6	1.00	
Rad. correction	513	1.00	1446
July			
No rainfall	0	−54	
Rainfall	46	74	
Max. correction	26.1	1.00	
Min. correction	11.3	1.00	
Rad. correction	540	1.00	1466
August			
No rainfall	0	242	
Rainfall	41	−229	
Max. correction	25.2	1.00	
Min. correction	9.9	1.00	
Rad. correction	445	1.00	1480

able for high yields. As a result, excessively heavy straw mulches were available for a high accumulation of organic matter in the top soil. The heavy rains caused deep percolation of water, particularly on summer fallow, accompanied by leaching of NO_3-N to depths possibly as great as 4 m (Doughty 1956; Campbell et al. 1973). During the next 6-yr period this moisture and NO_3 could have moved upwards, becoming slowly available for crop use, which, together with the slow decomposition of the accumulated organic material in the top soil, could have resulted in the persistently higher yield than expected based on weather data alone.

Poorest agreement, as measured by the coefficient of determination, was during the most recent years (1961–1972) when weather accounted for only 34% of the yield variability. Yield variability (277 kg/ha) was smaller than for any of the three subperiods, as were also the variability of the integrated effect of the weather (280 kg/ha) and the standard error of estimate (237 kg/ha). Although the average of the estimated yields was very close to the average of the actual yields, the slope (0.58) of the regression line departed considerably from unity, and the intercept (662 kg/ha) was far from zero.

The Effect of Weather on Yield for Individual Years

The factorial model provides a ready means for assessing the month-by-month effects of various weather elements on the final yield. This is illustrated by using, as an example, the long-term averages or normal weather for Swift Current (Table 14), and one of the droughtiest years on record, 1937 (Table 15). The first line shows the total summer-fallow season precipitation (normal = 541 mm), and the contribution or amount of yield (1,385 kg/ha) that this precipitation is expected to support. This estimate is subject to the inherent condition that normal

Table 15. Progressive contribution of weather elements to final yield as estimated by the crop–weather model for a season with a crop failure at Swift Current, 1937

Factor	Value	Contribution	Total (kg/ha)
Preseason precipitation	373 (mm)	886 (kg/ha)	886
May			
No rainfall	0	−256 (kg/ha)	
Rainfall	23 (mm)	222 (kg/ha)	
Max. correction	20.3 (C)	0.93	
Rad. correction	491 (g cal/cm²/day)	1.01	800
June			
No rainfall	0	−363	
Rainfall	15	101	
Max. correction	25.2	0.66	
Rad. correction	512	1.00	356
July			
No rainfall	0	0	
Rainfall	28	47	
Max. correction	29.1	0.76	
Min. correction	12.8	0.93	
Rad. correction	520	1.01	289
August			
No rainfall	0	242	
Rainfall	25	−141	
Max. correction	26.6	0.97	
Min. correction	10.4	1.02	
Rad. correction	452	0.99	383
		Actual	0

weather exists during the period after the estimate until harvest time. As time progresses, the yield is modified by various weather factors. The second line shows what might happen if no rain falls during May. Under normal conditions, rainfall would balance this no-rainfall deterioration to the crop. In 1937, May rainfall was only 23 mm, somewhat below normal and, therefore, the original yield estimate was reduced by 34 kg/ha. The modifications for temperature and radiation are ratio corrections. These have arbitrarily been adjusted so that they are unity at the normal value of the element at Swift Current. In 1937, the May maximum temperature was above normal, which led to a further deterioration of the crop by 10%. Radiation was favorable, but improved the crop condition by only 1%. The net result was that the crop condition deteriorated by 86 kg/ha during May. Weather conditions continued to be unfavorable throughout June and July and the crop deteriorated to an expected yield of 289 kg/ha at the end of July. In fact, the stand of grain was so poor by mid-June that the plots were tilled in order to control weeds; thus, the zero yield at the end of August.

In the case of the normal values (Table 14), a slight statistical bias crept into the results as calculations progressed from month to month. This was due to the slightly skewed distribution of certain weather elements, particularly rainfall.

