RURAL ECONOMY

PROJECT REPORT

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The Economics of Agricultural Chemical Use in Prairie Agriculture: Productivity and Environmental Impacts

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Abstract

The use of agricultural chemicals, particularly in crop production, has increased greatly in the prairie region of Western Canada. Pesticide use, chiefly the use of herbicides, increased 7.6 percent per year from 1948 to 1991, slowing down only after 1985 with depressed conditions in the grain economy. In this report, a general social assessment of the use of pesticides in prairie agriculture is attempted. The main focus is on the role of herbicides which are among the most important pesticides used in prairie agriculture.

Implicit quantity indexes for both pesticide use and fertilizer use over time were constructed by dividing annual expenditures on these items by the corresponding price index. The relatively rapid growth in agricultural chemical use in prairie agriculture over the past four decades is clearly evident, especially in the period from 1971 to 1985. However, since 1985, pesticide use has been relatively stagnant.

Partial productivity measures with respect to both pesticides and fertilizer were calculated. The average productivity of pesticides has generally declined over time, particularly since the early 1970s, as pesticide use accelerated and diminishing returns in pesticide use occurred. Aggregate production functions for prairie agriculture and the prairie crop sector were also estimated in which the role of the pesticide input was emphasized. The estimated crop output elasticities with respect to pesticide use range from 0.43 to 0.89 under different production function specifications over the time period from 1971 to 1991. The estimates, in general, imply a relatively high degree of responsiveness of output to pesticide use. However, it is difficult to accurately separate the effects of pesticides from the effects of other inputs, especially when pesticides are part of a wider and more intensive technological package.

The major social benefits associated with pesticide use relate to gains in agricultural production and productivity, and they are evaluated in the study. Estimates in the literature

indicate that considerable yield reductions would result from herbicide removal. Even if such yield losses are over-estimated, they appear to be significant. Among the social costs of pesticides are the private costs incurred by farm producers but also the possible external or spillover costs inflicted on humans and the environment. Our qualitative assessment of these external costs tends to suggest that the agricultural sector in Western Canada has a level of pesticide use that is low in comparison with intensive agriculture in other parts of the world, and a mix of herbicides with which minor, rather than major, health and environmental concerns are associated.

Nevertheless, the debate on the cost and benefits of pesticide use is far from settled. Recent developments in the literature cast doubts on the validity of traditional bioassays used to assess synthetic pesticide hazards. A possible area of concern which emerged in recent literature is the suggested increased risk of lymphomas for farmers and farm workers who may be exposed to 2,4-D for longer periods of time. Such issues should be monitored. At the least, guidelines for protective clothing should be considered for farm workers who are engaged in extensive spraying.

I. Introduction

Since the 1950s the use of agricultural chemicals, particularly in crop production, has greatly increased in the prairie region. Pesticide use, chiefly the use of herbicides, increased by 7.6 percent per year from 1948 to 1991 and now comprises approximately 7 percent of total farm operating expenses. Similarly, the use of fertilizer more than tripled between the late 1960s and the mid-1980s. This increased use of agricultural chemicals appears to have been important to the production and productivity gains which prairie farmers have achieved in the past four decades. Nevertheless, there is increasing consumer and public concern about the environmental side-effects of increased pesticide and fertilizer application. A major challenge of our times is to develop agricultural production practices and policies that are more environmentally sustainable over time. This inevitably involves the need for a deeper understanding of the relative benefits and costs of increased agricultural chemical usage in prairie agriculture.

I.1 Objectives

The objectives of the research project were:

1. To document statistically the increased use of agricultural chemicals, particularly pesticides, in prairie agriculture.
2. To analyze the production and productivity impacts of increased chemical usage, examining, for example, trends in the average partial productivity of chemical inputs over time as well as the impact of increased pesticide use on total factor productivity in prairie agriculture.
3. To estimate aggregate production functions for prairie agriculture, including the prairie grain sector, which emphasize pesticide use and which generate measures of the marginal productivity of pesticides as well as possible indications of

increasing or decreasing returns to pesticide use.

4. To develop a conceptual framework to study the major social benefits of increased chemical use (mainly more immediate production and/or productivity gains) and the major social costs of such usage, many of which are uncertain and deferred into the future.

5. To document and assess, quantitatively where possible but often qualitatively because of limited information, the major apparent costs of increased chemical usage on the prairies: ground water and surface water contamination, health impacts on farmers themselves and on the general public, adverse impacts on wildlife, etc.

6. To undertake a preliminary assessment of the relative social benefits and costs, as well as their incidence, of agricultural chemical use in prairie agriculture in order to assess the degree of seriousness, if any, of increased chemical use and to make policy recommendations for the development of prairie agricultural production which might be more environmentally sustainable.

I.2 Format of the Report

This final technical report contains four sections after the introductory section. In Section II, a brief overview of the role of agricultural chemicals, particularly pesticides, as a productive input in prairie agriculture is presented including a detailed statistical examination of the expansion of pesticide use from 1948 to 1991. In Section III, the partial productivity measures associated with the two major types of agricultural chemicals, fertilizers and pesticides, are presented and assessed. This is followed by an overview of production function estimates for prairie agriculture in which an attempt is made to isolate the marginal physical productivity of pesticide use. Then, in Section IV, the social benefit-cost framework in which increased pesticide use might be assessed is briefly presented. A qualitative overview of the major possible "external costs" associated with pesticide use is presented; this survey focuses on the health and environmental effects of 2,4-D and, to a lesser extent, wild oats herbicides. In the final section, Section V, the main conclusions and policy implications of the research are summarized.

II. Pesticide Use in Prairie Agriculture, 1948-1991

II.1 Pesticides as a Production Input in Agriculture

One of the most distinctive features of the change in the input mix in agricultural production is the increasing role played by off-farm inputs. The increased use of inputs such as specialized machinery, new seeds, and agricultural chemicals constitutes the core of the process of intensification of agriculture. Pesticides are members of the agrichemical group of farming inputs. We use the term "pesticide" to include all chemicals such as herbicides, insecticides, fungicides, etc., utilized to control weeds and pests.

One of the most important results of the introduction of new production inputs is the increased levels of productivity they introduce in agriculture. The concept of productivity refers to the technical efficiency relationship between the level of output produced and the amount of inputs used in production. Productivity concepts defined in terms of a single input are termed partial productivities--for example, labour productivity (output per person) and land productivity (yield per acre). When all inputs used in production are included, the resulting measure is defined as Total Factor Productivity (TFP), also known as multifactor productivity. This is a more useful measure of productivity since it gives an account of the overall technical efficiency of production. Nevertheless, we begin our discussion of the role of pesticide as an agricultural input in terms of yields or the partial productivity of land.

Crop yields are mostly determined by the genetic make-up of varieties (potential yield), the availability of plant nutrients, and the environmental conditions prevailing in a given growing season. The effects of natural nutrients contained in the soil and of soil moisture on plant growth are well known. Artificial or chemical fertilizer can also be applied to increase the availability of nutrients. Increased use of fertilizer inputs is an important feature of crop agriculture in Western Canada. The increased use of fertilizers and its effects, as well as the influence of weather conditions on crop yields and on productivity in Western Canadian agriculture have been empirically studied (Veeman and Fantino 1990). Simple econometric models comprising fertilizer and weather terms are able to account for a large proportion of the variation in yields and productivity in prairie agriculture.

