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THE INFLUENCE OF WEATHER AND TECHNOLOGY ON GRAIN YIELDS IN THE CANADIAN PRAIRIES

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ABSTRACT

This study is based on time-series data, 1921-75, covering the Canadian Prairies on a crop-district basis. The modified Fourier and regression analyses are used to measure the impact of weather and technology on grain yields. The significant importance of resource inputs, technology and weather in affecting crop yields is analyzed.

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Annual fluctuations in grain yields give rise to major agricultural problems. Over the past six decades wheat yields in the Prairie Provinces fluctuated widely, ranging from a minimum of 6.4 bushels per acre in the crop year 1937-38 to a maximum of 30.7 bushels per acre in 1980-81. These fluctuations lead to uncertainties that affect farm business decisions, whether they are related to investments in land or machinery, or other forms of capital. They affect productivity and optimal rates of fertilizer application, and they affect decisions about specialization or diversification of the farm business.

In like manner, policy makers find yield fluctuations a serious handicap in deriving adequate measures to assist farmers in reducing the fluctuation of uncertainties in grain production on farm incomes. This problem is especially important in the development of a sound crop insurance program which is a device designed to meet the problem of risks. Even within a crop insurance scheme, errors in estimates of yield variance, yield trends and yield forecast may be serious handicaps for budgeting of a crop insurance program.

The purpose of this study is to measure the influence of weather and technology on annual production and production trends of wheat, oats and barley in the Prairies. The specific objectives are: (1) to examine the most significant factors influencing yields; (2) to develop a method by which the influence of each factor can be measured; and (3) to predict future yields with an acceptable margin of error, based on the past weather pattern, a secular trend of technical advance, and a monthly assessment of rainfall and temperature during seeding, growing and harvesting periods in any given year.

This study is based on time series data covering the periods of: 1921-1975 for Manitoba; 1907-1975 for Saskatchewan; and 1921-1975 for Alberta, on a crop district basis. Manitoba is divided into 14 crop districts with 34 meteorological stations, Saskatchewan into 9 crop districts with 78 meteorological stations and Alberta into 7 crop districts with 57 meteorological stations.

Models and Methodology

Grain production in the Prairie Provinces is a function of a number of factors that combine in a very complex manner to produce the annual yield. The most significant variables influencing annual yields are resource inputs (R), technology (T), weather (W), and random residual (ε). This functional relationship may be expressed in the following model:

Model (1) $$\text{Yields } (Y_{ij}) = \text{Resource } (R_i) + \text{Technology } (T_i) + \text{Weather } (W_i) + \text{Residual } (\varepsilon_{ij})$$

$$(i = 1, 2 \ldots\ldots n; \; j = 1 \text{ for wheat}; \; 2, \text{ oats}; \; 3 \text{ barley})$$

where Y_{ij} = the actual annual yields per acre for a particular j^{th} crop over the i^{th} year; R_i = the average resource input per acre within the district over the i^{th} year; T_i = the average technological improvement within a particular crop district over the i^{th} year; W_i = the weather effects on the crop production in a particular crop district; and ε_{ij} = a random residual.

In Model (1) the resource and technological variables are directly under human control while the weather and residual variables are not subject to human control. Weather is much more significant than the residual variable in determining annual yields. In other words, year-to-year variation in the climate is assumed to give rise to corresponding variation in the crop yields. More detailed definitions and discussions of the factors are as follows:

Resource (R): Land, labor and capital influence yields. By using yield per acre, the relatively small changes in the amount of land used are eliminated. The other factors, labor and capital, are assumed to have received constant returns from a homogenerous production function of degree one.

Technology (T): This includes improvements in seed varieties and crop rotations, innovation in mechanization, increased use of fertilizer and of herbicides for weed control, better management, superior knowledge and improvements in quality of productive factors. In other words, these effects are assumed to be a blend of Solow's disembodied and embodied[1] technological changes.

Weather (W): This includes both direct weather influences (rainfall, temperature, etc.) and indirect influences (insect damage, plant disease, etc.). In any given year, several such effects may be operative, yielding a composite influence on the crops.

Residuals (ε): This includes all other factors influencing yields. In the absence of precise knowledge, it is assumed that the residuals left after subtracting the trend and weather cycles are normally and independently distributed.