Step-by-step calculations are illustrated for other exceptional years: a bumper-crop year in 1952 (Table 16) when conditions were favorable, particularly the abundant rainfall in June, the high radiation in May and the cool temperatures in July; a recent hot, dry year in 1961 (Table 17) when yield was reduced primarily by the low rainfall in May and June and by very high maximum temperatures during June; and for a year

Table 16. Progressive contribution of weather elements to final yield as estimated by the crop–weather model for a bumper crop at Swift Current, 1952

Factor	Value	Contribution	Total (kg/ha)
Perseason precipitation	691 (mm)	2,098 (kg/ha)	2,098
May			
No rainfall	0	−504 (kg/ha)	
Rainfall	53 (mm)	525 (kg/ha)	
Max. correction	17.9 (C)	1.00	
Rad. correction	509 (g cal/cm^2/day)	1.05	2,226
June			
No rainfall	0	−504	
Rainfall	104	666	
Max. correction	20.1	1.01	
Rad. correction	52.7	1.02	2,468
July			
No rainfall	0	−188	
Rainfall	61	101	
Max. correction	22.9	1.12	
Min. correction	9.4	1.09	
Rad. correction	539	1.00	2,899
August			
No rainfall	0	242	
Rainfall	51	−282	
Max. correction	23.9	1.03	
Min. correction	9.6	0.99	
Rad. correction	479	0.96	2,798
		Actual	2,650

Table 17. Progressive contribution of weather elements to final yield as estimated by the crop-weather model for a hot, dry season at Swift Current, 1961

Factor	Value	Contribution	Total (kg/ha)
Preseason precipitation	505 (mm)	1284 (kg/ha)	1,284
May			
No rainfall	0	−336 (kg/ha)	
Rainfall	23 (mm)	235 (kg/ha)	
Max. correction	17.7 (C)	1.00	
Rad. correction	473 (g cal/cm²/day)	0.96	1,137
June			
No rainfall	0	−397	
Rainfall	38	249	
Max. correction	27.1	0.30	
Rad. correction	574	1.53	457
July			
No rainfall	0	0	
Rainfall	28	40	
Max. correction	26.8	0.96	
Min. correction	11.2	1.00	
Rad. correction	554	0.99	477
August			
No rainfall	0	242	
Rainfall	10	−61	
Max. correction	29.7	0.90	
Min. correction	13.2	1.10	
Rad. correction	475	0.96	632
		Actual	921

with the driest growing season on record when rainfall was only 50 mm in 1973 (Table 18). In this latter example, preseason precipitation was just below normal but sufficient to support a 1,130 kg/ha crop. Low rainfall throughout the growing season steadily reduced this expected yield but near-normal temperature and favorable global radiation prevented a catastrophic deterioration in the crop yield such as happened during the excessive heat of 1937 and 1961. Harvest weather was very favorable in August and the final yield estimate was 1,056 kg/ha. Actual yield was 1,480 kg/ha, which differs from the estimated yield by 424 kg/ha, a little more than the standard error of estimate of 355 kg/ha.

Future Improvements in Weather–Yield Models

Even though the model appears to provide an acceptable estimate of the yield at the end of August, there is still ample room for improvement, as indicated by the scatter diagram for estimated yield, $\hat{Y}_s$, and observed yield, Y_0 (Fig. 8). It is doubtful that model improvement can provide better estimates at the end of April and May, as the important weather factors that contribute to yield are still unknown. A better manipulation of weather data for June, July, and August might provide better estimates. The use of calculated soil moisture instead of rainfall (Baier and Robertson 1966, 1968); of shorter biological time periods instead of calendar months (Robertson 1968); and the calculation and use of effective crop temperature (Robertson 1953) instead of air temperature extremes as measured in a meteorological shelter would all contribute to a more logical manipulation of the basic data and should lead to improvement in the estimates, particularly the final value.

