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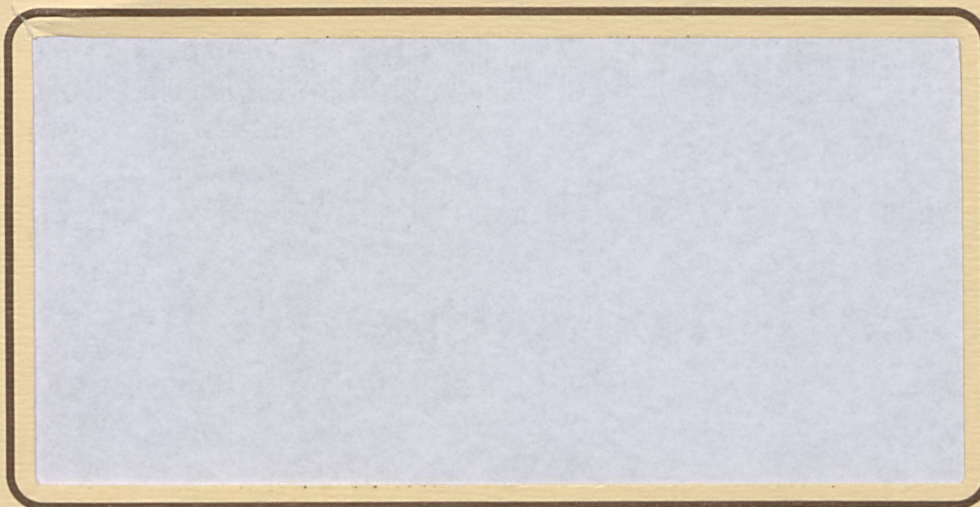
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# RURAL ECONOMY



## PROJECT REPORT



**FARMING  
FOR THE  
FUTURE**

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**The Role of Fertilizer, Weather, and Fertilizer-Weather  
Interactions in Prairie Grain Production and Productivity**

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## ABSTRACT

The measurement of productivity and the analysis of productivity trends--whether that be for a national economy such as Canada or the United States, or for a more specific sector, such as prairie agricultural or crop production, which is our area of interest--is vital to the monitoring of economic health and progress. Productivity in prairie crop production is estimated to have grown at a compound annual rate of some 1 to 1.5 percent between the early 1960s and the mid 1980s. This productivity increase has been associated with several features of increased intensification in prairie grain farming, including increased fertilizer and pesticide use and reduced summerfallow. The changing input use and production technology in the specific case of the Alberta grain sector was analyzed using a translog cost function.

In this research project, the main focus of analysis was the influence of weather, technology, and weather-technology interactions on productivity in the prairie crop sector. In analyzing productivity trends, it soon becomes apparent that productivity tends to rise secularly over time but that there is considerable year-to-year variation in productivity. In this research, technology--first represented by a time trend and then proxied by fertilizer use--was hypothesized to be the primary influence on the long run trend in productivity in crop production, whereas weather variables--particularly June rainfall, July rainfall, June temperature, and July temperature--were seen to be the cause of the short run fluctuations in crop productivity.

Estimated models of productivity-weather-technology interrelationships confirm the importance of these short and long run explanatory variables. For instance, the four weather variables and time are associated with 87 percent of the variation in total factor productivity in prairie crop production over 1948 to 1984. Fertilizer serves nearly as well as the technological trend proxy, "explaining", together with the weather variables, some 79 percent of the variation in productivity in the same time period. Models were also developed to analyze the influences of weather variables and fertilizer on grain yields. For example, an extra millimeter of rainfall in June and July was estimated to increase prairie wheat yields on average by an extra 4.9 and 4.3 kilograms per hectare respectively over the period from 1948 to 1984, whereas a degree Centigrade rise in June air temperature was estimated to reduce prairie wheat yields by 56.3 kilograms per hectare.

Finally, there is empirical evidence of significant interactions between fertilizer and weather variables, particularly June rainfall, on prairie crop productivity. In fact, a linear model including as significant explanators time, the four weather variables, a June rain-fertilizer interaction term, and a second interaction term based on fertilizer and either July or June temperature, "explains" 92 percent of the variation in productivity in prairie crop production between 1956 and 1984. There is also some suggestion that changes in technology associated with increased fertilizer use may be reducing the adverse effects of weather on productivity. Nevertheless, grain farming, as prairie farmers know all too well, remains--to a considerable degree, at least on the supply side--a "gamble on the rains."

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## I. Introduction

Fertilizer and weather-related variables appear to be very important influences on productivity performance in crop production in the prairies. Fertilizer, a key indicator of biochemical technical advance, is hypothesized to be important to productivity advance over time. On the other hand, summer rainfall and temperature variables, even from casual observation, are seen to be important determinants of the year-to-year fluctuations in output and productivity. In this project, the impacts of fertilizer, moisture, and possible synergistic fertilizer-moisture interactions on productivity in the prairie grain sector were estimated and analyzed.

### A. Nature and Scope of the Problem

Productivity advance is essential if the prairie grain sector is to reduce cost-price squeeze pressures and remain competitive in world markets. As a consequence, it is important to measure productivity, monitor closely its changes, and investigate its sources of increase and variation. Productivity gains in the grain sector appear critically dependent upon yield advances associated with higher-yielding crop varieties, increased fertilizer use, continued summerfallow reduction, and improved dryland moisture conservation. This research project is designed to shed light on some of these critical interrelationships. In particular, it should yield useful macro level evidence on the respective roles of fertilizer and weather on productivity, as well as on probable important interactions between fertilizer and weather (especially rainfall).

In previous research (Veeman and Fantino 1985), the influence of technology (as proxied by a time trend) and weather on productivity in Western Canadian agriculture as a whole was studied. Econometric evidence revealed that fertilizer use was likely to be an even more sensitive determinant of productivity advance than a time trend proxy. In recently completed research (Veeman, Fantino, and Rahuma 1989; Rahuma 1989), the study of agricultural productivity was disaggregated to the prairie crops sector, including detailed analysis for the five major prairie grains and oilseeds as well as a breakdown of productivity performance for each of the four major prairie soil zones. In this research project, detailed analysis of the impact of fertilizer and weather variables (particularly rainfall) on productivity is undertaken, using the specific productivity estimates for the prairie crop/grain sector which are now available. In some instances, the time frame of analysis can now be extended back to 1948.

The availability of quantity and price information for both outputs and inputs in grain (crop) production also permits more detailed analysis of the production technology of the prairie grain (crop) sector. Specifically, a translog cost function can be estimated to study several important features: the role of fertilizer as an input in prairie grain production; an assessment of the general directions of technical change in grain production; and the analysis of the possible impact of scale economies, as opposed to pure technical change, on estimated productivity.

A further question of interest is whether the impact of fertilizer and weather on yield -- a simple partial, but commonly used, measure of productivity -- is similar to that on total factor productivity. Finally, the degree to which the recent adverse conditions in the prairie grain sector between 1985 and 1988 retarded fertilizer use and the process of "intensification" in grain production needs further study.

## B. Research Objectives

The overall objective of the proposed research was to analyze the role of fertilizer, weather, and fertilizer-weather interactions in prairie grain production and productivity. Specific objectives included:

1. the examination of increased fertilizer usage and associated aspects of the process of intensification, considerably based on biochemical technology, which has been occurring in prairie grain production;
2. the analysis of input relations in prairie and Alberta grain production, using flexible form production and cost function approaches, focusing on fertilizer use;
3. the analysis of the possible impact of scale economies on estimated productivity;
4. the analysis of the role of fertilizer and suspected interactions between fertilizer and critical weather-related variables in explaining variation in (total factor) productivity in the prairie grains sector, extending the analysis, where data permitted, to the late 1940's and 1950's and to the individual province level;
5. the study of the impact of fertilizer and weather on yield per acre to compare such results with those from objective 4;
6. the investigation of whether the use of fertilizer and the process of intensification was retarded by the decline in prairie grain prices between 1985 and 1988.

## C. Format of the Report

This final technical report contains five sections after the introductory section. In Section II, a brief overview of increased fertilizer use and associated aspects of intensification in prairie grain production is presented. In Section III, the analysis of input relations and production technology in grain production, using the translog cost function approach, is briefly reported. In Section IV, the impact of fertilizer and weather related variables, chiefly rainfall, on total factor productivity in grain production is estimated, using econometric models, and assessed. The impacts of fertilizer and weather on yield, as opposed to total factor productivity, are presented in Section V. In the final section, Section VI, the main conclusions and policy implications of the research are summarized.



## II. Intensification in Prairie Crop Production

Technological change has been a pervasive influence on prairie crop production. For many decades, mechanical innovation, essentially of a labor-saving nature, has occurred in grain production in the prairie region. The grain booms of the mid 1960s and the 1973-81 period also led to greater intensification in prairie grain production and further adoption of biochemical technology, much of which is land-saving in orientation.

Several key indicators of increased intensification in prairie crop production are presented in Table II.1. Between 1970 and 1985, for example, the implicit quantity indexes for fertilizer and pesticides (annual expenditures for each divided by corresponding annual price indexes) increased annually at compound growth rates of 12.2 percent and 14.4 percent, respectively. By any yardstick, these are very rapid rates of growth in two key areas of biochemical input use. Rates of growth were slightly higher in Saskatchewan (albeit from a lower base) than in Manitoba and Alberta. The cropped land area in the prairie region increased by slightly over two percent per year while the area under summerfallow in the 1970-85 period decreased by 2.1% per year. The rate of summerfallow decline was highest in Manitoba, followed by Alberta and then Saskatchewan. The final two rows in Table II.1 indicate that the application rates of fertilizer and pesticides per acre (respective quantity indexes divided by cropped land area) also increased relatively rapidly in prairie crop production -- at approximately ten per cent per annum for fertilizer and twelve per cent per annum for pesticides between 1970 and 1985.

Table II.1      Intensification in Prairie Crop Production: Compound Annual Growth Rates of Selected Key Indicators, 1970 to 1985 (percent per year)

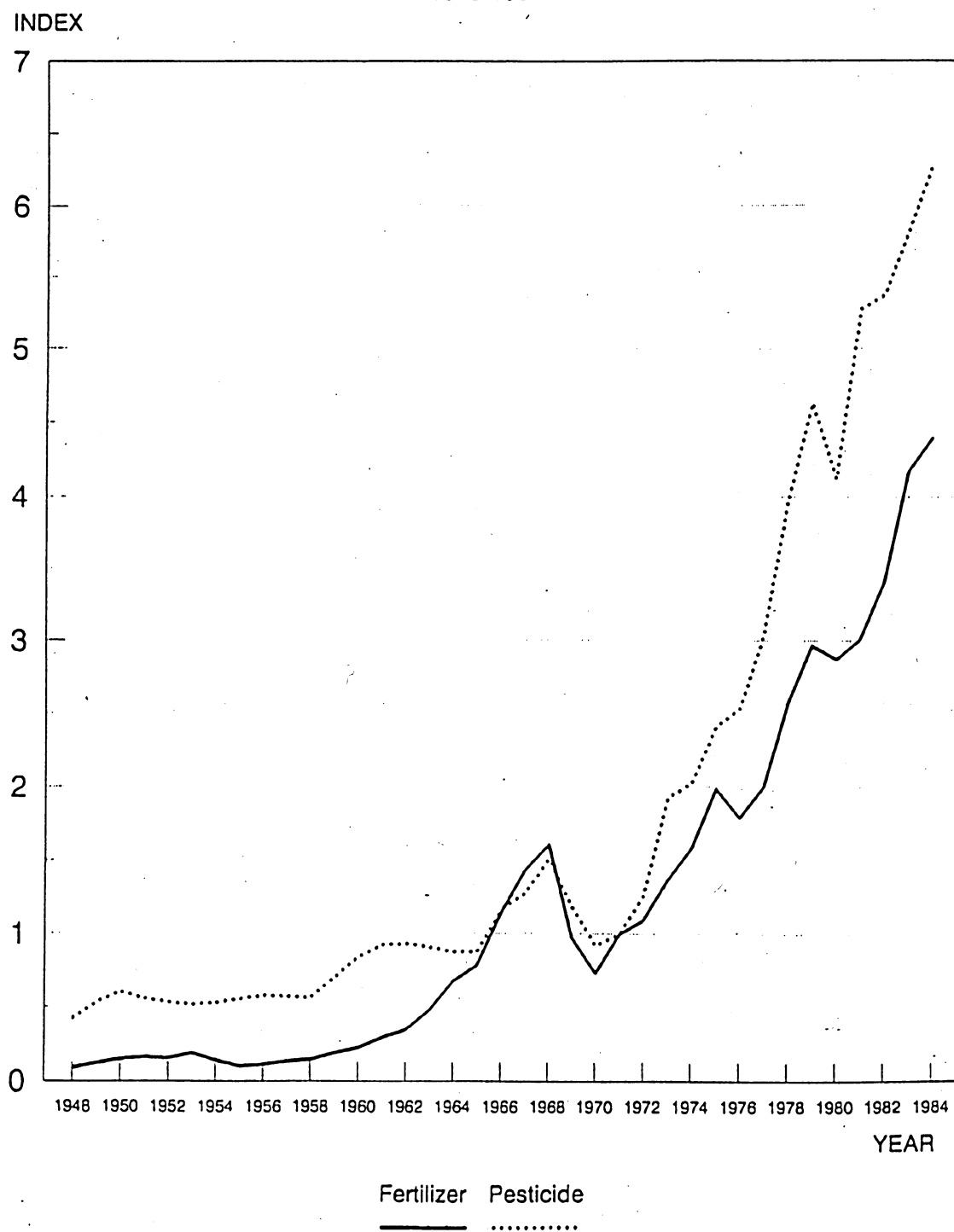
Indicator	Manitoba	Saskatchewan	Alberta	Prairies
Fertilizer Quantity Index	11.3	17.0	10.0	12.2
Pesticides Quantity Index	14.6	14.7	13.8	14.4
Summerfallow Area	-6.3	-1.1	-3.2	-2.1
Cropped Land Area	2.2	2.0	2.2	2.1
Fertilizer Application Rate	8.9	14.7	7.7	9.9
Pesticides Application Rate	12.2	12.4	11.4	12.1

Source: Derived from input data base used in this study.