Adequate growing conditions and the use of fertilizers are therefore reflected in higher yields and higher total factor productivity. However, even when growing conditions are adequate, crop yields as well as agricultural productivity may be adversely affected by the incidence of pests, plant diseases, and weed infestations. Epidemics of stem rust and leaf rust, for example, were responsible for reduced crop output in Canada between 1953 and 1955. Insect attacks also reduce actual yield. Weeds such as Russian Thistle, wild buckwheat, wild oats, and stinkweed, affect cereal yield. In all cases the effect of weeds and pest infestations is to reduce actual yields and to prevent the achievement of potential yields. This, in turn, reduces output and, other things being equal, decreases multifactor productivity.

The case of weed infestations is a particularly interesting case of the adverse effects of "pests" on productivity and total output. Following Hay (1980), the adverse effects of weed infestations on crops can be considered to result from competition and interference. Competition means that weeds take sunlight, water and nutrients necessary for crops to grow. Interference occurs when weeds produce toxic substances, particularly in the root systems, which have negative effects on crop growth. Weed infestations have historically been a major problem in prairie agriculture, particularly under cereal monoculture. As early as 1897, a bulletin called "The Worst Weeds" was published in the Canadian West. In 1921 the Indian Head Experimental Station stated that it was "impossible to keep the land free of weeds" (as quoted by Hay, 1980). Summerfallow and cultural practices were developed, at least in part, to cope with this serious problem. However, they were only partially successful and weed infestations remained a major problem in prairie cereal production until herbicides were introduced in the mid-1940s. New chemicals such as 2,4-D and MCPA were successful in controlling broad-leaved weeds. Following their introduction, herbicide use expanded rapidly in Western Canada.

The preceding discussion shows that weed control measures would have effects on productivity by preventing the adverse impacts of weeds. Pesticides, then, have a yield protecting role. They are inputs with a damage preventing role rather than inputs having direct productive effects such as fertilizer, for example. If pesticides are output protecting, their use in adequate quantities will be economically justified as long as the increases in total output made possible by the other inputs are such that the added value more than compensates for the increased incurred cost. The effects of pesticides on production and productivity, therefore, are indirect. Herbicides, for example, are not nutrients; their productivity enhancing effects are indirect. That is, herbicides prevent competition and interference from weeds. The increased productivity made possible by new technology embodied in off-farm inputs is realized through the protection provided by the use of herbicides. This means that the use of the pesticide input typically goes along with the use of other non-conventional inputs--that is to say, pesticides are a part of the overall technological package. In general, then, pesticides are productivity protecting and they play, at least in part, a role similar to that of insurance. The foregoing considerations illustrate the complex role of the pesticide input in agricultural production and foreshadows the difficulties involved in assessing the economic benefits of pesticide use.

II.2 Pesticide Use in Western Canadian Agriculture

Since World War II, pesticide use in prairie agriculture expanded relatively rapidly, up until the downturn in the agricultural economy in the mid-1980s. Nearly 900 million dollars of pesticides were sold in Canada in 1991, with Western Canada accounting for 64 percent of retail sales (AIC 1993). Herbicides are far and away the most important pesticides used, accounting for 73 percent of sales in Canada (and an even higher percentage in the prairie region where grain and oilseed production is concentrated). Insecticides account for 7 percent of overall pesticide sales in Canada, followed by fungicides with 4 percent, home and garden use at 8 percent, and the remaining 8 percent devoted to fumigants, seed treatments, and animal care products (AIC 1993, p. 2).

The main herbicides used in prairie crop production are broad-leaf weed herbicides, led by 2,4-D, and wild oats herbicides which have become increasingly important since the 1970s. In addition to 2,4-D, the other major broad-leaf herbicides include MCPA, bromoxynil, dicamba, and TCA. 2,4-D and MCPA are phenoxy herbicides which are typically sprayed on cereal crops in June to control broad-leaf weeds. In Table 1, a general picture of herbicide use in Western Canada in the 1980s is presented. These figures indicate a slow upward increase in the tonnage of broad-leaf weed herbicides applied, including 2,4-D. Further, it appears that nearly 40 percent of the prairie crop acreage was treated on average with wild oat herbicides in the 1980s.

Total 2,4-D usage in the prairie provinces did not change appreciably between 1966 and 1985. However, there did occur a clear substitution of the amine form of 2,4-D for the ester formulation--the former increasing by 6.4 percent per year and the latter declining by 2.6 percent per year between the mid 1960s and the mid 1980s. Roughly half the prairie 2,4-D tonnage is used in Saskatchewan, a reflection of the dominance of wheat in the crop mix. During the 1980s, approximately equal tonnages of 2,4-D and MCPA were applied in each of Manitoba and Alberta.

Table 1. **Herbicide Use in Western Canada, 1980-88**

	1980	1981	1982	1983	1984	1985	1986	1987	1988
					(million kilograms)				
2,4-D	2.9	3.6	3.1	3.1	3.4	3.2	4.3	3.4	3.2
TCA	0.7	0.4	0.4	0.3	0.4	0.2	0.3	0.3	0.1
MCPA	1.9	2.0	1.8	2.1	1.5	1.7	1.9	1.8	1.4
Bromoxynil and dicamba	--	--	1.8	2.4	2.2	1.4	2.2	2.2	1.9
Other herbicides	0.9	1.8	1.7	1.7	1.6	1.3	1.5	1.1	2.0
Total	6.4	7.9	8.7	9.6	9.1	7.8	10.2	8.8	7.6
					(million hectares)				
Area treated with wild oat herbicides	7.2	7.2	9.6	7.5	8.2	7.9	9.6	5.4	11.0
Area planted to six major crops[a]	19.4	20.8	21.2	21.5	22.2	22.6	23.0	22.3	21.8
Percent coverage	37.1	34.6	45.3	34.9	36.9	35.0	41.7	24.2	50.5

[a] Wheat, barley, oats, rye, canola, and flaxseed.

Source: Manitoba Department of Agriculture, Economic Analysis Branch; and Statistics Canada, *Field Crop Reporting Series*, cat. no. 22-002, September 1989.

A broader picture of the expansion of overall pesticide use in Western Canada is gained through examination of an implicit quantity index for pesticides. Such an index is a measure of the quantity of all pesticides combined. It is derived by deflating total expenditures on pesticides as measured in current dollars by Statistics Canada by an appropriate pesticide price index. The resulting annual series of "implicit quantities" are presented in Appendix 1 and are depicted in Figure 1. As one might expect, given their respective crop acreages, the province of Saskatchewan has the highest implicit quantity of pesticide use, followed by Alberta and Manitoba. When the use of pesticides is indexed to a common base, as in Figure 2, it can be seen that the Province of Manitoba has experienced growth above the prairie averages, and the