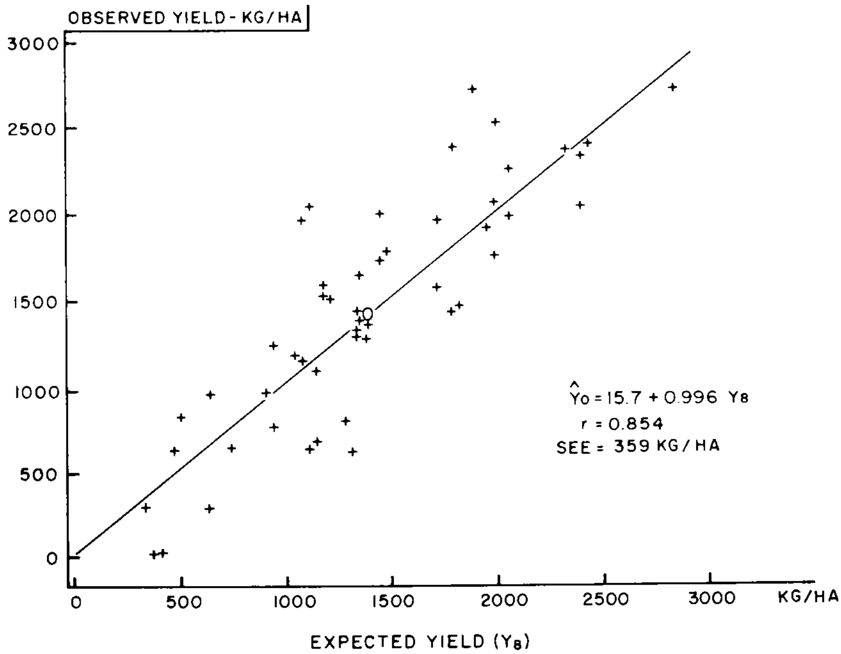

Fig. 8. Scatter diagram of the observed yields and the weather-based estimates of yields at the end of August ($\hat{Y}_8$).

Table 18. Progressive contribution of weather elements to final yield as estimated by the crop-weather model for a dry but temperate season at Swift Current, 1973

Factor	Value	Contribution	Total (kg/ha)
Preseason precipitation	437 (mm)	1,130 (kg/ha)	1,130
May			
No rainfall	0	−302 (kg/ha)	
Rainfall	10 (mm)	94 (kg/ha)	
Max. correction	17.8 (C)	1.00	
Rad. correction	534 (g cal/cm^2/day)	1.11	1,029
June			
No rainfall	0	−383	
Rainfall	23	148	
Max. correction	22.8	0.94	
Rad. correction	535	1.06	787
July			
No rainfall	0	0	
Rainfall	18	27	
Max. correction	26.3	0.99	
Min. correction	10.5	1.04	
Rad. correction	543	1.00	834
August			
No rainfall	0	243	
Rainfall	17	−93	
Max. correction	26.3	.98	
Min. correction	12.4	1.08	
Rad. correction	430	1.02	1,056
		Actual	1,480

CONCLUSIONS

The factorial yield–weather model described in this paper is expected to have applications for estimating wheat yield at other sites, and the yields of other crops. The regression coefficients are probably specific for the conditions of the experimental data from the plots at Swift Current. The coefficients and the resulting response curves for maximum and minimum temperatures and for global radiation (Fig. 4, 5 and 6) are expected to be characteristic of spring wheat cultivars similar to those grown at Swift Current. The coefficients of antecedent yield, $\hat{Y}_{t-1}$, and of rainfall are expected to vary from site to site, because of varying water-holding characteristics and fertility of the soil. These expectations, however, await verification at other sites and for other crops.

AMORES-VERGARA, EMMA P. 1973. A study on the effectiveness of four mathematical models on the development of sweet corn (H801) and the daily variations of solar radiation and air temperature. Thesis submitted to the College of Arts and Sciences, Univ. Philippines in partial fulfillment of the requirements for the degree of M.Sc., Manila.

ASANA, R. D. and WILLIAMS, R. F. 1965. The effect of temperature stress on grain development in wheat. Aust. J. Agric. Res. **16**: 1–13.

BAIER, WOLFGANG. 1973. Crop-weather analysis model: Review and model development. J. Appl. Meteorol. **12**(6): 937–947.

BAIER, W. and ROBERTSON, G. W. 1966. A new versatile soil moisture budget. Can. J. Plant Sci. **46**: 299–315.

BAIER, W. and ROBERTSON, G. W. 1968. The performance of soil moisture estimates as compared with the direct use of climatological data for estimating crop yields. Agric. Meteorol. **5**: 17–31.

CAMPBELL, J. B. 1971. The Swift Current Research Station 1920-1970. Can. Dep. Agric., Hist. Ser. No. 6, 79 pp.