The fertilizer and pesticide quantity indexes are portrayed graphically over a longer time frame, from 1948 to 1984, for the prairie region in Figure II.1. The pattern of fertilizer and pesticide use over time is remarkably similar -- limited use and little or no growth in the 1950s, an acceleration in use in the mid-1960s as Canada sold increasing grain exports to the centrally planned nations, a downturn in use between 1968 and

1970, and remarkable growth from the early 1970s onward to 1984. An interesting difference is that the pesticide quantity index lies consistently above the fertilizer index in the 1950s and accelerates somewhat more rapidly toward the end of the study period.

FIGURE II.1 FERTILIZER AND PESTICIDE QUANTITY INDEXES, (1971 = 1.00), PRAIRIE AGRICULTURE, 1948-1984





In Table II.2, annual compound rates of growth for fertilizer and pesticide use are presented for the prairie region and the respective prairie provinces over the 1948-1984, 1957-1984, 1966-1984, and 1971-84 time periods. The annual rate of growth of fertilizer use in the prairies over 1948 to 1984 is similar to that over the 1971 to 1984 period, although Saskatchewan's rate is higher and Alberta's is lower in the latter period. On the other hand, there is more clear-cut evidence of increase in pesticide use in all provinces in latter phases of the entire period under study.

A more detailed break-down of the growth of fertilizer use by nutrient category -- nitrogen, phosphate ( $P_2O_5$ ), and potash ( $K_2O$ ) -- is given in Table II.3. This break-down is based on recent data compiled by Agriculture Canada for the period from 1966 to 1987. As seen before, the rates of growth of nutrient use are very high, averaging 9.3 per cent per year for the prairies as a whole. The rate of increase of nitrogen use is considerably higher in Saskatchewan, although this increase is from a lower base than in Manitoba or Alberta. The annual rate of increase of use of phosphorus is the lowest, whereas the rate of increase of use of potassium is surprisingly high (again, from a very low base.)

**Table II.2**      **Annual Compound Rates of Growth of Chemical Input Use in Crop Production, Respective Prairie Provinces and Prairie Region, Various Time Periods (percent per year)**

	Manitoba	Saskatchewan	Alberta	Prairies
<b>Fertilizer</b>				
1948-1984	12.3	11.5	12.1	12.0
1957-1984	14.6	13.0	11.3	12.6
1966-1984	9.2	10.2	7.5	8.7
1971-1984	10.6	16.2	9.7	11.7
<b>Pesticides</b>				
1948-1984	9.5	7.3	6.8	7.6
1957-1984	11.5	9.0	8.3	9.3
1966-1984	12.9	12.0	10.7	11.8
1971-1984	15.2	14.4	14.1	14.5

**Source:** Calculated from the fertilizer and pesticide implicit quantity indexes in the input data base underlying this study. The fertilizer implicit quantity index in a given year, for instance, is generated by dividing total expenditure on fertilizer in that year by the corresponding fertilizer price index.

Table II.3      Annual Compound Rates of Growth of Use of Plant Nutrients in Prairie Crop Production, 1966 to 1987 (percent per year)

	Nitrogen	Phosphate	Potash	Total Nutrients
Manitoba	9.6	5.3	24.7	8.0
Saskatchewan	15.9	7.4	24.9	11.4
Alberta	9.1	5.2	22.0	7.7
Prairies	11.6	6.2	22.5	9.3

Source:      Compiled from data in Pidgeon (1988).

Much of the extensive data base on outputs and inputs in prairie crop production on which this study is based has been compiled from 1948 to 1984. Selective data on fertilizer use in the prairie region from 1984 to 1988, however, was collected (shown in Table II.4) to address the issue whether the intensification process in prairie crop production prior to 1984 was being retarded by the political and economic circumstances associated with the "grain subsidy war" since 1985. The empirical evidence portrayed in Table II.4 clearly shows that the use of nitrogen and the use of all nutrients declined in the prairie region in 1986, after fifteen years of continuous increase. Prairie fertilizer use decreased yet further in 1987, before rebounding to a limited degree in 1988. In Saskatchewan, fertilizer use was slower to decline (actually increasing in 1986), but also slower to recover (declining marginally in 1988).

Abstracting from the influence of weather and soil moisture conditions, there are three major economic influences which help to explain the preceding picture of fertilizer use on the prairies. The derived demand for fertilizer in prairie crop production is an outgrowth of three forces: the price of grain; the marginal physical productivity with which fertilizer is used in crop production; and the price of fertilizer. In 1986 and 1987, the price of grain was lower -- a definite negative influence on fertilizer use. In this period, it might be plausibly argued, following Willard Cochrane's "treadmill" theory, that farmers were motivated to continue to adopt technology in an attempt to maintain gross revenues, reduce unit costs of production, and overcome adverse movement in prices and net revenues from the market. If such were the case, the marginal physical productivity curve associated with fertilizer use would shift outward and, other things being equal, would increase fertilizer use. Of course, there are also plausible arguments that technological adoption could be retarded in a period of depressed conditions. Finally, the price of fertilizer was declining between 1984 and 1987, a positive influence on fertilizer use. Overall, it seems fair to hypothesize that the falling price of grain was the dominant influence, leading to reduced fertilizer use in prairie grain production in 1986 and 1987. This reduction in fertilizer use, coupled with lessened pesticide use in 1987 and 1988 and increased prairie summerfallow acreage in 1986 and 1987, are all signs that the process of "intensification" in prairie grain production was retarded, at least temporarily, by depressed conditions in the grain sector.

Table II.4 Fertilizer Use in Prairie Crop Production, 1984 to 1988 (thousand metric tonnes)

	1984	1985	1986	1987	1988
Manitoba					
Nitrogen (N)	205.1	236.1	236.0	222.5	248.0
All Nutrients (N+P+K)	326.1	362.6	360.8	340.1	380.4
Saskatchewan					
Nitrogen (N)	289.3	296.4	317.8	274.8	266.0
All Nutrients (N+P+K)	484.8	492.9	516.1	441.0	434.2
Alberta					
Nitrogen (N)	335.9	353.5	308.9	289.2	315.8
All Nutrients (N+P+K)	530.2	555.0	491.8	451.1	477.5
Prairies					
Nitrogen (N)	830.3	886.0	862.7	786.5	829.8
All Nutrients (N+P+K)	1,341.1	1,410.5	1,368.7	1,235.8	1,292.1

Source: Pidgeon (Agriculture Canada) (1988), with updated data for 1988 from Agriculture Canada (1989).

### III. Input Relations and Technology in Alberta Grain Production

The grain and oilseed production process involves inputs such as land, labor, machinery, fertilizer, and materials which are used to produce grains (wheat, oats, and barley) and oilseeds (flaxseed and canola). Estimating the production relations among these input factors -- such as substitutability between input pairs, own and cross-price elasticities of demand for each input factor, and the nature of technical change in the grain sector -- was a specific objective which was addressed in this study.<sup>2</sup> Alberta was chosen as a representative sub-unit in studying the grain sector in the prairie provinces, primarily because the data set for Alberta was more complete and extended back to 1957 which gives more flexibility in terms of degrees of freedom which are required for estimation of our model.

#### A. Estimation Procedures

The development of duality theory since the early 1970s permits the estimation of production relations either by using a production function or cost function approach. In this study, a specific flexible functional form -- namely, the translog cost function -- was utilized to estimate input relations and production technology in the Alberta grain sector. The translog cost function was specified as a function of the input prices of land, labor, machinery, fertilizer, and materials. Two further explanatory variables included were time as a technology proxy and output as a scale proxy. The basic model also involved five cost share equations, one each for land, labor, machinery, fertilizer, and materials. The translog cost function was estimated jointly with the share equations. In doing this, we had to utilize the restriction that the sum of the cost shares must equal to one. Hence, to overcome the over-identification problem in our model, one of the cost share equations (that relating to materials) was eliminated, and the remaining  $n-1$  cost share equations were estimated jointly with the translog cost function by using Zellner's Seemingly Unrelated Regression Procedure.

A general form of cost function (non-homothetic) was initially estimated. Several models such as the homothetic, Hicks neutral, constant returns to scale, and Cobb-Douglas were generated by imposing certain restrictions on this general form. The log likelihood ratio test was conducted to test different hypotheses concerning the production structure in the Alberta grain sector. The non-homothetic translog cost function could not be rejected statistically while the other specifications were rejected at the one percent level of significance. The preceding results imply that the production structure in the Alberta grain sector does not involve Hicks neutral technical change and is not characterized by constant returns to scale; further, the Cobb-Douglas specification is not the most appropriate functional form to study production structure in the Alberta grain sector. Therefore, the non-homothetic form was chosen as an appropriate specification to study the production relations in the Alberta grain sector.

#### B. Elasticities of Substitution

The estimated parameters of the non-homothetic translog cost function were then transformed into Allen partial elasticities of substitution (AES) for the Alberta grain sector. These elasticities were calculated

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<sup>2</sup> See Ali A. Rahuma, "Productivity Growth and Production in the Prairie Grain Sector," Unpublished Ph.D. dissertation, Edmonton: University of Alberta, Department of Rural Economy for a more detailed discussion of this work, particularly Chapter 6. The grain sector in this dissertation and in this section of the report is restricted to the five major cereals and oilseeds grown on the prairies.



at the mean value of the cost shares for the entire period and were also calculated for different points of time to examine changes in substitutability and complementarity over time. The results of these calculations are presented in Table III.1.

Table III.1 Allen Partial Elasticities of Substitution, Alberta Grain Sector.

Input Pair	Mean	1957-63	1964-70	1971-77	1978-84
L-N	-0.300**	-0.548	-0.391	-0.265	-0.449
L-K	0.704	0.498	0.633	0.684	0.838
L-F	3.018***	8.355	3.575	2.984	1.833
L-M	-1.644*	-2.397	-1.886	-1.865	-1.154
N-K	0.100**	0.206	0.111	0.092	-0.224
N-F	-0.010**	-0.912	-0.025	0.800	-0.035
N-M	1.045***	1.030	1.039	1.046	-1.091
K-F	7.100*	17.334	8.119	7.105	4.045
K-M	-0.940***	-0.847	-0.954	-1.180	-0.928
F-M	-2.900*	-6.965	-3.035	-2.957	-1.920

Notes: L = Land, N = Labor, K = Machinery, F = Fertilizer, and M = Materials.

$\sigma_{ij} > 0$  indicates that the i-th and j-th factors are substitutes.

$\sigma_{ij} < 0$  indicates that the i-th and j-th input factors are complements.

\*, \*\*, \*\*\* denotes the values of AES obtained from gamma coefficients significant at 1%, 5%, and 10% level, respectively.

Source: Rahuma (1989:158)

There is strong evidence supporting the conclusion that substitutability does exist between land and fertilizer, between labor and machinery, and between machinery and fertilizer in Alberta grain production. However, the degree of substitutability between each of these input pairs has declined over time. On the other hand, complementarity relationships were found between land and labor, between land and materials, between labor and fertilizer, and between fertilizer and materials. The substitutability between land and fertilizer and the complementarity between labor and fertilizer were expected results, typically confirmed in North American studies. The significant substitute relations between machinery and fertilizer, albeit declining in degree over time, are a broad indication of substitution between key facets of mechanical and bio-chemical technology, respectively.

### C. Own and Cross Price Elasticities

Own and cross price elasticities are measures of the responsiveness of the quantity demanded of a particular input, respectively, to the change in its own price ( $P_i$ ) or to the price of another input ( $P_j$ ). The parameters of the estimated non-homothetic cost function were used to calculate the own and cross price elasticities shown in Table III.2. The lowest own price elasticity occurs for land which implies that the demand for land is highly price inelastic. It can also be seen that the demands for labor and machinery are both price inelastic. However, the demand for labor shows a smaller response to the change in the wage rate per hour compared to the demand for machinery vis-a-vis a change in the price of machinery. The input demand elasticity for fertilizer has the highest negative value, exceeding unity, indicating that fertilizer is a price-elastic factor and the factor which is most sensitive or responsive to changes in its own price. Contrary to expectations, the own price elasticity of demand for materials is positive. The cross price elasticities indicate substitutability if the sign of the coefficient is positive and complementarity if the sign is negative. Fertilizer and machinery showed the highest degree of substitutability, while fertilizer and labor have the lowest degree of complementarity.

Table III.2 Own and Cross Price Elasticities of Input Demand for Alberta Grain Sector.

	L	N	K	F	M
L	-0.007	-0.115	-0.110	0.312	-0.300
N	-0.052	-0.153	-0.016	-0.002	0.191
K	0.123	0.038	-0.719	0.730	0.172
F	0.526	-0.004	1.102	-1.095	-0.530
M	0.286	0.401	-0.147	-0.300	0.333

Notes: L = Land, N = Labor, K = Machinery, F = Fertilizer, and M = Materials.

Diagonal elements are the respective input own-price elasticities of demand.

$\eta_{ij} > 0$  = input factors i and j are substitutes.

$\eta_{ij} < 0$  = input factors i and j are complements.

Source: Rahuma (1989:160).