Model (1) shows the hypothetical secular growth and variation of crop yield for a particular crop district over time. In addition, two assumptions have been made with respect to Model (1):

(a) the joint effect of changes in resource inputs (R_i) and the technological improvement variable (T_i) on the yield (Y_{ij}) is approximated by a linear increasing function of time T (i.e., $\hat{Y}_{ij} = a + b\,T_i$), and

(b) the weather effect has a cyclical nature with a constant period of p years (i.e., $W_i = W_{i+p}$ indicating that the weather effect on yield in year i, W_i, is the same as in year i + p, W_{i+p}). In addition, the weather effect is assumed to be additive. In any given year, several such weather effects may be operative, yielding a composite weather influence on the crops.

Spectrum analysis was performed on the reduced data ($Y - \hat{Y}$) and was achieved by subtracting a linear trend from the original data in an attempt to determine if corresponding cycles existed in the crop data (i.e., $Y - \hat{Y} = W + \varepsilon$).

The composite weather cycle may be defined as the sum of the individual cycle's influence which might be superimposed on one another in any given year. The composite weather cycle may be expressed in the following harmonic Model (2) as:

Model (2) $$W = \sum_{k=1}^{i} \frac{1}{N}\, C_k \left[\sin \left[\beta_k + \left(\frac{\pi}{N} k \right) (T - T_o) \right] \right]$$

where $\frac{1}{N} C_k$ = the amplitude of cycle; β_k = the phase angle of cycle; $\frac{\pi}{N} k$ = the frequency of cycle; and k = the index of each individual cycle which can be detected by using the "Modified Fourier Analysis" (Lanczos).

In regard to the weather factor, rainfall and temperature have always been considered as most important during seeding, growing and harvesting periods in any given year. Therefore, a model for the portion of yields resulting from rainfall and temperature may be formulated as:

Model (3) $y = f(X_1, X_2, X_3, \ldots X_9) + V$

where y = the portion of yields resulting from rainfall and temperature; X_1 = the preseasonal precipitation or total rainfall from September to April which may affect yields in the next growing season as a result of its influence on sub-soil moisture reserves; X_2 = total rainfall in May; X_3 = average temperature in May; X_4 = total rainfall in June; X_5 = average temperature in June; X_6 = total rainfall in July; X_7 = average temperature in July; X_8 = total rainfall in August; X_9 = average temperature in August; and V = a random residual .

Model (3) is designed to adjust the portion of long-run predicted yields derived from Model (1) by considering the fluctuations in monthly rainfall and temperature as the growing season advances. More specifically, unfavorable weather such as untimely frosts, wet seeding season or prolonged drought may reduce crop yields in any particular year while ideal weather may increase yields. Therefore, a monthly assessment of the quantitative effect of rainfall and temperature on crop yield should be considered as the seeding and growing seasons advance.

Empirical Results and Their Interpretation

Weather effects in Model (1) appear to have a non-random pattern in the distribution of yields over time. The evidence of the results shown in Table 1 indicates that long, medium and short-term cycles were apparently significant in affecting annual yields. On the average, long-term cycles (i.e., about ten years) dominate the model of the crops under consideration in the Prairie Provinces. In addition, and as expected, the weather effect on crop yields per acre was different among the districts as well as among the crops considered.

Table 2 summarizes the relative importance of: (1) resource inputs; (2) linear trend due to technology; and (3) weather cycles in affecting crop yields. It indicates that on the average, a major portion of yields depend on (a) resources (R), mainly soil fertility of which the depletion of soil nutrients over time could counterbalance the effects of increased fertilizer use, and (b) a better allocation of resources due to reorganization of a farm business. The linear trend is about one percent of the long-run average yield which accords well with a constant rate of increase in embodied technology applied to farming. These results also suggest that the rate of technological change, as revealed in this study varies from province to province or district to district as well as from crop to crop.

As shown in Table 2, the standard deviation of estimate for average wheat yields on the Prairies is ± 4.4 bushels per acre, or 22.1 percent of the average yields during the period studied, the standard deviation of estimate for oats is ± 8.9 bushels per acre, or 26.5 percent of average yields, and for barley ± 6.3 bushels, or 24.7 percent. They are all within a one standard deviation of estimate.