FIGURE 1. PESTICIDE USE IN THE PRAIRIES

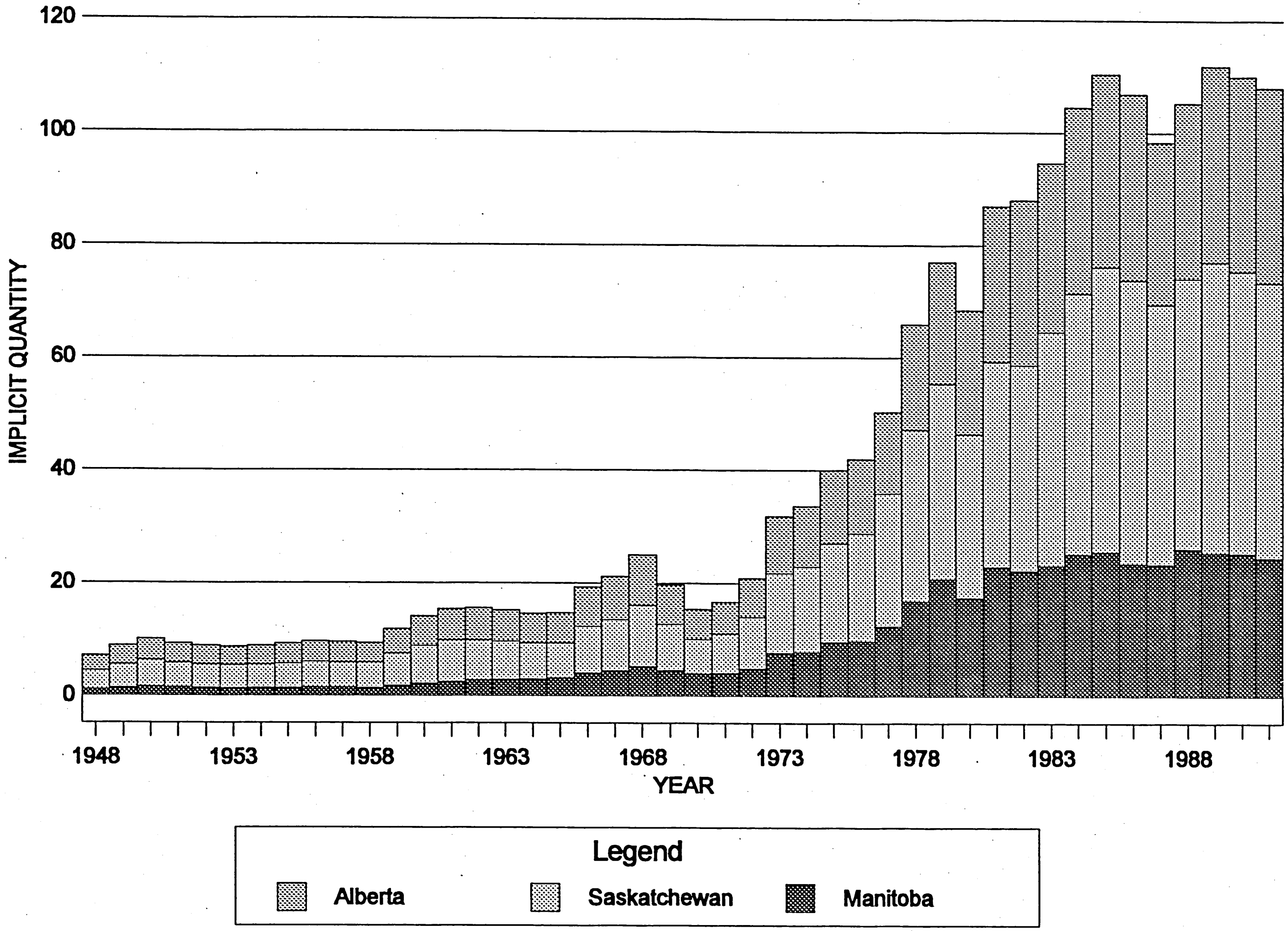
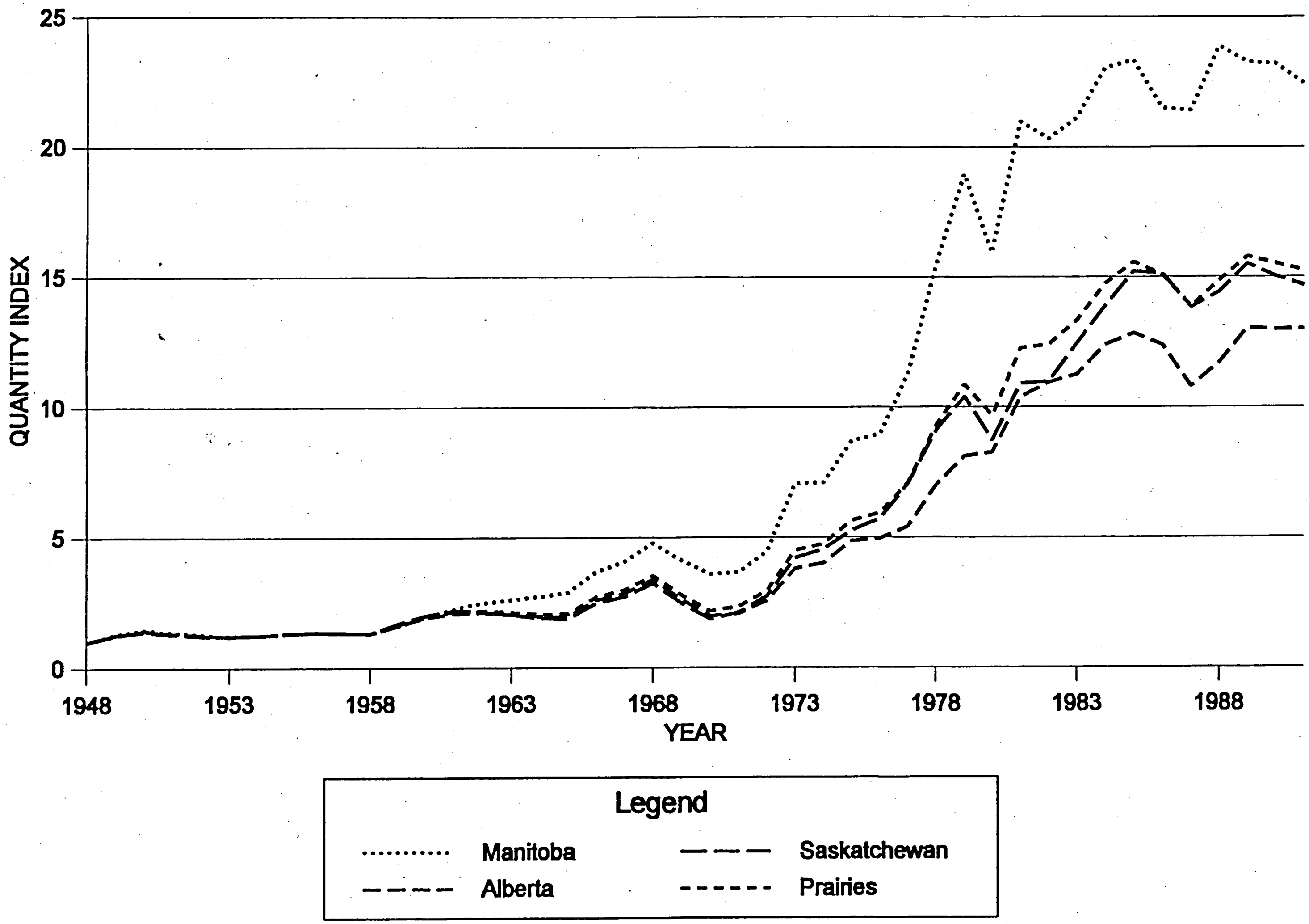


FIGURE 2. PESTICIDE USE IN THE PRAIRIES
IMPLICIT QUANTITY INDEX, 1948=1



Province of Alberta slightly below that average. Overall, during the entire period 1948-1991, pesticide use grew in prairie agriculture at the considerable compound annual rate of 7.56 percent.