### D. Technological and Scale Effects

In this study technical change and scale economies were introduced as a time variable (T) and an output quantity (Q), respectively, into the cost function. By examining the sign of the estimated coefficient of the interaction of the time and output variables with the i-th input price index, one can infer certain conclusions about the direction of technical change and scale effects. The estimated coefficients of these two variables are presented in Table III.3.

Table III.3 Technical Change and Scale Effects.

Input	Technical Effect	Scale Effect
Land	$\gamma_{LT} = -0.0017$ (-0.23)	$\gamma_{LQ} = 0.0261^{***}$ (1.36)
Labor	$\gamma_{NT} = -0.0441^*$ (-4.99)	$\gamma_{NQ} = -0.1098^*$ (-3.99)
Machinery	$\gamma_{KT} = (0.0186)$ (1.788)	$\gamma_{KQ} = 0.0321^{**}$ (1.62)
Fertilizer	$\gamma_{FT} = 0.0263^*$ (3.18)	$\gamma_{FQ} = 0.0278^{***}$ (1.21)
Materials	$\gamma_{MT} = 0.0009$ (0.49)	$\gamma_{MQ} = 0.0238^{***}$ (1.23)

Notes: t values are in parentheses

\* = significant at 1% level

\*\* = significant at 5% level

\*\*\* = significant at 10% level

$(\gamma_{iT}) > 0 \rightarrow$  input using technical change.

$(\gamma_{iT}) < 0 \rightarrow$  input saving technical change.

$(\gamma_{iT}) = 0 \rightarrow$  Hicks neutral technical change.

$(\gamma_{iQ}) > 0 \rightarrow$  scale effect is input using.

$(\gamma_{iQ}) < 0 \rightarrow$  scale effect is input saving.

$(\gamma_{iQ}) = 0 \rightarrow$  neutral scale effect.

It can be seen from this table that the general direction of technical change in the Alberta grain sector has been labor saving, and machinery and fertilizer using. The coefficient of labor is negative and highly significant which indicates that technical change has been labor-saving. This finding is consistent with the result which is reported by Furtan and Lee (1978) for Saskatchewan wheat production. This conclusion is sensible and expected on *a priori* grounds, because the wage rate per hour has shown remarkable increases since the early 1970s. Therefore, grain farmers have employed relatively less expensive input factors in their production process. The coefficient of land is negative, but it is not statistically significant, which implies that technical change has been neither land-saving nor land-using. The coefficients of machinery and fertilizer use are both positive and significant which implies that technical change in Alberta grain production has been both machinery and fertilizer using. Finally, the coefficient of materials input is positive but not significant which means that there is no strong conclusion which can be made with respect to the effects of technical change on the use of materials input over time.

The scale effects or the effects of the change in output level on the demand for various input factors also can be examined from Table III.3. The coefficient of the interaction term between labor and output is negative and highly significant which implies that the scale effect with respect to labor is labor saving. This latter result indicates that both technical change and the scale effect operate in the same direction towards labor saving. Further, the coefficient of the interaction term between machinery and output is positive and significant which implies that this scale effect is machinery using. These two strong results with regard to the effect of scale impacts on labor and machinery are expected on *a priori* grounds, since labor and machinery are substitutes in the production process. Therefore, any expansion or reduction in output level will effect the demands of labor and machinery in opposite directions. The remaining scale coefficients with respect to land, fertilizer, and materials are positive and significant at only the ten percent level of significance, which indicates that the remaining scale effects are weakly land, fertilizer, and materials using.

#### E. Productivity and Economies of Scale

In addition to estimating the impacts of scale effects on respective input demands, we had also hoped to estimate the overall extent of economies of scale in grain production and to subdivide estimated productivity growth into a sub-component associated with nonconstant returns to scale and a sub-component associated with pure technical change. Due to estimation and econometric difficulties, this has not, as yet, been satisfactorily accomplished. The basic decomposition relationship, following Capalbo (1988), is:

$$\begin{array}{l} \text{Rate of growth of} \\ \text{estimated total} \\ \text{factor productivity} \end{array} = \text{Scale effect} + \begin{array}{l} \text{Pure technical change} \\ \text{(shift of the cost} \\ \text{function)} \end{array} + \text{Residual}$$

If constant returns to scale prevail (and the residual equals zero), then estimated productivity growth would be identical with pure technical change. In Capalbo's case of United States agriculture between 1950 and 1982, measured technical changes (as represented by the estimated shift of the translog cost function) was twelve percent greater than the estimate of productivity growth due to the estimated presence of decreasing returns to scale in U.S. agriculture. Prairie grain production is typically thought, by most observers, to be characterized by (modest?) economies of scale (increasing returns to scale). If this is the case, estimated productivity growth would somewhat overstate the extent of pure technical change.



#### IV. The Impact of Fertilizer and Weather on Productivity

In this section of the report, the impact of fertilizer (and other technology proxies), weather, and possible synergistic interactions of fertilizer and weather on productivity in prairie crop production is examined.

The productivity measures used in this section are total factor (or multi-factor) productivity measures, rather than partial productivity measures such as output per man or yield. The productivity estimates, in fact, are in the form of index numbers of the Divisia type, obtained in the past and refined in current Farming for the Future projects (Veeman and Fantino, 1985; Veeman, Fantino, and Rahuma, 1989). In this analytical framework, outputs and inputs in crop production are respectively aggregated using flexible weight, Tornqvist-Theil index number procedures rather than fixed base weight, Laspeyres procedures. The level of productivity in any one year is merely aggregate crop output divided by aggregate input use in crop production. Consequently, productivity growth is estimated residually by subtracting the rate of growth of aggregate input from the rate of growth of output in crop production. Estimates of output, input, and productivity in the prairie crop sector are portrayed graphically in Figure IV.1.

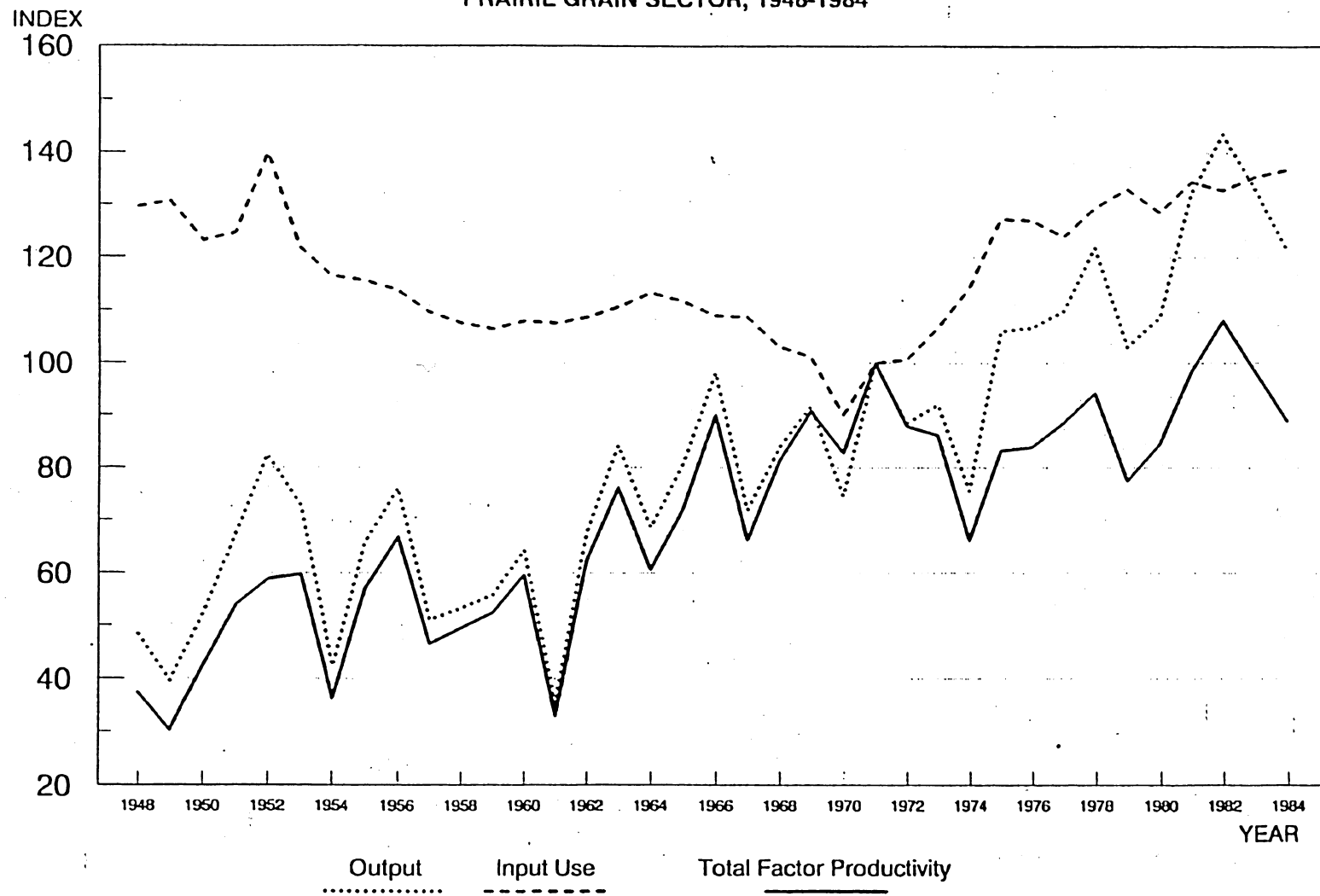
##### A. Productivity/Technology/Weather Relationships

As can be seen in Figure IV.1, the productivity index for prairie crop production exhibits a rising trend over the period with considerable year-to-year fluctuations around this trend line. The trend represents the long term change in productivity which, we hypothesize, is associated with technological and structural factors. The year-to-year fluctuations or short term productivity variations appear to be related primarily to weather/climatic factors and prevailing economic conditions. Below trend years are, in most cases, easily associated with environment-weather effects, for example the years of 1954 (rust) and 1961 and 1971 (drought). Above trend years, in turn, are associated with very favorable weather conditions, such as the bumper crops of 1966, 1978, and 1982.

In the long run, technological change has been recognized as the major source of productivity improvement, and therefore the study of technological factors affecting productivity is essential. In this study, time and fertilizer are used as two key proxies for technological change. Fertilizer use has increased dramatically in prairie production and represents a major component of bio-chemical technical change. Since technological innovation and the adoption of technology take place over time, economists have often used a time trend as an approximation for technological change. Other factors affecting agricultural productivity and production in the long run, beside pure technological change, might include: economies of scale, increased efficiency resulting from learning processes, better educated farmers and workers, more effective extension services, and technological change occurring in other industries which are transferred to agriculture through higher quality of purchased inputs such as machinery, seeds, fertilizer and pesticides. Some of these latter factors are often included in a broad interpretation of technological change.

Factors affecting productivity in the short run, on the other hand, have mostly to do with general economic conditions and with the effect of environmental factors, of which weather, principally rainfall and temperature in the growing season, is the most apparent factor causing changes in productivity and agricultural output from season to season. There is an obvious difficulty in defining "weather" for such a large and extended area as that of the grain growing regions of the prairies. In this research, weather variables relevant for prairie agriculture were defined as arithmetic combinations of weather station monthly

FIGURE IV.1 INDEXES OF OUTPUT, INPUT USE AND  
TOTAL FACTOR PRODUCTIVITY, (1971 = 100),  
PRAIRIE GRAIN SECTOR, 1948-1984



observations. Weather data on rainfall, air temperature, and solar radiation were collected from 25 weather stations located in important grain producing areas across the prairies. A particular weather variable--total June rainfall, for example--was constructed as a weighted average of all the observations from the weather stations. The weights used were the respective fractions of area planted to six major crops (grains) in a region around each weather station to the total area planted in the prairies to these six crops. The two constructed prairie weather relating to rainfall, June rain and July rain, are portrayed graphically in Figure IV.2. Similarly, the composite temperature variables for the prairies, June temperature and July temperature, are shown in Figure IV.3.