CAMPBELL, C. A., BIEDERBECK, V. O., WARDER, F. G. and ROBERTSON, G. W. 1973. Effect of rainfall and subsequent drying on nitrogen and phosphorus changes in a dryland fallow loam. Soil Sci. Soc. Amer. Proc. **37**: (in press).

CAMPBELL, C. A., PELTON, W. L. and NIELSEN, K. F. 1969. Influence of solar radiation and soil moisture on growth and yield of Chinook wheat. Can. J. Plant Sci. **49**: 685–699.

CAMPBELL, C. A. and READ, D. W. L. 1968. Influence of air temperature, light intensity and soil moisture on the growth, yield and some growth analysis characteristics of Chinook wheat grown in the growth chamber. Can. J. Plant Sci. **48**: 299–311.

DOUGHTY, J. L. 1956. Soil Research Laboratory, Swift Current Progress Rep. 1948–1954. Min. of Agric., Ottawa, Ontario.

FRIEND, D. J. C., HELSON, V. A. and FISHER, J. E. 1962. The rate of dry matter accumulation in Marquis wheat as affected by temperature and light intensity. Can. J. Bot. **40**: 939–955.

HURD, E. A. 1964. Root study of three wheat varieties and their resistance to drought and damage by soil cracking. Can. J. Plant Sci. **44**: 240–248.

ROBERTSON, G. W. 1953. Some agrometeorological problems in Canada. Can. Branch R. Meteorol. Soc. **4**: 1–21.

ROBERTSON, G. W. 1964. Evaporation measurements at Research Branch Stations in Canada Department of Agriculture. Publ. 1210, Can. Dep. Agric. Res. Branch, Ottawa, Ontario.

ROBERTSON, G. W. 1968. A biometeorological time scale for a cereal crop involving day and night temperatures and photoperi[illegible] J. Biometeorol. **12**(3): 191–223.

ROBERTSON, G. W. 1971. Solar radiation data for eleven years at Los Banos, Philippines in relation to bright sunshine. Tech. Ser. No. 6, WMO/UNDP Proj. "Meteorological training and research, Manila", Philippine Weather Bureau.

ROBERTSON, GEO. W. and RUSSELO, D. A. 1968. Astrometeorological estimator for estimating time when sun is at any elevation, elapsed time between the same elevations in the morning and afternoon, and hourly and daily values of solar energy, Q_0. Tech. Bull. 14, Agrometeorol. Sect., Plant Res. Inst., Can. Dep. Agric, Ottawa, Ontario.

SNEDECOR, GEORGE W. and COCHRAN, WILLIAM G. 1968. Statistical methods. Iowa State Univ. Press, Ames, Iowa.

STAPLE, W. J. and LEHANE, J. J. 1952. The conservation of soil moisture in Southern Saskatchewan. Sci. Agric. **32**: 36–47.

STAPLE, W. J. and LEHANE, J. J. 1954. Weather conditions influencing wheat yields in tanks and field plots. Can. J. Agric. Sci. **34**: 553–564.

THOMPSON, LOUIS M. 1962. Evaluation of weather factors in the production of wheat in the United States. J. Soil Water Conserv. **24**: 219–224.

THORNE, G. N., FORD, M. A. and WATSON, D. J. 1968. Growth, development and yield of spring wheat in artificial climates. Ann. Bot. **32**: 425–546.

WILLIAMS, G. D. V. 1973. Estimates of prairie provincial wheat yields based on precipitation and potential evapotranspiration. Can. J. Plant Sci. **53**: 17–30.

WILLIAMS, G. D. V. and ROBERTSON, G. W. 1965. Estimating most probable prairie wheat production from precipitation data. Can. J. Plant Sci. **45**: 34–47.