This high rate of growth, coupled with an even higher rate of growth of fertilizer use (some 10.7 percent per year), is indicative of intensification in agriculture production in the prairie region. Intensification represents a process of technological change that took place in prairie agriculture (Veeman and Fantino 1990). Increased use of agricultural chemicals in the input mix is part and parcel of this intensification process.

Productivity, as measured by yields and total factor productivity, increased correlatively indicating technical change associated with the whole process (Veeman and Fantino 1990 and 1992). The fact that both fertilizer and pesticide usage grew concurrently suggests that these inputs are complements in production. This relationship could be rationalized as follows. Increased use of fertilizer input promotes plant growth in general--not only growth of cereals or oilseeds but also that of damaging weeds in the same fields. This compromises the output and productivity increasing role of fertilizer. In order to protect yields, increased pesticide use is encouraged. In such a scenario, fertilizer use and pesticide use might be viewed as complementary.

To facilitate the analysis of Figure 1, rates of growth of pesticide use for various sub-periods of interest are presented in Table 2. Pesticide use expanded in the 1950s reaching an initial ceiling or plateau. By the end of that decade, pesticide use started to grow once again. Unfavourable conditions in grain and oilseed world markets in 1967-1969 not only halted this growth but there was a considerable reduction in pesticide use in those years. Steady and very fast growth in pesticides reinitiated after the end of the LIFT program in 1971 and the beginning of the grain boom. From there on, until the mid 1980s, pesticide use in prairie agriculture increased exponentially at very high rates averaging 13.7% per year in the Prairies overall. This very rapid increase came to a virtual halt in the mid 1980s: growth rates for the period 1985-1991 are virtually zero across the prairie provinces. The data therefore suggest that a new ceiling in pesticide use was reached, a ceiling associated with adverse derived demand conditions for pesticides in the circumstances of a depressed grain economy.

Table 2. **Growth Rates of Pesticide Use, Implicit Quantities, Prairie Provinces, Percent Per Year**

Period	Manitoba	Saskatchewan	Alberta	Prairies
1948-1991	9.03	7.44	6.88	7.56
1957-1991	9.93	8.55	7.84	8.58
1957-1980	11.20	8.22	7.28	8.50
1971-1985	14.06	13.68	13.46	13.70
1985-1991	0.42*	-0.03*	1.15*	0.43*

* indicates rates non-significantly different from zero at the 10% level.

A similar pattern is to be found in the growth rates of current dollar expenditures on pesticides which are presented in Table 3. Increase in expenditure on pesticides was particularly rapid during 1971 to 1985 with compound growth rates averaging 27 percent per year. Obviously, this reflects both increases in quantity used and the price inflation prevailing in those years (see Table 4). It should also be noted that expenditures on wild oat herbicides in 1986 (some $291 million) were more than ten times the expenditures on 2,4-D ($26 million) or on MCPA ($19 million) (Stemeroff, et al. 1991).

Table 3. **Growth Rates of Dollar Expenditures on Pesticides on the Prairies, Percent Per Year**

Period	Manitoba	Saskatchewan	Alberta	Prairies
1948-1991	15.36	17.30	13.05	13.81
1957-1991	17.83	19.43	15.60	16.40
1971-1985	27.40	29.26	26.73	27.00
1985-1991	1.50	-3.00	2.24*	1.52

* Indicates non-significant rate at the 5% level.

Table 4. **Growth Rates of Pesticide Prices, Canadian Prairies, Percent Per Year**

Periods	1948-1991	1957-1991	1971-1985	1985-1991
Rate of Growth	5.8	7.2	11.7	1.1

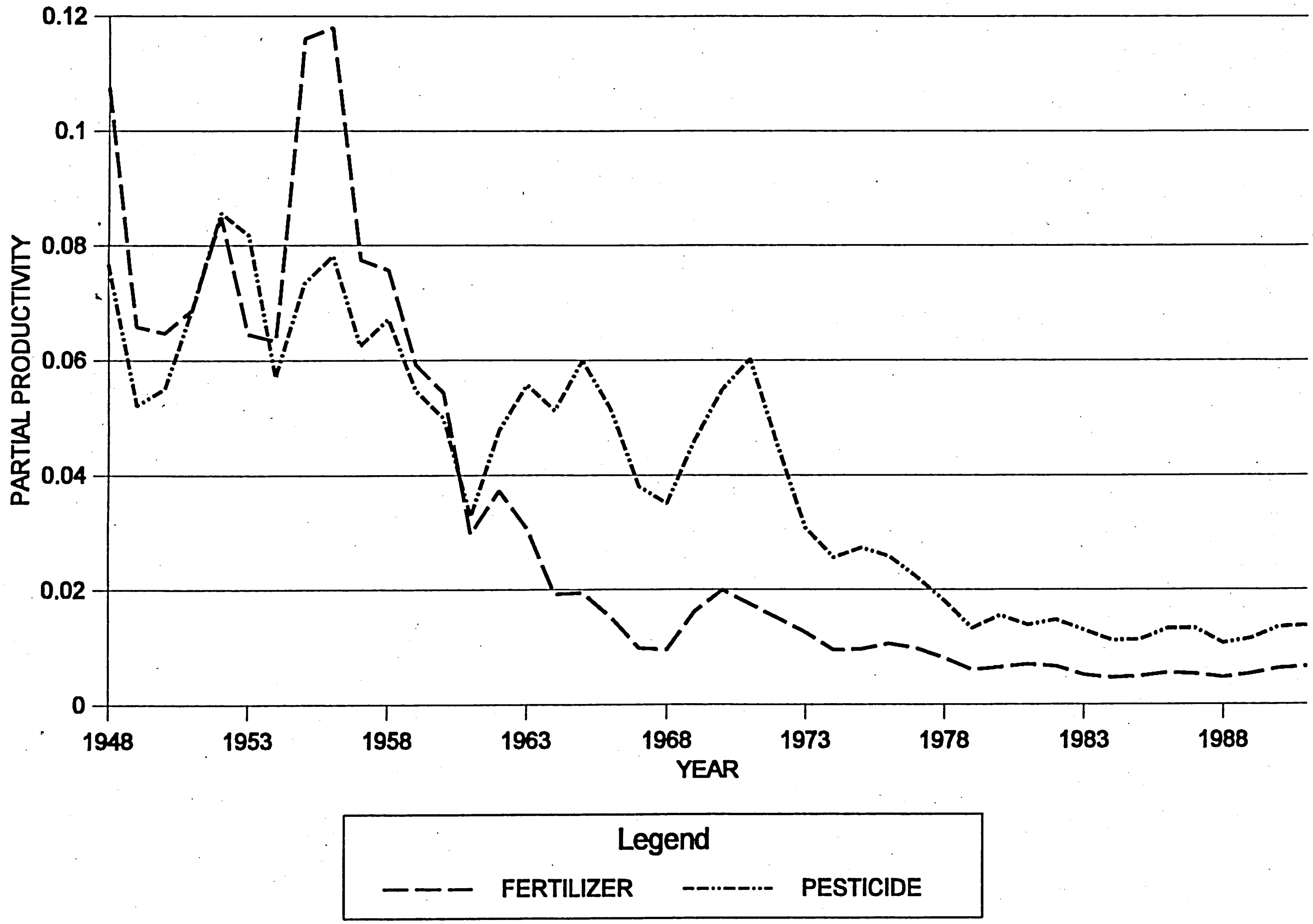
III. Productivity of Agricultural Chemicals

III.1 Partial Productivity Measures

The relationship between the use of chemicals and agricultural productivity can be easily understood in terms of the effects of fertilizer on yields and the control which pesticides exercise on damaging or competing insects and weeds. Quantification of these effects are, nevertheless, difficult to do with accuracy. The reason for this is the high degree of input substitution taking place in the agricultural system. A first indication of these effects can be obtaining by calculating partial productivities for sub-categories of agricultural chemicals. The partial productivity of an input is defined as the amount of output per unit of that input. For example, output per unit of land or yield is the partial productivity of the input land. To begin with, the partial productivity of fertilizer and the partial productivity of pesticides were calculated. The results are portrayed in Figure 3.