**FIGURE IV.2 WEATHER VARIABLES: JUNE RAIN AND JULY RAIN, PRAIRIE GRAIN SECTOR, 1948-1984**

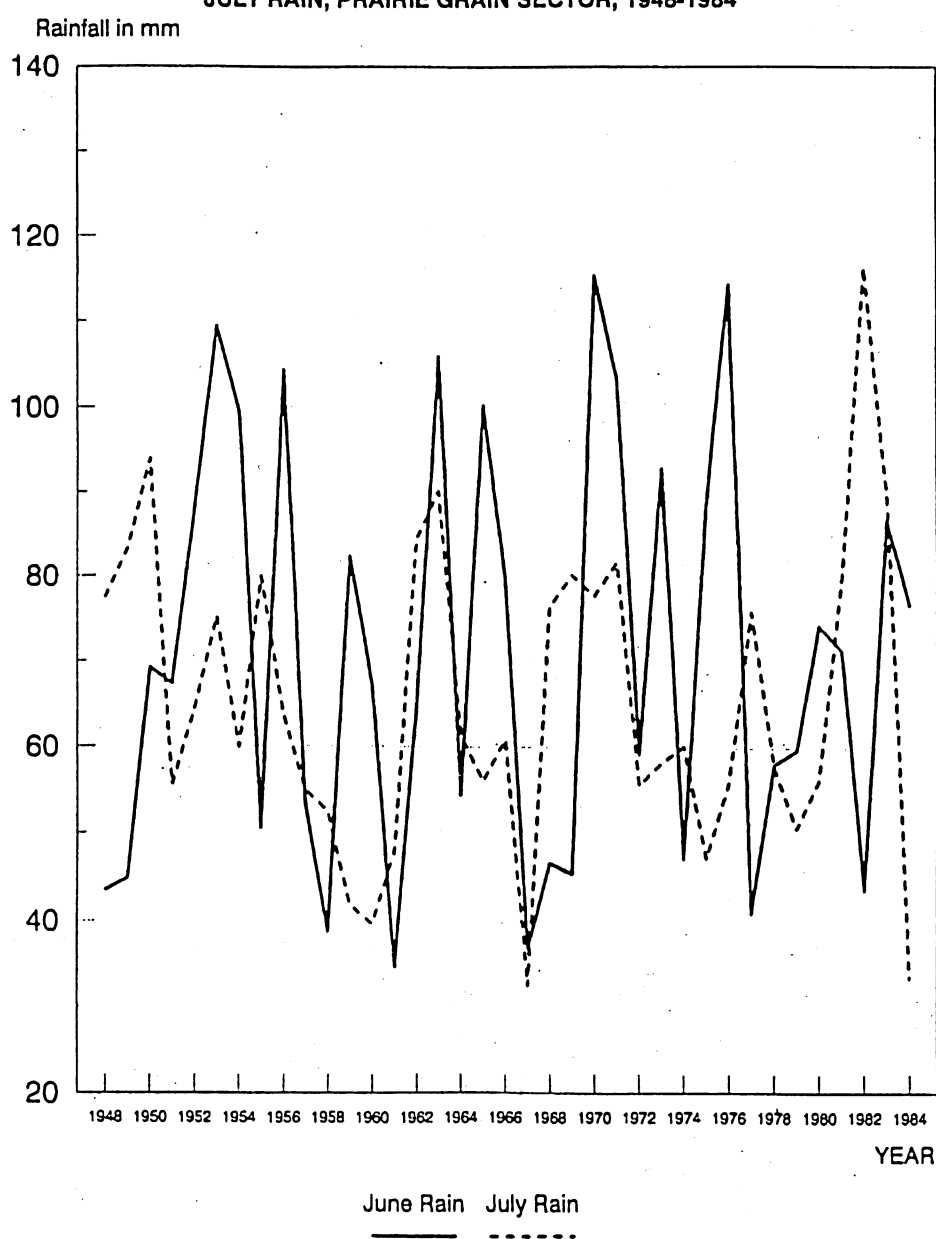
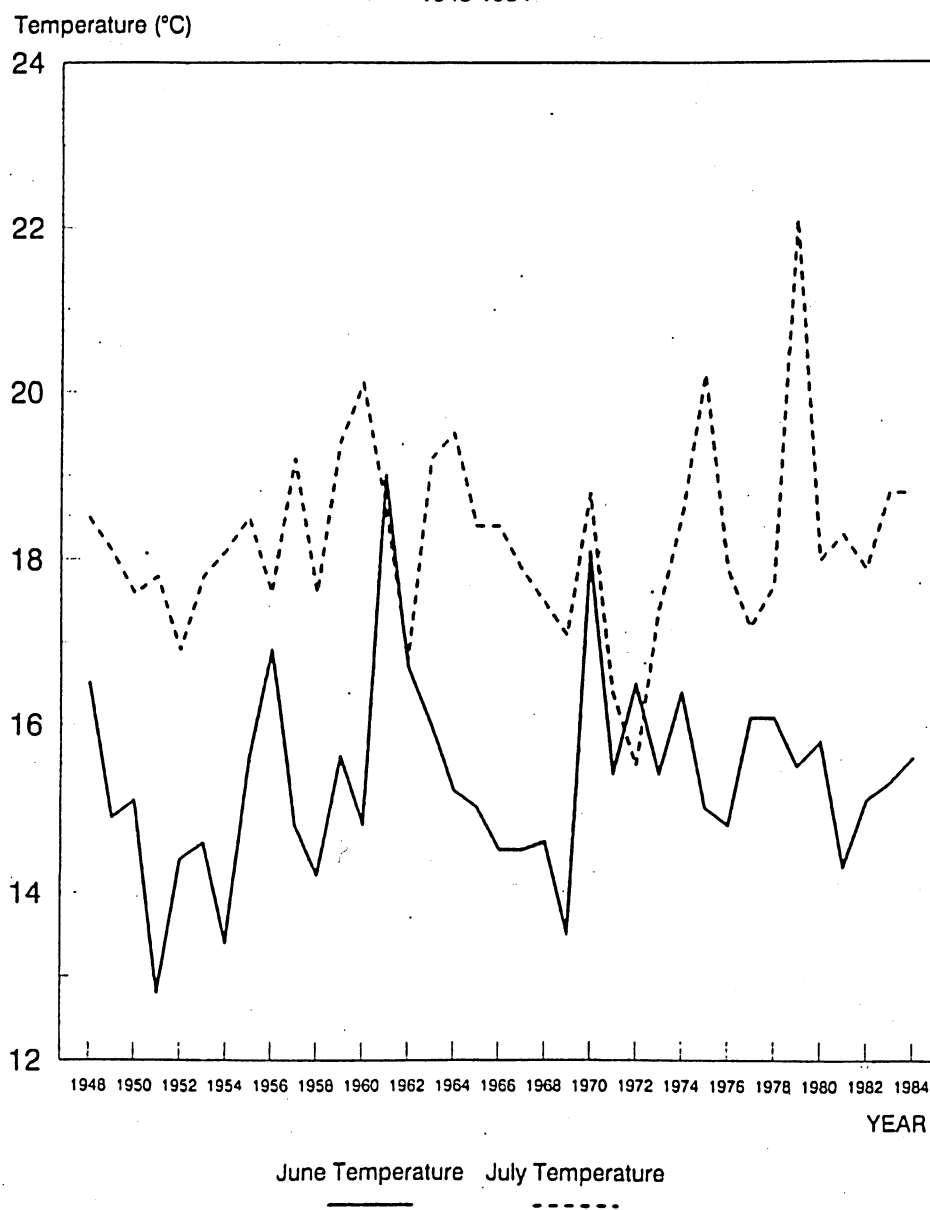


FIGURE IV.3 WEATHER VARIABLES: JUNE TEMPERATURE  
AND JULY TEMPERATURE, PRAIRIE GRAIN SECTOR,  
1948-1984





In the study of effects of the weather variables on productivity, the statistical technique of regression analysis was utilized. This technique allows meaningful or significant correlations between productivity and each weather variable to be identified and tested. The result is an estimated equation showing the relationship between productivity on the one hand (the dependent variable) and each and all the weather variables (the independent variables). The equation shows us how--that is to say, in what direction and by how much--the yearly variations in weather affect productivity in agriculture. In order to take into account the rise of productivity over time, a variable T, equal to the number of years since the first year in the period, is added to the equation. This is the time trend term which is used initially as a "proxy" variable for technical change.

A representative equation estimated in this research was of the general form:

$$TFP = C + A(\text{June rain}) + B(\text{July rain}) + D(\text{June temp}) + E(\text{July temp}) + gT + e$$

In this equation, TFP is the series of yearly values of total factor productivity estimated in some time period; C is the constant term; A, B, D, and E are coefficients of the weather-productivity relationship and measure the respective effect of each weather variable on TFP; T is the time trend, and its coefficient, g, measures how fast productivity was rising on average in the period; and e is the disturbance or error term which accounts for the fact that random effects are also present.

Since we are dealing here with simple linear models of the effect of weather on productivity, which, in reality, is a highly complex phenomenon, care should be exercised when interpreting results. It should be kept in mind that productivity measures in this study, and the weather and technology effects on such measures, are estimated at a high level of aggregation: the prairie region. As a consequence, the estimates are averages over this entire region as well as over time. Moreover, there are several conceivable shortcomings of such simple models which may lead to biases in the estimates. Specification errors may result if variables that may be of relevance are not included in the model, or if an improper mathematical form -- for instance, linear as opposed to non-linear -- is utilized for the equation. Examples of variables not included in the simple models that may be of relevance are soil moisture at planting time, precipitation during the harvest period, and solar radiation. Trial regressions including some of these variables or proxies were performed when data were available. The results suggest that proxies for soil moisture are of relevance in the weather-productivity relationships. However, the true relationship appears to be highly non-linear in these variables. Future research is aimed at a more detailed study of these variables and non-linear effects. The weather coefficients or impacts presented in this report, then, should be considered to be estimates under average conditions, including soil moisture conditions and output mix, prevailing in the prairies in the time period considered.

Some of the estimated equations are presented in Table IV.1. As an example, consider Equation 1 which gives the estimated productivity-weather-technology relationship, with time as a proxy for technology, for the period 1948-1984 in prairie agriculture as a whole:

$$TFP = C + 0.010(\text{June } r) + 0.015(\text{July } r) - 0.022(\text{June } t) - 0.018(\text{July } t) + 0.017 T$$

We first note that the coefficients of rainfall are positive and those of temperature are negative. The relationship is telling us that the effect of additional rainfall on productivity is beneficial, while the effect of higher average temperatures is detrimental for agricultural productivity and production. This is in accordance

Table IV.1 Productivity-Weather-Technology Relationships Using Time as a Proxy for Technology, Prairies and Alberta

Eq.	Region	Sector	Period	Rainfall <sup>2</sup>		Temperature		Time	R <sup>2</sup>
				June	July	June	July		
1	Prairies	Agric.	1948-84	0.010	0.015	-0.022	-0.018	0.017	89
2	Prairies	Crop	1948-84	0.016	0.020	-0.024	-0.031	0.017	87
3	Prairies	Crop	1956-84	0.020	0.025	-0.040	-0.032	0.015	88
4	Prairies	Crop	1959-84	0.016	0.025	-0.048	-0.031	0.014	88
5	Alberta	Crop	1948-84	0.014	0.022	-0.028*	-0.012	0.016	86
6	Alberta	Crop	1959-84	0.010	0.021	-0.014	-0.013	0.013	79

<sup>1</sup> The agricultural sector includes both crops and livestock. The crop sector comprises cereals, oilseeds, and specialty crops.

<sup>2</sup> Rainfall is measured in centimetres; temperature is measured in degrees Centigrade; and productivity is measured in terms of index numbers based on 1971 = 1.000.

<sup>3</sup> Statistical notes: all coefficients statistically significant at the 5% level of confidence (except \* at the 10% level); R<sup>2</sup> is the correlation coefficient which indicates the "goodness of fit" of the estimated equation; and estimation procedure involved correction for auto-regression when necessary.

with what can be expected by experience and common sense, since moisture is a limiting factor in the prairies and higher temperatures increase evapo-transpiration of crops and moisture stress. All four weather variables are statistically significant in this equation. "Goodness of fit" is relatively high: 89 percent of the variation in productivity is associated with the explanatory variables in this equation.

A positive coefficient for the time trend means productivity is rising over the period; more precisely, this means a yearly increase of 0.017, or an average productivity growth over the period of 0.017 productivity index points per year. Expressed as a simple linear rate of growth (divide  $g$  by the average productivity and multiply by 100), this increase in productivity is 1.9% per year. Such growth in productivity is considerable, representing approximately a doubling of the output produced with the use of the same set of inputs in about fifty years.

Equation 2 in Table IV.1 refers to the crop sector of prairie agriculture. The magnitude of the coefficients of the weather variables in this equation are somewhat higher, reflecting the higher sensitivity of the crop sector to weather influences. The coefficients of June rainfall and temperature indicate that productivity increases 0.016 index points (1.9% using the same procedure as before) per each additional centimeter of rain in the month of June and decreases 0.024 points (2.8%) with an increase of one degree in average monthly temperature in June. It is not surprising that there is a positive and statistically significant relationship between productivity and June rainfall -- see Figure IV.4. In Equation 3, the prairie crop sector results for a slightly shorter time period, 1959-84, are quite similar to those for the 1948-84 period, with the

coefficients for July rainfall and June temperature being higher but the time trend coefficient (and hence the linear rate of productivity growth) being slightly lower. In the final two equations in Table IV.1, crop productivity-weather-technology relationships for the province of Alberta are portrayed. As anticipated, productivity in the crop sector in Alberta is less sensitive to weather influences than in prairie crop production as a whole.

In Table IV.2, the estimated results of productivity-weather relationships are presented wherein the amount of applied fertilizer is used as a proxy for technology. Our previous research indicated that fertilizer appeared to be highly correlated with productivity. In addition, the fertilizer variable is more directly linked to technical change than is a proxy variable such as time. Our estimated results indicate that fertilizer in lieu of time serves nearly as well as a technology proxy: the weather coefficients have the correct sign, they are generally highly statistically significant (except, in Alberta, for June temperature), and the explanatory variables continue to "explain" a high proportion of the variation in productivity. The estimated coefficient on fertilizer in Equation 2 indicates that a 10 percent increase in the amount of applied fertilizer translates into an increase of 0.0116 index points (or approximately 1.65 percent) in productivity in prairie crop production.