Table 1. The Component and Composite Weather Cycles Influencing the Fluctuation of Crop Yields in Manitoba, Saskatchewan and Alberta[a]

		Long-term (L)		Medium-Term (M)		Short-term (S)		Composite ΣW_R		Long-run Average Yield $\bar{Y}$
Province	Period	BU/A	$L/\bar{Y}$	BU/A	$M/\bar{Y}$	BU/A	$S/\bar{Y}$	BU/A	$\Sigma W/\bar{Y}$	BU/A
Wheat										
Manitoba	1921-75	2.66	12.9	2.1	10.2	1.94	9.4	6.68	32.5	20.6
Saskatchewan	1907-75	4.10	23.4	2.95	16.9	2.30	13.1	9.35	53.4	17.5
Alberta	1921-75	3.44	15.6	2.87	13.0	2.48	11.2	8.79	39.8	22.1
Oats										
Manitoba	1921-75	4.67	13.9	3.77	11.2	4.41	13.9	12.80	38.0	33.7
Saskatchewan	1907-75	8.10	25.7	6.30	20.0	4.80	15.2	19.20	61.0	31.5
Alberta	1921-75	5.73	16.1	4.72	13.2	4.72	13.2	15.17	42.5	35.7
Barley										
Manitoba	1921-75	2.71	10.2	2.03	7.7	2.97	11.2	7.70	29.1	26.5
Saskatchewan	1907-75	5.58	23.3	4.24	17.7	3.12	13.1	12.93	54.1	23.9
Alberta	1921-75	4.05	15.0	3.54	14.0	3.29	13.1	10.88	40.3	27.0

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[a] The long-term weather cycle (L) means around ten years, the medium-term about five years and the short-term about two years. The algebraic sum of all cycles were judged to be significant (tested by the standard deviation of cycles) in these three categories is the composite weather cycle.

Table 2. A Summary of Yield Fluctuations Caused by Each of the Resource, Technological, Weather and Residual Effects

	WHEAT			OATS			BARLEY		
	Man.	Sask.	Alta.	Man.	Sask.	Alta.	Man.	Sask.	Alta.
Period	1921-75	1907-75	1921-75	1921-75	1907-75	1921-75	1921-75	1907-75	1921-75
Resource (R)									
BU/A	+ 15.36	+ 15.22	+ 16.23	+ 26.72	+ 30.00	+ 26.80	+ 23.29	+ 21.59	+ 20.87
%	+ 74.6	+ 86.6	+ 73.4	+ 79.29	+ 95.24	+ 75.07	+ 87.89	+ 90.33	+ 77.30
Technology (T)									
BU/A	+ 0.19	+ 0.20	+ 0.144	+ 0.23	0	+ 0.32	+ 0.08	+ 0.02	+ 0.20
%	+ 0.92	+ 1.14	+ 0.65	+ 0.68	0	+ 0.90	+ 0.30	+ 0.01	+ 0.74
Weather (W)									
BU/A	± 6.68	± 9.35	± 8.79	± 12.80	± 19.20	± 15.17	± 7.70	± 12.93	± 10.88
%	± 32.50	± 53.4	± 39.8	± 38.0	± 61.0	± 42.5	± 29.10	± 54.1	± 40.3
Residuals (R)									
BU/A	± 4.34	± 3.86	± 5.12	± 7.56	± 10.03	± 8.99	± 5.39	± 7.38	± 6.19
%	± 21.10	± 22.05	± 23.16	± 22.43	± 31.84	± 25.18	± 20.34	± 30.88	± 22.93
Long-run Av. Yield ($\bar{Y}$)									
BU/A	20.6	17.5	22.1	33.7	31.5	35.7	26.5	23.9	27.0

Crop Predictions

Assuming that the same patterns of the studied period continue, crop yields can be predicted by substituting the values of a, b and W into Model (1). Predicted yields of wheat, oats and barley in each of the Provinces are presented in Table 3, which demonstrates that the predicted yields of wheat, oats, and barley in the studied period were reasonably close to the actual yields in each of the Provinces. On the average, on the Prairies, the deviation between actual and predicted yields in the recent period 1979-81 was about 2.4 bushels per acre for wheat, 5.4 bushels per acre for oats, and 5.0 bushels per acre for barley. They are all within a one standard deviation of estimate. In addition, the same results reveal that the deviations between actual and predicted yields were much smaller in the Provinces of Manitoba and Alberta, than that in the Province of Saskatchewan. In other words, the annual fluctuation of grain yields was relatively larger in Saskatchewan than that in Manitoba and Alberta.