FIGURE 3. PARTIAL PRODUCTIVITIES

Prairie Agriculture.

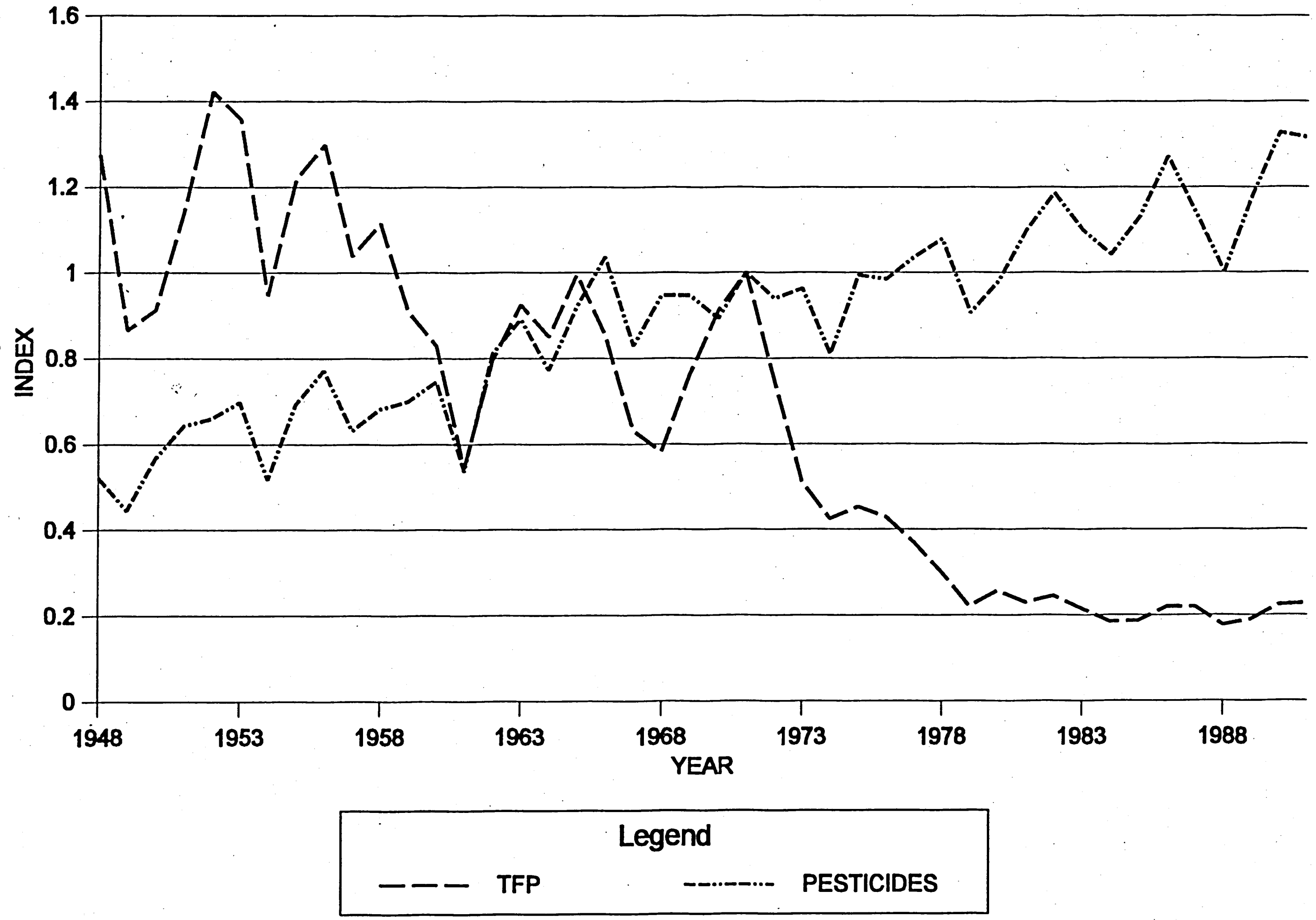


It can be seen that both types of agricultural chemical have experienced a downward trend in their partial productivities. The reduction in productivity is particularly steep for fertilizer. The negative slope of the trend in these chemical productivity measures means the use of the input in question is growing faster than total agricultural output.

From the point of view of conventional production theory, this result is to be expected when use of a given input is increased relative to other inputs in the input mix, at least when such input substitution is effected beyond a certain point. In other words, although some increased returns to the input in question may be expected, eventually a range of diminishing returns is reached. This is the economic zone of operation. On the other hand, reductions in these partial productivities may be accompanied by increases in the partial productivities of other inputs, for example, land and labour. In fact, partial productivity measures may be misleading, if taken uncritically and not in context.

A measure which is much less subject to these kind of biases is Total Factor Productivity (TFP) which is a measure of total output per unit of all inputs combined. The authors of this report have estimated TFP for Canadian and Prairie Agriculture (Veeman and Fantino 1989, 1994), and for the crop sector of the Canadian Prairies. These estimates are now used in Figure 4 along with the foregoing partial productivity measure for pesticides, all of which are reduced to an index form with base 1971=1. The most salient feature of Figure 4 is that overall total factor productivity continues to increase (albeit with considerable fluctuations around the rising trend) even as the partial productivity of pesticides declines considerably in the 1970s and reaches a plateau in the 1980s. Fertilizer experienced a large drop in productivity with increased usage in the late fifties and early sixties, and then further decline with the second wave of increased use after 1971. Pesticides experienced a small reduction in partial productivity relative to fertilizer. This illuminates the different effects on production of these agricultural chemicals. The most important effects of pesticides seems to be damage control and the realization of increased agricultural

FIGURE 4. PRODUCTIVITY OF PESTICIDES and TFP, PRAIRIE AGRICULTURE, 1971=1



productivity. Both fertilizers and, to a lesser degree, pesticides have direct effects on output, resulting in higher yields per hectare and therefore increasing the productivity of other inputs. Nevertheless, the effects of pesticides are also indirect, in the sense that by controlling pests they allow the productive potential of the other inputs to be realized. In other words, despite the decline of pesticide partial productivity, pesticides play an important role in the maintenance and realization of production and overall productivity gains. The relationships and pattern of interaction among inputs are certainly complex, of course, but the foregoing is a reasonable interpretation of the critical role of pesticides in production.