Table IV.2      Productivity-Weather-Technology Relationships Using Fertilizer as a Proxy for Technology, Prairies and Alberta

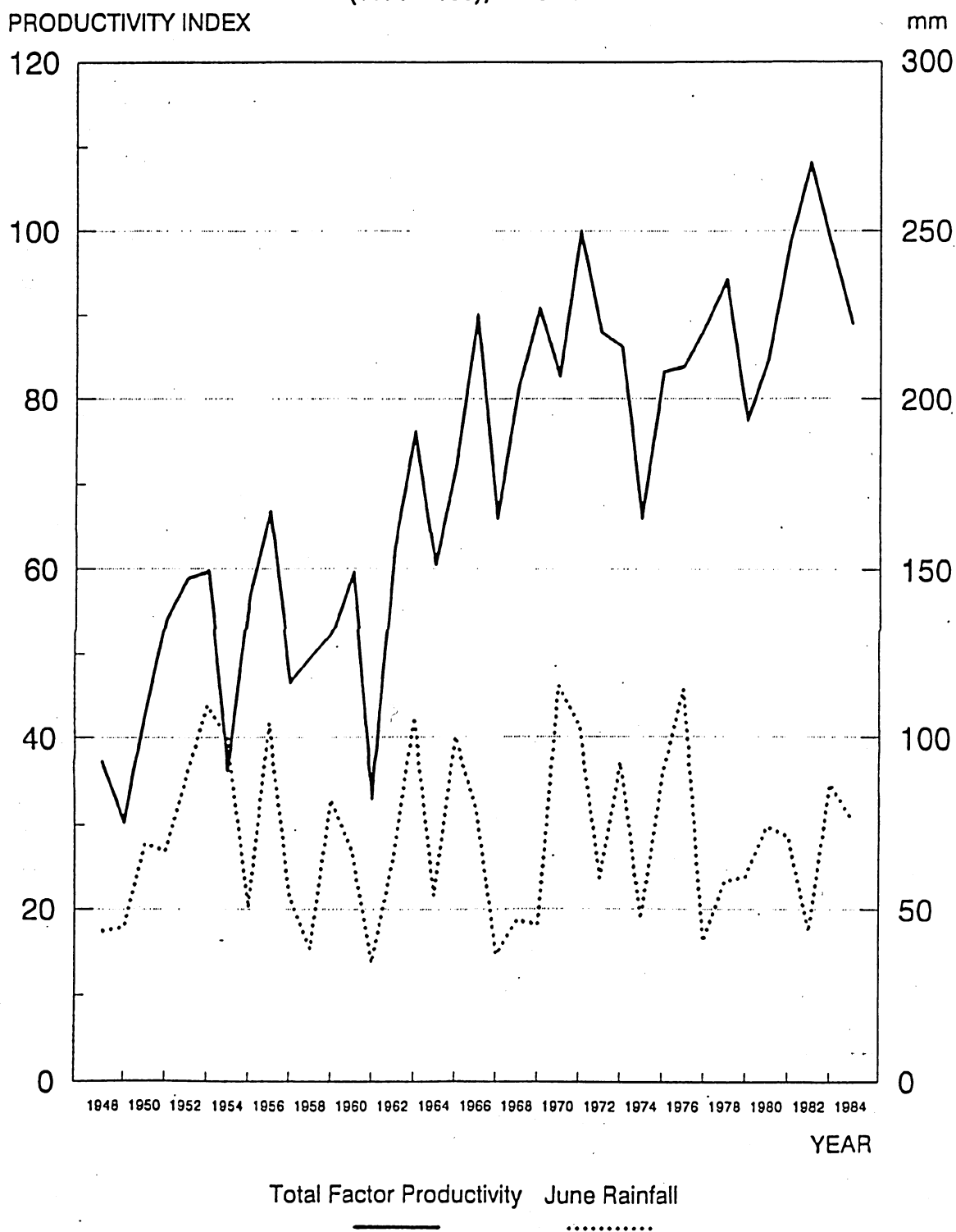
Eq.	Region	Sector	Period	Rainfall <sup>2</sup>		Temperature		Fert.	R <sup>2</sup>
				June	July	June	July		
1	Prairies	Agric.	1948-84	0.014	0.025	-0.019	-0.023	0.124	84
2	Prairies	Crop	1948-84	0.017	0.030	-0.024	-0.025	0.116	79
3	Prairies	Crop	1959-84	0.017	0.030	-0.044	-0.029	0.078	84
4	Alberta	Crop	1948-84	0.015	0.022	-0.004*	-0.014	0.127	82
5	Alberta	Crop	1959-84	0.010	0.021	-0.012*	-0.015	0.077	77

<sup>1</sup> The agricultural sector includes both crops and livestock. The crop sector comprises cereals, oilseeds, and specialty crops.

<sup>2</sup> Rainfall is measured in centimetres; temperature is measured in degrees Centigrade; and productivity is measured in terms of index numbers based on 1971 = 1.000.

<sup>3</sup> Statistical notes: all coefficients statistically significant at the 5% level of confidence (except \* at the 10% level); R<sup>2</sup> is the correlation coefficient which indicates the "goodness of fit" of the estimated equation; and estimation procedure involved correction for auto-regression when necessary.

FIGURE IV.4 TOTAL FACTOR PRODUCTIVITY AND  
JUNE RAINFALL, PRAIRIE GRAIN SECTOR,  
(1971 = 100), 1948-1984





## B. The Detection and Estimation of Weather-Technology Interactions

The next step in the study of relationships between productivity and weather/technology variables involved the analysis of possible interactions between weather variables, such as rainfall, and technological trend proxies, such as fertilizer. The introduction of composite weather-fertilizer terms into estimated equations could have two potential effects. First, such interaction terms could be statistically significant influences on productivity in and of themselves. Secondly, where such terms prove to be significant, the estimated coefficients of weather variables in estimated equations could now be viewed as being variable over time or dependent upon technology.

The motivation to study these interaction effects basically originated from our empirical work -- observation of variations over time of the estimated weather coefficients and visual observation of regression residuals. Interactions of technology with crop responses to weather, if such interactions are of proper magnitude and if technological change proceeds over time, may lead to weather coefficients which either increase or decrease over time. Interactions, then, can take the form of changes in the estimated productivity-weather relationship caused by (or, more correctly, correlated with) technology variables. Significant weather-technology interactions can be interpreted to imply that weather-productivity relationships are not fixed but alter with changes in technology. In order to explore this idea, terms composed of both a weather variable and a technology variable were added to the equations in Tables IV.1 and IV.2. Such terms often turn out to exhibit various degrees of statistical significance, in particular for the most recent portion of our time period.

If the inspiration to look into the stability of the coefficients in the estimated equations was mostly empirical, there are also a number of considerations of a more general nature pointing to interactions between weather and technology. For example, the fact that water is required for fertilizer to provide nutrients to plants suggests that the role of soil moisture in production may change with increased fertilizer use. Similarly, joint effects involving pairs of production inputs, such as fertilizer and pesticides, are at least conceivable. A common feature in these examples is that the level of use of a given production factor/input impinges on the production efficiency of a second factor. These effects are known in the literature as "synergistic" effects. In addition to synergistic effects, technology-weather interactions may also result, in a similar fashion, from features of the new technology "package" being adopted. For example, if a new technology package includes new varieties that use water more efficiently and are drought resistant, yields and productivity would be less susceptible to variations in rainfall and the productivity-weather relationships may change as the new package is adopted. Something similar is to be expected if new technology includes cultural practices which change moisture availability, such as snow management, or which alter the efficiency in the use of water by crops.

## C. Introducing Interaction Effects Into the Model

The specification of the relationship developed previously in Section III was modified by the addition of interaction terms. A simple specification for such terms is to form the product of a weather variable and a technology variable -- for example, the product of June rainfall and fertilizer use. This formulation of the problem is perhaps too simplistic to expect that it will be able to account completely for the complexities of synergistic and technological interaction effects in agriculture. Nevertheless, terms of this form are used in this study in order to empirically explore interactions in the productivity-technology-weather relationship. Both technology proxies, time and fertilizer, were utilized in this study for both the long run trend and the technology-weather interaction terms. Various combinations are possible, given that either time or fertilizer

can be used as the technology proxy. Let (T,F), for example, stand for a combination where time is used to represent the secular trend and fertilizer is used in constructing the weather-technology interaction terms. The following combinations were, in fact, considered: (T,T), (T,F), and (F,F). Interaction terms for all four weather variables considered in the equations in Tables IV.1 and IV.2, in conjunction with-time or fertilizer, were studied.

The initial investigation of interaction terms took the form of adding single, and then multiple, interaction terms to the productivity/technology/weather specifications reported in Tables IV.1 and IV.2 and examining, in terms of Students t-statistic, whether the estimated coefficients on interaction terms were statistically significant. The estimation of such equations over the longer time frame from 1948 to 1984 proved less useful, largely because fertilizer use did not play that important a role prior to the late 1950s. As a consequence, more attention was paid to equations estimated from the mid 1950s to 1984. As an example, consider the following equation of the (T,F) form estimated for productivity in prairie crop production in the 1956-1984 period and in which four interaction terms are included:

$$\begin{aligned} \text{TFP} = & 150.82 + 1.430T + 0.404 \text{ June } r + 0.188 \text{ July } r - 0.464 \text{ June } t - 0.412 \text{ July } t - 0.0030 \text{ June } r * F - 0.00009 \text{ July } r * F + 0.00055 \text{ June } t * F \\ & (4.81) \quad (3.34) \quad (4.64) \quad (1.46) \quad (-3.80) \quad (-2.51) \quad (-2.99) \quad (0.13) \quad (0.34) \\ & + 0.0007 \text{ July } t * F \\ & (0.56) \end{aligned}$$

In order to facilitate the reporting of interaction effects, total factor productivity (TFP) is re-scaled in terms of 1971=100, rainfall is measured in terms of tenths of centimetres (millimetres), temperature is measured in terms of tenths of a degree Centigrade, and F is the fertilizer implicit quantity (not, however, indexed to 1971). The figures in brackets are the respective t-statistics of the estimated coefficients. In the above equation, the constant term, the technological trend variable proxied by T, three weather variables (that is, the "direct" effects of June rainfall, June temperature, and July temperature), and the interaction term between June rainfall and fertilizer are all highly statistically significant (at the 1 percent level of significant). July rainfall exhibits weaker statistical significance (at the 10 percent level) and the remaining three interaction terms are not statistically significant. "Goodness of fit" of the estimated equation, indicated by  $R^2$ , is 92 percent and the Durbin-Watson test for autoregression is inconclusive.

The foregoing equation illustrates common results in our work. The effects of rainfall in June and July on productivity are always positive, whereas the interaction effects between fertilizer and rainfall are always negative. The reverse is true for temperature: the effects of June and July temperature are negative, whereas the interaction effects of fertilizer and temperature are typically positive. Granted that interaction terms are not always statistically significant, it might nevertheless be suggested that the respective interaction effects appear to be making the overall influence of rainfall on productivity less positive and the overall influence of temperature on productivity less negative. In short, the negative interaction between rain-fertilizer (shown in our example to be statistically significant only for June rainfall) and the likely positive interaction between temperature-fertilizer suggest that fertilizer application, a key aspect of biochemical technical change, may be attenuating or lessening the sensitivity of prairie agricultural productivity to climatic variations. We shall return to this theme later and discuss the difficulties of interpreting our results unambiguously.

#### D. Formal Testing of Individual Interaction Terms

The inclusion of all or several interaction terms in the same estimating equation often proved to be too cumbersome and led to regressions prone to econometric problems such as multicollinearity. In general, equations of the (T,F) form performed better than those of the (F,F) form, because of multicollinearity between fertilizer and interaction terms involving fertilizer. Given the complexity of the equations, a more formal and systematic testing procedure, involving one interaction variable at a time, was implemented to test the relevance of the possible interaction terms in the linear productivity-technology-weather relationship. The test procedure involves an F-test designed to appraise the relevance of the inclusion of an additional variable in a given model on the basis of the change in the coefficient of determination,  $R^2$ , when the extended model is re-estimated and assuming an adopted level of significance (for details of this test, see Kmenta, 1971, p. 370).

Many permutations involving over 100 runs were calculated under the following scenarios: interactions involving four possible weather variables (June rain, July rain, June temperature, and July temperature), plus a combined summer rainfall alternative; three technology trend/interaction alternatives [(T,T), (T,F), and (F,F)]; two specifications of the fertilizer variable (total fertilizer use, FQ, as measured by the fertilizer implicit quantity index, and average fertilizer application rate, FR, measured as FQ divided by the number of cropped acres); two spatial regions (the overall prairie region and the province of Alberta); and three time periods (1948-84, 1956-84, and 1959-84). The dependent variable in all cases was total factor productivity in crop production at either the prairie or Alberta level. Where autoregressive disturbances were detected, the estimating equation was corrected using the Cochrane-Orcutt procedure.

The positive test results for the 1956-84 period are presented in Table IV.3. By far the most important interaction terms are those involving June rainfall or, by extension, summer rainfall (that is, combined rainfall in June and July). Linear interaction terms, involving rainfall in June are, therefore, highly relevant for inclusion in the linear model (based on the four direct weather variables as reported in Tables IV.1 and IV.2) for the prairies. Other interaction terms involving July rainfall, June temperature, and July temperature -- when tested one at a time -- did not prove statistically significant at the relatively highly demanding 5 percent level for the prairie region. Nor did any interaction terms prove statistically significant for crop productivity in Alberta -- indirectly pointing to the considerable impact of conditions in Saskatchewan on variations in crop productivity on the prairies as a whole. The insignificance of linear interaction terms for Alberta crop productivity, of course, does not rule out the possibility that interactions may be present in more complex or curvilinear specifications, or that the proper specification of the model actually involves more than one interaction term.

Table IV.3      Productivity-Weather-Technology Relationships: Testing Linear Interaction Terms With Time and Fertilizer as Technology Proxies. Prairie Crop Sector, 1956-1984.