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5. W.A. Phillips, S.C. Rao, R.L. Dalrymple, E.L. Klepper. Annual Cool-Season Grasses 781-802. [Crossref]
6. Yong He, Lingling Hou, Hong Wang, Kelin Hu, Brian McConkey. 2015. A modelling approach to evaluate the long-term effect of soil texture on spring wheat productivity under a rain-fed condition. *Scientific Reports* **4**:1. . [Crossref]
7. K. A. Congreves, B. B. Grant, C. A. Campbell, W. N. Smith, A. J. VandenBygaart, R. Kröbel, R. L. Lemke, R. L. Desjardins. 2015. Measuring and Modeling the Long-Term Impact of Crop Management on Soil Carbon Sequestration in the Semiarid Canadian Prairies. *Agronomy Journal* **107**:3, 1141-1154. [Crossref]
8. Yong He, Yongsheng Wei, Ron DePauw, Budong Qian, Reynald Lemke, Asheesh Singh, Richard Cuthbert, Brian McConkey, Hong Wang. 2013. Spring wheat yield in the semiarid Canadian prairies: Effects of precipitation timing and soil texture over recent 30 years. *Field Crops Research* **149**, 329-337. [Crossref]
9. Robert A. McLeman, S. Kate Ploeger. 2012. Soil and its influence on rural drought migration: insights from Depression-era Southwestern Saskatchewan, Canada. *Population and Environment* **33**:4, 304-332. [Crossref]
10. Kröbel R., Campbell C. A., Zentner R. P., Lemke R., Steppuhn H., Desjardins R. L., De Jong R.. 2012. Nitrogen and phosphorus effects on water use efficiency of spring wheat grown in a semi-arid region of the Canadian prairies. *Canadian Journal of Soil Science* **92**:4, 573-587. [Abstract] [Full Text] [PDF] [PDF Plus]
11. Genevieve Gilbert, Robert McLeman. 2010. Household access to capital and its effects on drought adaptation and migration: a case study of rural Alberta in the 1930s. *Population and Environment* **32**:1, 3-26. [Crossref]
12. Budong Qian, Reinder De Jong, Richard Warren, Aston Chipanshi, Harvey Hill. 2009. Statistical spring wheat yield forecasting for the Canadian prairie provinces. *Agricultural and Forest Meteorology* **149**:6-7, 1022-1031. [Crossref]
13. A.W.McKeownA.W. McKeown, J.WarlandJ. Warland, M.R.McDonaldM.R. McDonald. 2006. Long-term climate and weather patterns in relation to crop yield: a minireview. *Canadian Journal of Botany* **84**:7, 1031-1036. [Abstract] [Full Text] [PDF] [PDF Plus]

14. B. L. Duggan, D. B. Fowler. 2006. Yield Structure and Kernel Potential of Winter Wheat on the Canadian Prairies. *Crop Science* **46**:4, 1479-1487. [Crossref]

15. F. U. Hassan, M. H. Leitch. 2001. Dry Matter Accumulation in Linseed (Linum usitatissimum L.)*. *Journal of Agronomy and Crop Science* **187**:2, 83-87. [Crossref]

16. Adrian M. Johnston, Francis J. Larney, C. Wayne Lindwall. 1995. Spring Wheat and Barley Response to Long-Term Fallow Management. *Journal of Production Agriculture* **8**:2, 264-268. [Crossref]

17. B.G McConkey, W Nicholaichuk, H.W Cutforth. 1990. Small area variability of warm-season precipitation in a semiarid climate. *Agricultural and Forest Meteorology* **49**:3, 225-242. [Crossref]

18. D. Poulain, S. Keller, J. Le Guen, P. Berthelem. 1989. Influence des facteurs climatiques sur la phenologie de la feverole (Vicia faba (L.)). *Agricultural and Forest Meteorology* **45**:3-4, 195-214. [Crossref]

19. R. De Jong, R.P. Zentner. 1985. Assessment of the SPAW model for semi-arid growing conditions with minimal local calibration. *Agricultural Water Management* **10**:1, 31-46. [Crossref]

20. W. Baier, J.C. St-Pierre, J.H. Lovering. 1980. Analysis of environmental factors affecting Timothy yields. *Agricultural Meteorology* **22**:3-4, 319-339. [Crossref]

21. A. O. Skjelvåg. 1980. A crop-weather analysis model applied to field bean. *International Journal of Biometeorology* **24**:4, 301-313. [Crossref]

22. W. Hartley Furtan, George E. Lee. 1977. ECONOMIC DEVELOPMENT OF THE SASKATCHEWAN WHEAT ECONOMY. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie* **25**:3, 15-28. [Crossref]