Table 3 also summarized the long-run predicted yields for 1982 wheat, oats and barley in the Prairie Provinces. It indicates that these crops most likely will be above the average yields for the studied period in the Prairie Provinces. More specifically, the numerical results show that the long-run predicted yields in the Prairies would be 24.5 bushels per acre for wheat, 40.4 bushels for oats, and 35.5 bushels for barley if the past pattern of weather cycles and the current trend of technical advance would continue. However, the long-run predicted yields for 1982 wheat, oats and barley would be adjusted if the actual data on total subsoil moistures from September 1981 to April 1982, and rainfall and temperature in May, June, July and August of 1982 were different from the average

Table 3. A Comparison Between Actual and Predicted Yields for Wheat, Oats and Barley in the Prairie Provinces, 1979-1982[a]

	Wheat		Oats		Barley	
	Actual	Predicted	Actual	Predicted	Actual	Predicted
	bushels per acre					
Manitoba						
Av. 1921-75	20.6		33.7		26.5	
1979	25.0	22.2	44.4	40.1	40.0	36.4
1980	21.0	23.1	40.0	43.2	36.0	33.5
1981	31.7	28.4	52.3	47.5	46.9	39.7
1982	-	25.3	-	41.6	-	30.8
Saskatchewan						
Av. 1907-75	17.5		31.5		35.7	
1979	21.9	19.5	40.9	32.7	34.6	31.7
1980	22.8	24.0	44.4	40.6	39.4	32.8
1981	27.0	29.3	47.8	44.4	41.1	42.7
1982	-	22.3	-	35.6	-	38.6
Alberta						
Av. 1921-75	22.1		35.7		27.0	
1979	28.3	26.9	58.3	50.6	45.9	38.0
1980	33.1	29.2	63.0	55.4	50.8	44.0
1981	33.4	31.2	59.9	54.2	48.0	42.0
1982	-	26.0	-	45.2	-	37.0

[a] All the predicted yields were derived from the long-run model (1). However, the long-run predicted yields in 1979, 1980 and 1981 were adjusted by monthly rainfall and temperature during the periods of seeding, growing and harvesting seasons. The predicted yields are all within a one standard deviation of estimate.

monthly rainfall and temperature in the period studied. The adjusted portion[2] of long-run predicted yields can be derived from a curvilinear regression relationship (Yeh, p.10).

Concluding Remarks

1. A separation of weather cycles from random residuals is successfully demonstrated in this study. Variation in crop yields is significantly influenced by year-to-year fluctuations of the climate. More specifically, the relative importance of the cycles of long, medium and short-term is apparently significant in affecting crop yields. On the average, the long-term cycles dominate the model of the crops studied in the Prairies with the single exception of barley in Manitoba, for which the short-term cycle is predominant.

2. The significant importance of resources and technology in affecting crop yields is confirmed by this study. On the average, it indicates that a major portion of the yield depends on soil fertility. The linear trend is about one percent per annum of the long-run average yield which accords well with a constant rate of increase in technology applied to farming. The adopted rate of technology varies from district to district as well as from crop to crop.

3. The predicted yields for 1979 to 1981 wheat, oats and barley in each of the Prairies are reasonably close to the actual yields while the long-run predicted yields for 1982 crops in the entire Prairie region will likely be above the long-run average if the past weather pattern and the current trend of technological advance would continue.

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Footnotes

[1] Disembodied technological change is defined as an increase in productivity resulting from improved productive techniques, superior knowledge and better management while embodied technological change is defined as an increase in productivity resulting from improvement of fact or quality over time.

[2] The adjusted portion of long-run predicted yields refers to the portion of crop yields which is affected by monthly rainfall and temperature during the periods of seeding, growing and harvesting seasons. This portion of yields, derived from a curvilinear regression line, is used to adjust the long-run predicted yields.