No.	Interactions		Standard Regression		Autoregression Corrected	
	Type	Term	Confidence (%)	DW <sup>1</sup>	Confidence (%)	t <sup>2</sup>
1	(T,T)	Time & June Rain	99.5	1.95	99.5	3.1
2	(T,T)	Time & Summer Rain	96.2	2.00	93.8	2.0
Fertilizer Variable: Total Fertilizer Quantity (FQ)						
3	(T,F)	FQ & June Rain	92.2	1.90	92.0	1.9
4	(F,F)	FQ & June Rain	99.2	1.58*	98.4	2.6
5	(F,F)	FQ & Summer Rain	93.2	1.48*	86.0	1.6
Fertilizer Variable: Average Fertilizer Application Rates (FR)						
6	(T,F)	FR & June Rain	95.7	1.92	95.6	2.1
7	(F,F)	FR & June Rain	99.5	2.00	98.5	2.7
8	(F,F)	FR & Summer Rain	93.8	1.69*	91.0	1.8

<sup>1</sup> Durbin-Watson (DW) Statistics

<sup>2</sup> t-statistic

\* Suggests significant autoregression

#### E. Expanded Models Involving Interactions

Given the statistical importance of weather-technology interaction terms involving June rainfall on the prairies, four estimated equations including a June rainfall interaction term are presented in Table IV.4. In the first equation, the interaction is between June rainfall and time. In the latter three cases, the interaction term involves June rainfall and fertilizer. In all four equations, the linear interaction term is statistically significant at the 5 percent level. The weather variables are also statistically significant, June rain and July rain each having positive impacts on productivity and June temperature and July temperature having negative influences. In each instance, the significant interaction term has a negative estimated coefficient. Such a result can be plausibly interpreted as implying a reduced impact of June rainfall over time or, more generally speaking, along the path of technological change.

Where significant interaction occurs, the weather coefficients should be interpreted somewhat differently. In Tables IV.1 and IV.2, in which no interactions are involved, the estimated June rainfall coefficients should be regarded as average estimated effects of June rainfall on productivity over the time period. In Table IV.4, however, where interaction effects are incorporated, the estimated June rainfall coefficient should now be interpreted as the impact of June rain on productivity at low levels of fertilizer application (or early period of time) -- that is to say, the impact under the technological conditions prevailing

Table IV.4      Estimated Linear Productivity-Technology Weather Relationships Including Linear June Rainfall-Technology Interaction Terms, Prairie Crop Sector, 1956-1984.

No.	Interaction		Trend	Rainfall		Temperature		R <sup>2</sup>	DW
	Type	Coefficient		June	July	June	July		
1	(T,T)	-0.0020	2.88	0.64	0.18	-0.44	-0.34	92	1.95
2	(T,F)	-0.0110	2.05	0.26	0.22	-0.44	-0.28	90	1.90
3	(F,F) <sup>2</sup>	-0.0034	0.41	0.47	0.18	-0.39	-0.46	87	1.58
4	(F,F) <sup>3</sup>	-0.0026	0.34	0.38	0.23	-0.43	-0.33	88	2.07

<sup>1</sup> In these equations, productivity is re-scaled in terms of 1971=100; rainfall is measured in millimetres rather than centimetres; and temperature is measured in tenths of a degree C. This re-scaling implies that the estimated rainfall and temperature coefficients will be ten times larger than those in Tables IV.1 and IV.2.

<sup>2</sup> Equation for which Durbin-Watson test indicates possibility of autoregression (inconclusive case).

<sup>3</sup> Estimated by iterative procedure to correct autoregression.

<sup>4</sup> Statistical notes: all estimated coefficients are significant at the 5% level of confidence; most coefficients are also significant at the 1% level.

in the later 1950s, the beginning of our time of study. In Table IV.4, then, the estimated June rainfall coefficient could be called a "direct" effect of June rain on productivity, while the interaction term involving June rain (and either fertilizer or time) could be regarded as a "indirect" effect of June rain on productivity. Since the direct effect is positive while the indirect effect is negative, the overall effect of June rainfall on productivity, through the interaction impact, is reduced. For example, if fertilizer is applied at the mean level for our time period (roughly at the level of use in the early 1970s), the coefficient on June rainfall is reduced from 0.26 (Equations 2 in Table IV.4) to an overall impact of 0.17 additional units of TFP (indexed 1971=100) per extra millimetre of June rainfall. The negative interaction between June rain and fertilizer implies, then, that fertilizer application may be attenuating the sensitivity of productivity in prairie crop production to climatic variations.

The results of our linear models also imply that the overall impact of June rainfall on productivity, via the negative interaction impact, can be reduced to zero over time. Such a conclusion is unrealistic, and arises because the linear model is just an approximation to a presumably curvilinear relationship. Nevertheless, it is interesting and indicative to note that these results appear to suggest that the effects of a weather-related variable may be lessening over time as fertilizer application increases and technological change occurs. A reduced impact of weather on agricultural productivity is, of course, an issue of considerable importance. We caution the reader, however, on the appropriateness of interpreting the results a necessarily implying such a reduction of weather effects. In addition to problems of variable definition, the degree of aggregation of data, and model specification, the interaction terms themselves are capable of alternative interpretations.

Significant interactions terms may not necessarily arise only from technology-weather interactions. For example, the interactions terms may act as a proxy for non-linear effects or any other specification error. This is particularly so if, in addition, the weather variables exhibit upward or downward trends over time. All in all, the results of this investigation of interactions suggest a shifting weather-productivity relationship which indicates the possibility that the effects of weather on variation in agricultural productivity may be changing over time. Naturally, such a possibility should be empirically investigated further.

The productivity/weather/technology model involving a June rainfall interaction term was extended to include a second interaction term. A July rainfall-fertilizer interaction term did not prove to be statistically significant in the presence of the June rainfall-fertilizer interaction term. However, a second interaction term involving temperature and fertilizer proved to be more promising. For example, the following equation where the second interaction term involved July temperature and fertilizer was estimated for prairie crop productivity over the 1956-1984 period.

$$\begin{aligned} \text{TFP} = & 154.85 + 1.47T + 0.40 \text{ June } r + 0.17 \text{ July } r - 0.44 \text{ June } t - 0.45 \text{ July } t - 0.0030 \text{ June } r * F - 0.0011 \text{ July } t * F \\ & (5.60) \quad (3.69) \quad (5.07) \quad (2.54) \quad (-4.48) \quad (-3.85) \quad (-3.17) \quad (2.45) \end{aligned}$$

In this equation, 92 percent of the variation in TFP is associated with the explanatory variables in this model. Moreover, all the explanatory variables, including both the June rainfall-fertilizer and the July temperature-fertilizer interaction terms, are statistically significant. Further, the addition of the July temperature-fertilizer interaction term to the model was statistically relevant at a 97.7 percent level of confidence.

The inclusion of a June temperature-fertilizer interaction term instead of a July temperature-fertilizer interaction term provides similar results. The corresponding estimated equation when June temperature-fertilizer is the second interaction term is as follows:

$$\begin{aligned} \text{TFP} = & 143.25 + 1.43T + 0.40 \text{ June } r + 0.18 \text{ July } r - 0.49 \text{ June } t - 0.34 \text{ July } t - 0.0028 \text{ June } r * F + 0.0013 \text{ June } t * F \\ & (5.50) \quad (3.49) \quad (5.01) \quad (2.72) \quad (-4.84) \quad (-3.51) \quad (-3.12) \quad (2.38) \end{aligned}$$

Again, "goodness of fit" is high (92 percent); all explanatory variables, including June temperature and fertilizer as the second interaction term, are statistically significant; and the addition of this second interaction term to the model is statistically relevant at a 97.3 percent level of confidence. In both of these equations, the results are in conformity with our earlier results: June rainfall and July rainfall, as expected, influence productivity in prairie crop production positively; June temperature and July temperature influence productivity adversely; and the respective weather-fertilizer interaction terms dampen the influence of the rainfall or temperature variable in question.

#### F. Curvilinear Relationships

Finally, the possibility of a non-linear relationship between prairie crop productivity and the technology variable, proxied by time, was briefly explored. A curvilinear relation was introduced through the use of a quadratic term involving T -- that is, through an additional  $T^2$  term. This quadratic term was introduced in order to observe whether interaction terms remain significant in the presence of this term. In addition, the



equation included the usual four weather variables and two interaction terms, one involving June rainfall-fertilizer interaction and the other comprising June temperature-fertilizer interaction. The estimated equation of the (T,F) form over the 1956-1984 period is as follows:

$$\text{TFP} = 127.74 + 2.72T + 0.043 T^2 + 0.40 \text{ June } r - 0.20 \text{ July } r - 0.47 \text{ June } t - 0.34 \text{ July } t - 0.0027 \text{ June } r * F - 0.0019 \text{ June } t * F$$

(3.04)   (-1.60)   (5.21)   (3.06)   (-4.78)   (-3.65)   (-3.07)   (2.94)

In the above example, all estimated coefficients are highly statistically significant (at the 1 percent level) except the curvilinear-related term,  $T^2$ , which is weakly significant at the 10 percent level. "Goodness of fit" is very high: 93 percent of the variation in total factor productivity in prairie crop production over time is associated with the explanatory variables in this particular model. What is particularly of interest in these results is that significant interaction effects occur in this simple curvilinear model; that is, the interaction terms appear to be important in and of themselves, and not merely serving as a possible proxy for curvilinear effects.

#### G. Concluding Comment

The preceding research underscores the important roles that both technological factors and weather/climatic factors play in influencing productivity trends and variation in the prairie grain sector. Relatively simple linear models involving four weather variables (June rainfall, July rainfall, June temperature, and July temperature) and a technological trend proxy (proxied either by time or fertilizer use) are capable of "explaining" some 77 to 88 percent of the variation in total factor productivity in the prairie crop sector over time.

There is also empirical evidence of significant interactions between technology variables (fertilizer or time) and weather variables. This is particularly true for rainfall in June. A plausible interpretation of a significant negative interaction between June rainfall and fertilizer is that fertilizer application may be attenuating sensitivity of agriculture to climatic variations. A reduced dependency on weather is naturally very important to farmers. Our preliminary results on weather-technology interactions suggest changes of technologies associated with fertilizer, pesticides, and new varieties not only have had a direct impact of improved productivity but may also be associated with reducing the impact of adverse weather effects on crops in the prairies. The latter conclusion is tentative and merits further study.

## V. The Impact of Fertilizer and Weather on Yield

In the previous section, the influence of weather, fertilizer, and weather-fertilizer interaction on total factor productivity (TFP) in prairie crop production was analyzed. Typically, TFP estimates are difficult to obtain and are not provided by federal or provincial statistical reporting agencies. In these circumstances, more conventional partial productivity measures such as yield are the best estimates of agricultural productivity which are at hand. In this section, the influence of weather and fertilizer on yield is briefly investigated to see whether the impact is similar to that on total factor productivity. The presumption is that TFP is the preferred productivity estimate but that yield, in some circumstances, might be a passable alternative to be using in the study of productivity/weather/technology relationships.

### A. Grain Yield Growth in Prairie Agriculture

Yield growth rates for four major grains and oilseeds in the prairie region and in Alberta over our period of study are presented in Table V.1. The following points are noteworthy. Barley yields have grown somewhat faster than wheat yields in the prairie region. Wheat and barley yields have been much the same in the province of Alberta as in the prairie region, except during the 1972-83 period when wheat yields grew more rapidly in Alberta. Yield increases in the prairie region in the 1972-83 period are lower than in the longer time frames, but, nevertheless, at over one percent per year, are not as stagnant as some observers have suggested.

Table V.1 Rates of Growth of Yields, Major Grains, Prairies and Alberta, 1948-1984, 1959-1984, and 1972-1983 (percent per year).

Period	Wheat	Oats	Barley	Canola	Grains
1948-1984					
Prairies	1.58	1.60	2.04	1.12	1.57
Alberta	1.54	1.78	2.07	1.50	1.63
1959-1984					
Prairies	1.88	1.65	2.21	1.80	1.81
Alberta	1.85	1.74	2.06	2.08	1.73
1972-1983					
Prairies	1.24	1.35	1.90	1.60	1.17
Alberta	2.16	1.43	1.96	3.13	1.54

In Figure V.1, wheat and barley yields, respectively, are plotted against total factor productivity in prairie crop production. Both yields and overall productivity trend upward over time with generally similar peaks and troughs. Nevertheless, there are differential growth trends apparent in various sub-periods of time. These differences are illustrated in Figures V.2 through V.4. Up to the late 1960s, TFP was growing faster than either wheat yield or barley yield. Since the late 1960s, however, yields, especially for barley, grew somewhat faster than TFP in the prairie region, at least until the late 1970s. These differential growth trends over time can be seen visually in Figure V.2 where wheat yield, barley yield, and TFP are all indexed to the same base (1971=1.00.)