III.2 Production Function Estimation

As part of this research, production functions were estimated. The focus was on pesticides and the aim was to measure and quantify the effects of these chemicals on agricultural or crop output. Such calculations, in turn, are useful in estimating the benefits of agrichemical use. If production functions can be properly estimated, the benefits of pesticides could be quantified. For example, if it is possible to estimate a Cobb-Douglas type of production function in a given time period, the average output elasticities of the different inputs are obtained. The marginal productivity of respective inputs can then be calculated as the product of the relevant elasticity and the average productivity of the input in question. The accuracy of the estimates and even the feasibility of any estimate are dependent on the quality of the production function estimates.

For the purpose of production function estimation, variables were constructed as follows: an index of total agricultural output and an index of crop output; implicit quantity indexes for fertilizer and pesticides; a composite index measuring total capital which includes machinery, land and buildings; several indexes of individual items of machinery input and of land and buildings input; an index measuring total labour hours; and an index of energy inputs such as fuel and electricity. Data were obtained in the form of input expenditures, quantities produced and the relevant prices, usually in the form of price indexes. The data were obtained from Statistics Canada publications.

An important consideration involved in production function estimation is the mathematical form of the equations. The following functional forms were specified and used: the Cobb-Douglas double log production function; a quadratic function; the transcendental logarithmic or translog production function; and a generalized power production function including the variables and their logs along with exponential terms and interaction terms.

Production functions of these four types relating to overall prairie agricultural production and to crop production were estimated econometrically for different time periods included in the period 1948-1991 for which the variables were defined and constructed. The actual task of estimating the production function proved to be rather arduous and disappointing when all the inputs were introduced in the estimating equation. The main reason was the lack of significance of the estimated coefficients. It was apparent that the estimations were plagued with severe econometric problems. The most frequent and persistent problem was the high degree of multicollinearity that is present in the data. This introduces large standard errors in the estimates which are therefore very inaccurate.

A reduction in the number of variables involved proved beneficial and the rest of the analysis was conducted in terms of a reduced number of variables emphasizing pesticides. These variables were: Pesticide (P), Fertilizer (F), Total Capital (K) and Labour as defined above. Although many econometric problems remained in most of the regression runs, it was possible to estimate a number of equations with significant coefficients, particularly for the terms involving the variable of interest: the pesticide input. The most frequent problem encountered was again that of multicollinearity. Since multicollinearity results from highly correlated regressors, the correlations in Table 5 give an idea of the extent and nature of the problem. All variables are

Table 5. Matrix of Coefficients of Simple Correlation, Prairie Agriculture

	Output	Pesticide	Fertilizer	Capital	Labour
1948-1991					
Output	1.00				
Pesticide	0.89	1.00			
Fertilizer	0.91	0.98	1.00		
Capital	0.91	0.88	0.91	1.00	
Labour	-0.81	-0.73	-0.78	-0.91	1.00
1958-1991					
Output	1.00				
Pesticide	0.88	1.00			
Fertilizer	0.89	0.98	1.00		
Capital	0.89	0.90	0.93	1.00	
Labour	-0.84	-0.83	-0.88	-0.90	1.00

highly correlated; in particular, note the high correlation between the pesticide and fertilizer variables.

Despite the high correlation between the fertilizer and pesticide variables, it was considered relevant to keep fertilizer in the picture. Eliminating that variable may reduce multicollinearity but at the cost of introducing specification errors.[1] The econometric difficulties encountered in trying to isolate the effects of inputs such as fertilizer and pesticides may be interpreted in the light of our previous discussion of these productive inputs. The fact that the effects on output of these inputs cannot be easily separated suggests that fertilizer and pesticide use are associated and that these inputs belong to a "technology package" as discussed Section

[1] This is an elaboration of the simple expedient of running regressions of output on the pesticide variable only. Obviously, this amounts to attributing all of the increase in output to pesticide alone. This clearly would introduce a serious specification error in the estimates.

II.1. In a previous report (Veeman and Fantino 1990), this kind of conceptual approach was utilized to study the role of fertilizer use in agricultural productivity. In that study, a fertilizer use variable proved to be a good "proxy" for technological change in the sense of being able to explain long run growth of productivity equally or even better that the commonly used time trend variable. Some of our findings included non-lineal behaviour and the existence of significant weather-fertilizer interaction. Pesticide variables, on the other hand, also perform well as a "proxy" and also display non-linear behaviour. When both fertilizer and pesticide proxies are used, however, the only significant terms are those associated with the fertilizer proxy. This interesting behaviour may be related to the different type of impacts fertilizer and pesticides have on output and productivity as stated in earlier discussion.

A related issue regarding the production function is whether a shifter or time trend should be incorporated in the equations. Such a time trend would represent "disembodied" technical progress, that is, increases in output over time not related to the variables included in the equations. Equations with such a time trend were estimated which showed coefficients with very low levels of significance due to multicollinearity. In almost all cases the coefficient for pesticides was negative and non-significant. This type of equation was abandoned in subsequent work.

All four types of aggregate production functions were estimated. Given the frequent occurrence of various econometric problems, tests were run systematically along with the regressions. The tests include the following: the Durbin-Watson (DW) for autoregression; the Breusch-Pagan and the Glesjer tests for heteroscedasticity; and the Chow test for stability of estimated coefficients. If the DW statistics indicated autorregression or were inconclusive, the regressions were estimated by means of the Cochrane-Orcutt iterative procedure. The Chow test and the Goldfeld and Quandt test helped in the determination of breaking points in time defining subperiods where the relationships appeared more stable. Only equations with significant coefficients (at the 10% level of confidence at least), and free from signs of autorregression and heteroscedasticity, were retained. The best results were obtained with the translog specification of the production function. A number of these equations are reported in Appendix II. Based on the estimated production function, output elasticities and marginal productivities of pesticides were estimated. Two levels of input use are defined: the mean level of all input use in the period (Mean), and the levels prevailing after intensification took place (High). Table 6 presents a representative sample of the results.

Table 6. Output Elasticities and Marginal Productivities of Pesticides Derived from Production Function Estimations, Prairies

	Output Elasticity		Marginal Productivity	
Functional Form	Mean	High	Mean	High
Cobb-Douglas (Prairie Crop Sector)				
1948-1991	0.11	--	0.09	0.03
1958-1991	0.14	--	0.11	0.04
1971-1991	0.43	--	0.35	0.11
1975-1991	0.67	--	0.55	0.17
Quadratic (Prairie Crop Sector)				
1958-1991	0.03	1.05	0.02	0.26
Translog (Prairie Agriculture)				
1948-1991	0.05	0.26	0.04	0.07
1958-1991	0.23	0.50	0.19	0.13
1971-1991	0.27	1.65	0.22	0.41
Translog (Prairie Crop Sector)				
1968-1991	0.36	2.87	0.30	0.72
1971-1991	0.89	2.80	0.71	0.70
Power (Prairie Crop Sector)				
1948-1991	0.07	0.83	0.06	0.21

Estimated output elasticities of pesticides vary according to the type of production function used in estimation. This is to be expected and gives an indication of the specification bias. The variations, however, are not large enough to compromise the whole exercise. Elasticities also vary with the time period considered, according to the level of intensification of input use and between the whole of agriculture and the crop sector in the Prairies. The more recent the period, the higher the elasticities, which is an indication of the productive effects of pesticide use together with interactions with intensified use of the other inputs. The same applies to the increase in elasticities with intensification. The large difference in estimated elasticities between aggregate agriculture and the crop sector indicates the more important role of pesticides in the latter. All in all, the results in Table 6 appear reasonable and consistent with our previous discussion of the productive role of pesticides.

The results in Table 6 can be utilized to estimate the production benefits associated with the use of pesticides. Although this can be conducted by means of either output elasticities or physical productivities, the former are easier to use and have a clear interpretation. For example, the output elasticity estimated by means of the Cobb-Douglas production function for the period 1948 to 1991 is 0.11 in Table 6. This means that a one percent increase (reduction) in pesticide use increases (reduces) output by 0.11 percent [2]. For the agriculture sector as a whole in the most recent period, 1971-1991, elasticity estimates with respect to pesticides range from 0.27 for the mean level of intensification to 1.65 at a high level of intensification. Conservative estimates could be regarded to be 0.3 and 1.0, respectively. Similarly, for the crop sector, elasticities range from 0.43 to 0.89 for the mean, and up to 2.8 for the high level of intensification. In short, these estimates of output elasticities indicate a relatively high degree of responsiveness of agricultural

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[2] This in turn can be translated into a dollar value assuming constant prices as the same percentage of the value of production. A cautionary note, however, is that these elasticities are valid in the neighbourhood of the input levels used in their calculation.

output to pesticide use. This degree of responsiveness is even higher for crop output alone and when other complementary inputs in the technological package are being used more intensively.

III.3 Benefits Associated with Intensification in the Prairies

In previous sections the productive benefits resulting from pesticide use have been identified and qualitatively assessed. The aim in this section centres on the problem of evaluating these benefits. In general terms, an economic quantitative assessment of the benefits associated with technical progress in the process of intensification can be construed as the value of the increased agricultural output produced.

In the same vein, the benefits of pesticide use could be defined as the value of the increased output that can be attributed to that use. However, the transition from a general assessment of intensification to that of a particular input involved in the process is not a straightforward one. According to our discussion in the previous sections, it is rather difficult to give a simple formulation for the estimation of the increased output due to pesticide application. The main reason for this is the difficulties experienced when trying to isolate the effects on output of a single input such as pesticides. Studies at the field level have estimated yield losses as a function of the extent of weed infestations. At a high level of aggregation, however, it is difficult to estimate increases in output "produced" by pesticides. The production functions estimated in this report suggest the productivity of pesticides is dependent on the levels of other inputs. Moreover, the indirect nature of the effect of pesticide on output means that other variables, notably fertilizer, are a better proxy for the productive effects of intensification.

What we can observe and measure is the increased production and enhanced total factor productivity associated with the input package with which fertilizer and pesticides are associated. The technology increases the level of output produced with a given set of inputs. A measure of these increases, according to our definition in section I.1, is given by Total Factor Productivity. In addition to increases in physical output, the increase in revenue associated with the technology obviously depends on the level of output prices. On the other hand, production costs depend on input use and input price levels. The effects on revenues and costs of the level of output and input prices can be summarized by the Terms of Trade index. This is defined as the ratio of the index measuring prices received by farmers divided by an index of prices paid by farmers. The authors have estimated (Veeman and Fantino 1994) Total Factor Productivity (TFP) as a ratio of the Divisia quantity indexes of output and inputs (see Appendix I). As well, Terms of Trade (TT), defined as the ratio of the Divisia price indexes of output and inputs for the Prairies, has been derived.

A profitability measure, which in our case takes into account the opportunity cost of land and buildings and of farm operator labour, is the Return to Cost Ratio (RCR) which is the ratio of an index of total returns to farmers over an index of total costs. RCR can also be defined as the product of Total Factor Productivity and the Terms of Trade. An alternative measure of aggregate profitability in the sector is given by the difference between revenues and costs. The following profitability measures for the prairie agricultural sector can be calculated:

$$RCR = TFP.TT$$

$$Profit = Revenues - Costs$$

$$Profitability = Profit / Costs = RCR - 1 = TFP.TT - 1$$

All measures are in index form. The change in profitability between the base year and year t can be derived from these index numbers. The base year is defined as 1971 which is the year when chemical use began to increase rapidly.[3] The final value is calculated as either the value of the

[3] The choice of 1971 as the base year is not without problems. Pesticides, particularly herbicides, were in use in the Prairies since the 1950s. Using the 1950s or early 1960s as a base would result in much higher changes in agricultural productivity. The data presented in section II, however, indicate that the amounts involved in these early years were small in comparison with the levels of use in the 1970s and 1980s.

index in 1991 or, more realistically (to avoid any possible end year bias), the average value of the index in the late 1980s and early 1990s-- that is, the average between 1986 and 1991. Using our estimated indexes, we obtain the following index changes in output, TFP, TT and RCR for the prairie agricultural sector:

	Average Index Level 1986-1991	Percentage Change 1971-1991	Percentage Change 1971-1986/91
Output	1.31	48.2%	31.0%
TFP	1.21	31.5%	21.0%
TT	0.82	-31.8%	-24.8%
RCR	0.90	-10.3%	-10.2%

The change in profitability between 1971 and the late eighties is a 10% decrease, or less than half what the fall in the terms of trade would imply. This means that the measure of profitability has changed little since 1971 despite a considerable impact of unfavourable market conditions and the deterioration of farmers' terms of trade. In other words, it was the increase in productivity resulting from the technological package, of which pesticides are a part, that has prevented a drastic reduction in overall profitability in prairie agriculture in the last two decades. The contribution of the technology can be estimated as a 21 percent increment in output over the same period. This is also an estimate of the contribution to profitability if the influences of adverse movements in the terms of trade are not included in the picture.

Benefits can also be defined on the basis of the results of withdrawing pesticides from production entirely. Our calculations do not essentially change. The main factor which should be considered is that withdrawal would stimulate the introduction of substitute pesticides and/or

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Moreover, technical change in the 1950s was chiefly associated with substitution of capital for labour through mechanization. The 1960s saw increased use of fertilizer. Moreover, changes of cultural practices, including reduced summerfallow, and increased used of capital inputs which can be associated with intensification accelerated in the 1970s.

alternative measures of pest control. This would invalidate the use of our estimates to a considerable extent. Withdrawal represents more than a mere reversal of the process of technical change. An alternative to the approach developed so far would be to consider the increase in costs associated with pesticide withdrawal. This is the "dual" approach to the production function and productivity index approaches. The dual approach was not utilized in our estimations.

A different approach based on estimations of yield losses by experts has been utilized in a number of recent studies. Stemerof, Groenewegen and Krystynak (1991) provide estimates of cost increases resulting from the discontinuation of 2,4-D, the most widely used herbicide in the Canadian Prairies. The authors use cost per hectare estimates for herbicides used in the Prairies. They also report estimates from several sources of yield losses resulting from 2,4-D withdrawal (Stemerof et al, Table 12). The estimates are based on consultations with agrologists and other experts as well as previous similar studies. Cereal losses vary from 10 to 15 percent in the short term, and as high as 35 percent in the long term. The presence of dynamic effects associated with pest control technologies are apparent in these figures. This is to be expected. Our methodology, however, does not explicitly include dynamic effects. Our results are to be regarded rather as averages over the entire time period considered in each case. Nevertheless, they appear to be consistent with the losses estimated by Stemerof et al., particularly since in the 1980s yields and TFP moved in a similar fashion.