**FIGURE V.1 TOTAL FACTOR PRODUCTIVITY,  
WHEAT YIELDS AND BARLEY YIELDS,  
PRAIRIE GRAIN SECTOR, 1948-1984**

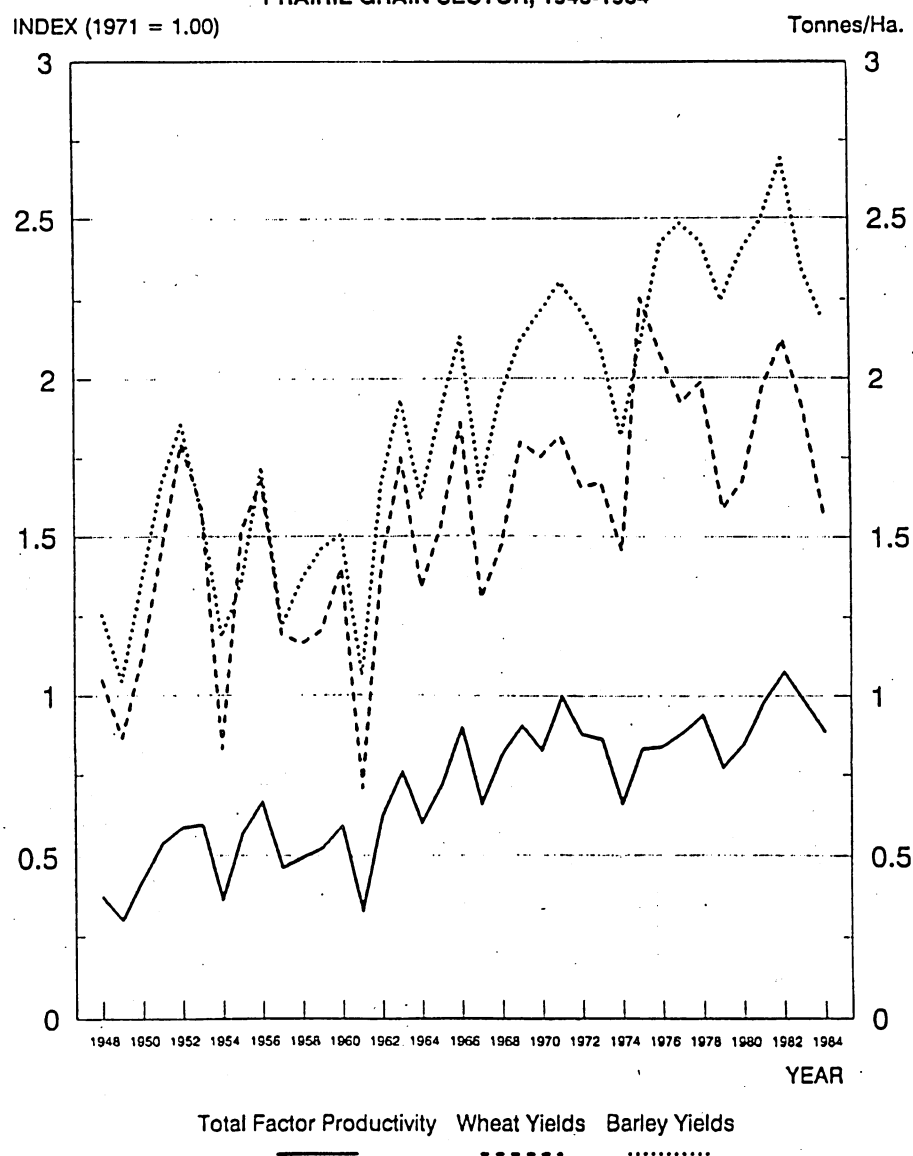
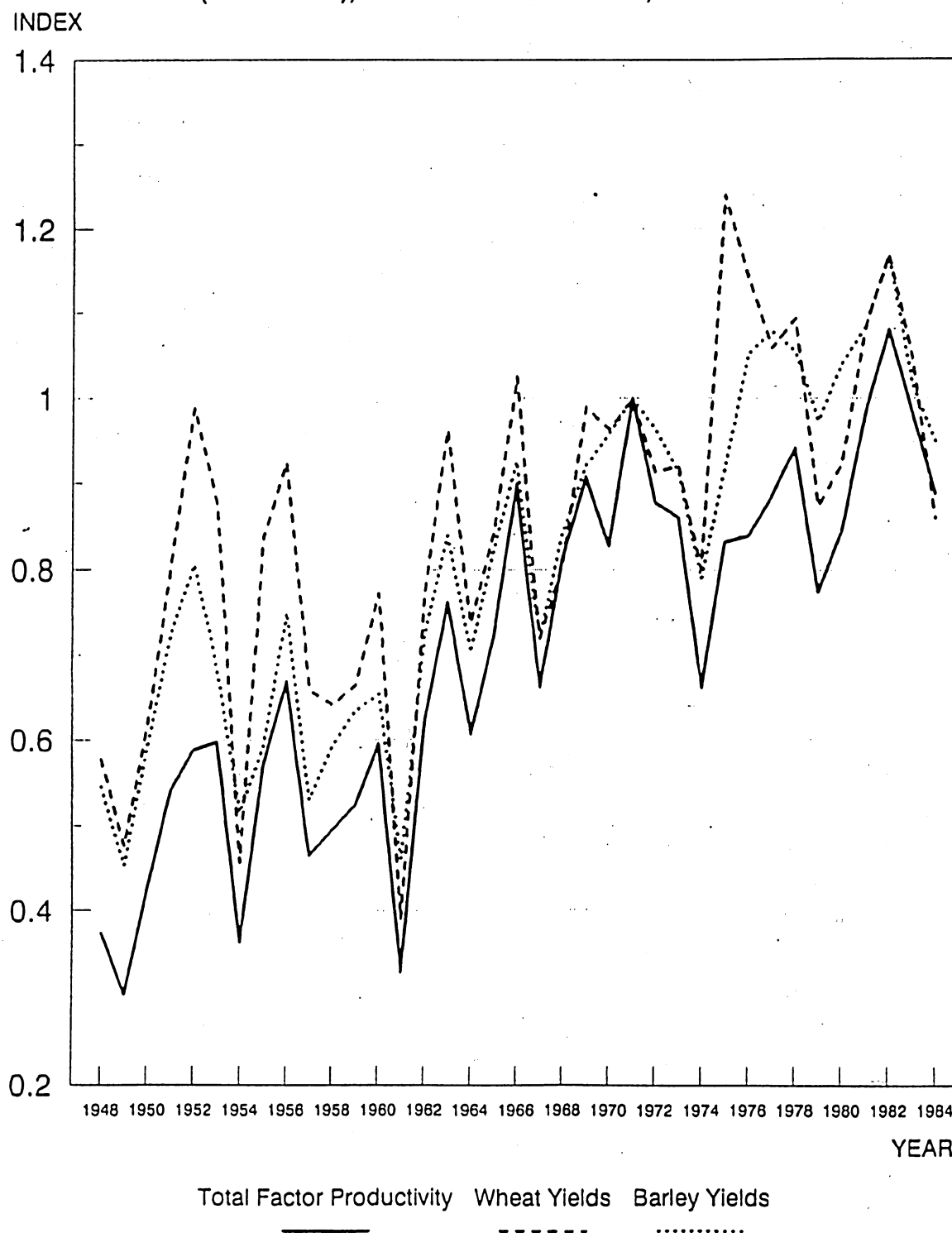


FIGURE V.2 TOTAL FACTOR PRODUCTIVITY AND  
INDEXES OF WHEAT YIELD AND BARLEY YIELD,  
(1971 = 1.00), PRAIRIE GRAIN SECTOR, 1948-1984



Illustrated yet another way, the differential growth of TFP and yields over time is seen in Figures V.3 and V.4 where the ratios of wheat yield, barley yield, and aggregate grain yield to TFP are plotted. These respective ratios generally decline in the 1950s and 1960s, rise during the early years of the grain boom in the 1970s, and then fall again to levels reached prior to the reversal.

#### B. Yield-Weather-Technology Relationships

The impacts of weather and technology on grain yields, rather than on total factor productivity, were investigated using the methodology developed in section IV. Estimated linear relationships, exclusive of interaction terms, for the prairie region for wheat yields, barley yields, and overall composite grain yields are reported in Tables V.2, V.3 and V.4, respectively. In the case of wheat yield, the model typically "fits" reasonably well, although not as well as in the previous case of total factor productivity. In Equation 4, for example, the technological trend proxy (time, in this instance), together with the four rainfall and temperature variables, explain some 75 percent of the variation in prairie wheat yields over 1958 to 1984. In this equation, all explanatory variables are statistically significant at the 5 percent level.

Table V.2      Estimated Yield-Technology-Weather Relationships for Wheat<sup>1</sup>, Prairies, 1948-1984 and 1958-1984 (Periods 1 and 2, respectively).

No.	Type <sup>2</sup>	Period	Trend <sup>3</sup>		Rainfall <sup>3</sup>		Temperature <sup>3</sup>		R <sup>2</sup>	DW
			Proxy	Coeff.	June	July	June	July		
1	SR	1	Time	23.5	4.90	4.29	-56.3	-25.1*	64	1.97
2	SR	1	Fertilizer	3.1	5.59	3.16	-26.0*	-41.9*	52	1.59
3	AP	1	Fertilizer	2.9	4.81	4.86	-36.6*	-28.9*	54	
4	SR	2	Time	23.4	4.93	4.88	-90.3	-11.6*	75	1.7
5	AP	2	Time	23.0	4.71	5.26	-91.9	-8.5*	75	
6	SR	2	Fertilizer	2.2	5.71	5.53	-82.2	-25.3*	65	1.33
7	AP	2	Fertilizer	1.9	4.77	6.31	-88.8	-11.0*	69	

<sup>1</sup> The dependent variable, wheat yield, is measured in kilograms per hectare. Rainfall is measured in millimeters and temperature in degrees C.

<sup>2</sup> SR and AP: estimation by Standard Regression and iterative procedure for autoregression, respectively. Problems of autoregression or inconclusive Durbin-Watson test are evident in Equation Nos. 2, 4, and 6.

<sup>3</sup> All coefficients significant at the 5% level of confidence except those marked \*.

FIGURE V.3 RATIOS OF WHEAT AND BARLEY YIELDS TO  
TOTAL FACTOR PRODUCTIVITY,  
PRAIRIE GRAIN SECTOR, 1948-1984

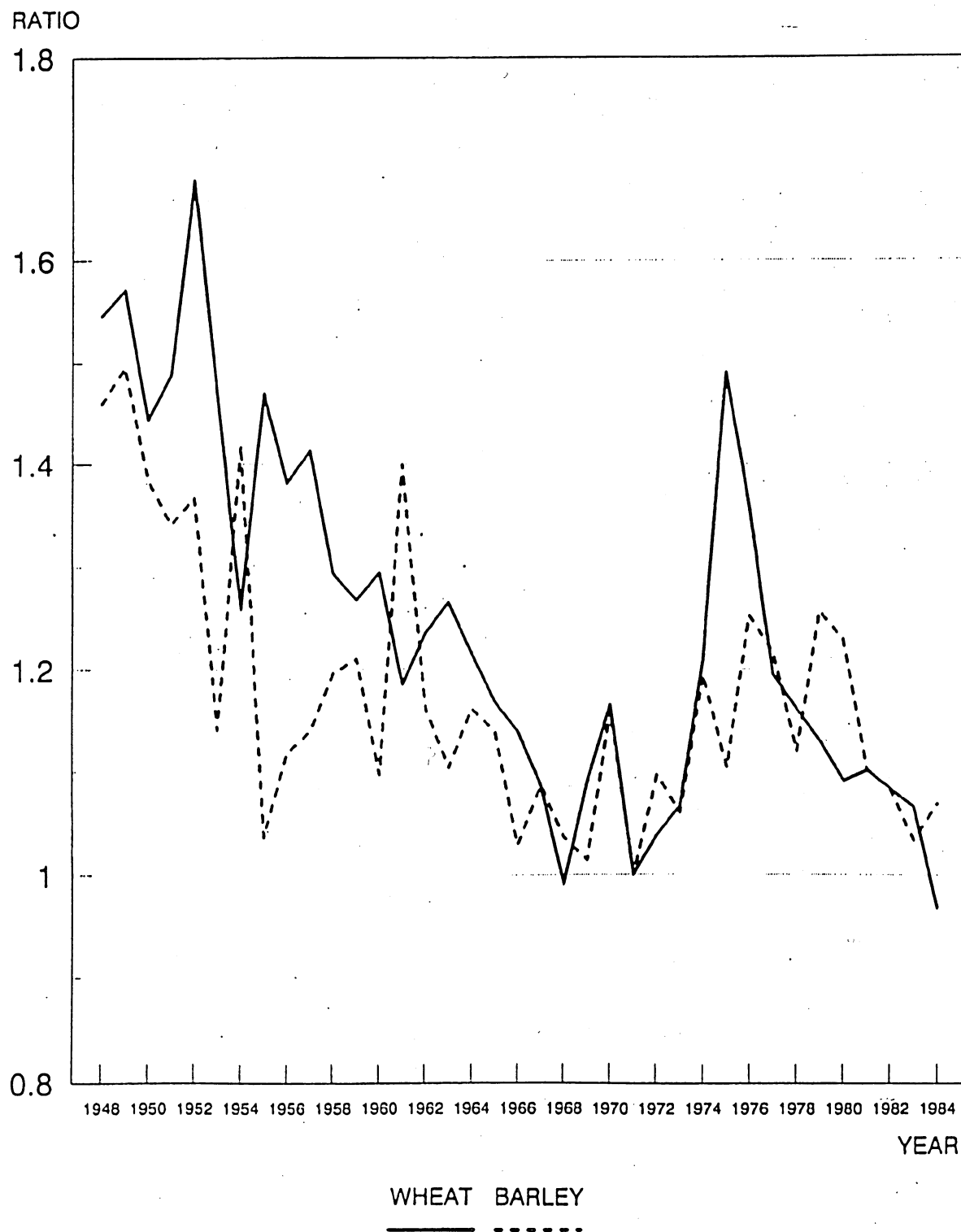


FIGURE V.4 RATIOS OF AGGREGATE GRAIN YIELD TO  
TOTAL FACTOR PRODUCTIVITY,  
PRAIRIES AND ALBERTA GRAIN SECTORS, 1948-1984

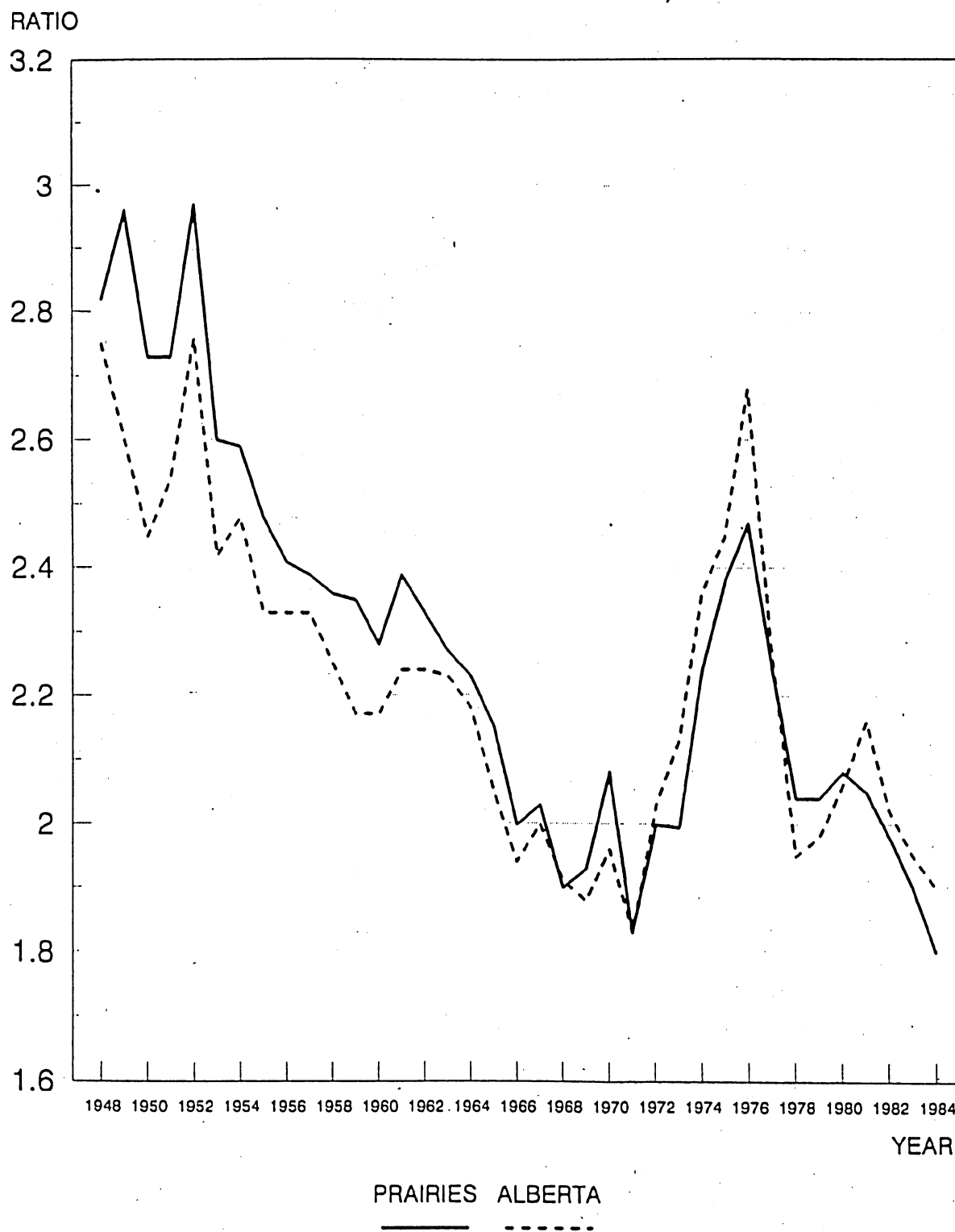


Table V.3      Estimated Yield-Technology-Weather Relationships for Barley<sup>1</sup>, Prairies, 1948-1984 and 1958-1984 (Periods 1 and 2, respectively).

No.	Type <sup>2</sup>	Period	Trend <sup>3</sup>		Rainfall <sup>3</sup>		Temperature <sup>3</sup>		R <sup>2</sup>	DW
			Proxy	Coeff.	June	July	June	July		
1	SR	1	Time	37.6	3.83	4.16	-44.3	-61.5	87	1.54
2	SR	1	Fertilizer	5.2	4.96	2.27	4.01*	-91.66	73	1.00
3	AP	1	Fertilizer	3.9	4.00	4.85	-2.13*	-60.25	81	
4	SR	2	Time	38.3	3.72	4.79	-55.45	-44.58	88	1.34
5	AP	2	Time	37.7	3.48	5.58	-49.47	-35.41*	90	
6	SR	2	Fertilizer	3.9	5.04	5.58	-39.05*	-70.79	76	0.93
7	AP	2	Fertilizer	2.8	3.72	6.39	-39.85*	-39.71*	84	

<sup>1</sup> The dependent variable, barley yield, is measured in kilograms per hectare. Rainfall is measured in millimeters and temperature in degrees C.

<sup>2</sup> SR and AP: estimation by Standard Regression and iterative procedure for autoregression, respectively. Problems of autoregression or inconclusive Durbin-Watson test are evident in Equation Nos. 2, 4, and 6.

<sup>3</sup> All coefficients significant at the 5% level of confidence except those marked \*.

The magnitudes of the impacts of weather and fertilizer on prairie wheat yields, under average soil moisture conditions in the period considered, are represented by the respective estimated coefficients. Looking at Equation 1 in Table V.2, it can be seen that an extra millimeter of rain in June increases wheat yields on average over the 1948-1984 period by 4.9 kilograms per hectare (or an extra 1.85 bushels per acre per additional inch of rain in June). The impact of July rain is nearly as important: an extra millimeter of rain in July increases prairie wheat yields by 4.29 kilograms per hectare (or an extra 1.62 bushels per acre per additional inch of rainfall in July). The effect of temperature, as expected, is negative. An extra degree Centigrade in June air temperature reduces prairie wheat yields by 56.3 kilograms per hectare (0.84 bushels per acre). The responsiveness of wheat yields to fertilizer are most readily reported and analyzed in the form of elasticities. The average elasticity of wheat yields with respect to fertilizer over the 1958 to 1984 period (derived from the coefficient on the technological trend proxy in Equation 6 and calculated at mean values for wheat yields and the implicit fertilizer quantity index) is 0.12. This implies that a one percent increase in fertilizer use increased wheat yields on the prairies, on average, by 0.12 percent -- that is, by 2.16 kilograms per hectare if wheat yields were 1800 kilograms per hectare.

The weather and technology variables do an even better job of explaining the variation in barley yields than in wheat yields. For example, in Equation 1 in Table V.3, the explanatory variables, all of which are statistically significant, are associated with 87 percent of the variation in prairie barley yields over the period from 1948 to 1984. The technological trend proxy (either time or fertilizer), as well as both June rain and July



Table V.4      Estimated Yield-Technology-Weather Relationships for Grain<sup>1</sup>, Prairies, 1948-1984 and 1958-1984 (Periods 1 and 2, respectively).

No.	Type <sup>2</sup>	Period	Trend <sup>3</sup>		Rainfall <sup>3</sup>		Temperature <sup>3</sup>		R <sup>2</sup>	DW
			Proxy	Coeff.	June	July	June	July		
1	SR	1	Time	24.0	4.35	4.00	-50.7	-50.1	74	1.88
2	SR	1	Fertilizer	3.2	5.05	2.84	-19.8*	-67.8	61	1.40
3	AP	1	Fertilizer	2.8	4.18	4.94	-33.1	-51.1	65	1.81
4	SR	2	Time	23.5	4.24	4.67	-74.6	-35.7*	82	1.53
5	AP	2	Time	23.0	4.00	5.18	-75.0	-31.5*	83	
6	SR	2	Fertilizer	2.2	5.02	5.26	-65.9	-50.2	71	1.13
7	AP	2	Fertilizer	1.8	4.11	6.02	-70.4	-34.1*	77	

<sup>1</sup> The dependent variable, grain yield, is measured in kilograms per hectare; it is derived as a production weighted average of the yields of six major prairie grains and oilseeds.

<sup>2</sup> SR and AP: estimation by Standard Regression and iterative procedure for autoregression, respectively. Problems of autoregression or inconclusive Durbin-Watson test are evident in Equation Nos. 2, 4, and 5.6

<sup>3</sup> All coefficients significant at the 5% level of confidence except those marked \*.

rain, are significant in all seven barley equations reported in the table. An extra millimeter of rain in June, for example, increases prairie barley yields, using the estimated coefficient from Equation 1, by 3.83 kilograms per hectare (or by an extra 1.78 bushels per acre per additional inch of rain). June temperature is statistically significant in only three of the seven equations. The most interesting result is that July temperature seems to be relatively more important as an adverse influence in the case of barley yields than in the case of wheat yields. For instance, an extra degree Centigrade in July reduces barley yields on the prairies by 61.5 kilograms per hectare (1.14 bushels per acre). The average elasticity of barley yields with respect to fertilizer use over the 1958 to 1984 period was 0.18 (derived from the coefficient on fertilizer in Equation 6).

Finally, examining the results for a composite measure of grain yield on the prairies, as in the equations in Table V.4, it can be seen that the grain yield-weather-technology model variations perform nearly, but not quite, as well as the TFP-weather-technology counterparts in Section IV. For example, in Equation 5 in Table V.4, the independent variables -- the four rainfall and temperature variables, as well as fertilizer--"explain" some 83 percent of the variation in prairie grain yield over 1958 to 1984. All these independent variables, excluding July temperature, are statistically significant. In short, yield, a partial measure of productivity, performs relatively well as a productivity proxy to use in estimating productivity-weather relationships. This may be due to the reason that the impacts of weather on productivity are primarily resulting from the impacts of weather on land productivity or yield. Nevertheless, total factor productivity (TFP) measures are to be preferred in productivity-weather analysis if such measures are available.

## VI. Conclusions and Implications

The measurement of productivity and the analysis of productivity trends--whether that be for a national economy such as Canada or the United States, or for a more specific sector, such as prairie agricultural or crop production, which is our area of interest--is vital to the monitoring of economic health and progress. Productivity in prairie crop production is estimated to have grown at a compound annual rate of some 1 to 1.5 percent between the early 1960s and the mid 1980s. This productivity increase has been associated with several features of increased intensification in prairie grain farming, including increased fertilizer and pesticide use and reduced summerfallow. The changing input use and production technology in the specific case of the Alberta grain sector was analyzed using a translog cost function.

In this research project, the main focus of analysis was the influence of weather, technology, and weather-technology interactions on productivity in the prairie crop sector. In analyzing productivity trends, it soon becomes apparent that productivity tends to rise secularly over time but that there is considerable year-to-year variation in productivity. In this research, technology--first represented by a time trend and then proxied by fertilizer use--was hypothesized to be the primary influence on the long run trend in productivity in crop production, whereas weather variables--particularly June rainfall, July rainfall, June temperature, and July temperature--were seen to be the cause of the short run fluctuations in crop productivity.

Estimated models of productivity-weather-technology interrelationships confirm the importance of these short and long run explanatory variables. For instance, the four weather variables and time are associated with 87 percent of the variation in total factor productivity in prairie crop production over 1948 to 1984. Fertilizer serves nearly as well as the technological trend proxy, "explaining", together with the weather variables, some 79 percent of the variation in productivity in the same time period. Models were also developed to analyze the influences of weather variables and fertilizer on grain yields. For example, an extra millimeter of rainfall in June and July was estimated to increase prairie wheat yields on average by an extra 4.9 and 4.3 kilograms per hectare respectively over the period from 1948 to 1984, whereas a degree Centigrade rise in June air temperature was estimated to reduce prairie wheat yields by 56.3 kilograms per hectare.

Finally, there is empirical evidence of significant interactions between fertilizer and weather variables, particularly June rainfall, on prairie crop productivity. In fact, a linear model including as significant explanators time, the four weather variables, a June rain-fertilizer interaction term, and a second interaction term based on fertilizer and either July or June temperature, "explains" 92 percent of the variation in productivity in prairie crop production between 1956 and 1984. There is also some suggestion that changes in technology-associated with increased fertilizer use may be reducing the adverse effects of weather on productivity. Nevertheless, grain farming, as prairie farmers know all too well, remains--to a considerable degree, at least on the supply side--a "gamble on the rains."

## References

- Agriculture Canada. 1989. *Handbook of Selected Agricultural Statistics 1988*. Ottawa: Supply and Services.
- Capalbo, S.M. 1988. "Measuring the Components of Aggregate Productivity Growth in U.S. Agriculture." *Western Journal of Agricultural Economics* 13(July):53-62.
- Christensen, L.R. 1975. "Concepts and Measurement of Agricultural Productivity." *American Journal of Agricultural Economics* 57(December):910-915.
- Cochrane, W.W. 1958. *Farm Prices: Myth and Reality*. Minneapolis: University of Minnesota Press.
- Furtan, W.H. and G.E. Lee. 1977. "Economic Development of the Saskatchewan Wheat Economy." *Canadian Journal of Agricultural Economics* 19(July):66-76.
- Pidgeon, E. 1988. "Statistics on Canadian Fertilizer Consumption, Shipments and Trade: Fertilizer Year 1986/87." Ottawa: Agriculture Canada, Policy Branch, Farm Development Policy Directorate.
- Rahuma, Ali A. 1989. "Productivity Growth and Production Technology in the Prairie Grain Sector." Unpublished Ph.D. dissertation. Edmonton: University of Alberta, Department of Rural Economy, 243 pp.
- Rahuma, A.A. and T.S. Veeman. 1988. "Productivity Growth in the Prairie Grain Sector and its Major Soil Zones, 1960s to 1980s." *Canadian Journal of Agricultural Economics* 36(December):857-870.
- Veeman, T.S. and A.A. Fantino. 1985. "Productivity Growth in Western Canadian Agriculture." Final Technical Report, Department of Rural Economy, University of Alberta.
- Veeman, T.S., A.A. Fantino, and A.A. Rahuma. 1989. "Productivity Growth and Profitability in the Prairie Grains Sector." Farming for the Future Final Report, Project No. 84-0365.