In another set of studies, a group of agricultural economists and consultants based at Texas A&M University utilized the Delphi survey technique to arrive at expert estimations of yield losses in different regions of the United States.[4] They report considerable yield losses from the assumed withdrawal of agricultural chemicals. Wheat, corn and barley yields are reduced by

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[4] Knutson, Taylor, Penson, and Smith (1990) which contains results for various crops for the United States as a whole; and Knutson, Smith, Miller, Taylor, and Penson (1990) which presents the results for wheat yields and costs for various regions of the United States.

23, 30 and 28 percent, respectively, under the no herbicides scenario; if nitrogen fertilizer is also withdrawn, the figures are 35, 51 and 41 percent, respectively. For the purpose of comparison with the Canadian Prairies, we use the wheat yield losses estimates for the Northern Plains: a 30 percent reduction under no herbicides and a 39 percent reduction under a no herbicides-no fertilizer scenario. These loss ranges are higher than our estimate of productivity change (approximately 21 percent) between 1971 and the late 1980s. They are comparable to our estimates of changes in TFP since the 1960s.[5]

Returning to our 1986-1991 based calculations, in the Prairies the increase in output is 31% over the 1971 base, the increase in TFP is 21%, and the remaining 10 percentage points in output growth is due to increases in the level of input use. If we consider 1971 and 1991 as initial and final years the percent changes over the entire period are: output 48.2%, input 12.7% and TFP 31.5%. Levels of output and TFP are subject to considerable year to year variations which mostly reflect growing conditions due to weather. This affects comparisons over time considerably. Averages over a number of years can reduce but not eliminate this variability. Given the nature and purpose of the estimations, the following calculations are conducted in approximate terms only and use the average over 1986-91, and not merely the 1991 figure, as the end point. The dollar value of crop production in the Prairies in and around 1971 is 1,100 million dollars. Deflated by the level of farm prices of agricultural products, it represents $3,000 million at 1991 prices. The prairie average value of crop output in the period 1986-1991 is $4,660 million dollars at 1991 farm product prices. The total output value change therefore is $1,660 million. This means that the annual contribution of technical change, which represents 68% of the total, can be

[5] This would tend to suggest that the American estimates attribute to agri-chemicals the whole of the productivity effects of technical change, which is likely to constitute an overestimation.

estimated to be $1,100 million or 0.17% of Gross Domestic Product in 1991.[6] In a similar fashion, a rough estimate of the value of crop production which would be foregone with the removal of herbicides from agriculture can be derived from the estimates in the Canadian study quoted above. Any short term reduction in yields of 10 percent would result in a reduction in value of $466 million, whereas, in the long run, a 35 percent yield loss would lead to a $1.6 billion value reduction. Of course, such estimates are exaggerated to the extent that they do not fully reflect the counter measures and adjustments that farm producers would make to a partial or complete chemical withdrawal. For example, Stemerof et al (1991) estimate the withdrawal of 2,4-D and MCPA from Canadian farm production would have a cost impact of $365 million as farmers switched to higher costs herbicides and suffered some yield losses. Overall, it seems reasonable to conclude that the removal of some or all herbicides from prairie crop production would have appreciable negative impacts on both production and productivity.

IV. Assessing the Use of Pesticides

The use of agrichemicals such as pesticides involves advantages and disadvantages, both to the farm producer and to society as a whole. In this section, a general methodological framework for the assessment of pesticides is presented. Thereafter, an extensive literature survey of the potential human health and environmental impacts of some common herbicides used in prairie crop production is undertaken in order to develop a qualitative feeling for the potential "external costs" associated with their use.

IV.1 Private and Social Benefit-Cost Analysis

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[6] Pesticide constitute an important component of the technology in current use, and they make an significant contribution to output and productivity. However, not all increase in productivity can be attributed to pesticides alone.

In using pesticides, farmers reap certain private benefits, largely production-related, and bear the private costs of buying and using fertilizer. In assessing the merits and drawbacks of pesticide use from a social point of view, however, a wider accounting framework is needed. One such conceptual framework for assessing social feasibility is that provided by social benefit-cost analysis. If spillover (or external) benefits are not present and if secondary benefits are ignored, then the social benefits of pesticide use can be derived in terms of the private benefits or rewards generated by all farmers in terms of the enhancement (or maintenance) of their production with pesticides versus being without pesticides.

The social costs of pesticide use, in this approach, are viewed to be the sum of the private costs and the external costs of pesticide use. The calculation of private costs is relatively straight-forward and involves the actual costs borne by farmers in buying and applying pesticides. The enumeration and evaluation of the external or spillover costs of pesticide use, however, is very critical but difficult to do. Possible spillover costs, not taken into account in decision-making by the farm operator, include health impacts on the farm family or on society at large or adverse impacts on wildlife, biota, or the environment. To the natural resource or environmental economist, the foregoing situation represents the case of an externality--specifically, the circumstance of an external diseconomy wherein a divergence exists between the private and social costs of production.

Where such external effects can be identified and measured in dollar terms, they should be included in the social benefit-cost format. In some instances, extra-market valuation techniques such as the direct survey or contingent valuation method, can be used to measure environmental loss or gain. In many circumstances, however, precise adverse environmental or health impacts may be very difficult to pin down and measure precisely. This is largely true with respect to the environmental and health effects of pesticide use and the best an economic analyst can do is to provide a qualitative discussion of the possible impacts. In what follows, we provide an extensive literature survey of the apparent health and environmental impacts for some key herbicides used in prairie agriculture. We concentrate initially on 2,4-D and then briefly discuss wild oats herbicides.

IV.2 Effects of Herbicides on Human Health and the Environment[7]

Extensive and increased use of herbicides in the last two decades coupled with increasing attention to health and environmental concerns has led to research into the potentially adverse effects of these agrichemicals. This research includes toxicity studies, epidemiological studies and studies of the effects on the environment.

In relation to toxicity of 2,4-D and its effects on human health, some evidence has been found that seems to show an association between phenoxy herbicides, including 2,4-D, and various cancers and reproductive effects. The studies do not provide enough evidence to demonstrate that 2,4-D is responsible for these adverse effects which led to speculation that dioxins found in 2,4-D as impurities might be the cause for the observed effect. The National Research Council of Canada in its 1982 report on 2,4-D concludes that it is unlikely that the dioxins present in 2,4-D are responsible for the reproductive effects observed and recommended further studies to determine if 2,4-D alone is responsible for these effects.

Turning to risk associated with handling 2,4-D, two recent epidemiological studies found evidence that farmers or farm workers exposed to 2,4-D may have an increased risk of developing non-Hodgkin's lymphomas. Evidence from Kansas and Nebraska suggest that farm workers exposed to 2,4-D for more than 20 days have such an increased risk (U.S. National Academy of Sciences 1989). As well, Wigle et al (1990) report that male farm operators in Saskatchewan were at greater risk if they sprayed more than 250 acres with 2,4-D. The National Research Council of

[7] We gratefully acknowledge the help of Ana Salazar in assisting with the preparation of this summary of the health and environmental effects of 2,4-D.

Canada (1982) also states that as it is unlikely to find high concentrations of 2,4-D residues in food or water, the major risk to human health seems to be exposure during manufacture and application of this herbicide. The absorption routes are oral, dermal and inhalation, with the oral route the most important one for the general population. However, the dermal route is the most important for workers and bystanders. Finally, with respect to possible mutagenic effects on animals, "the evidence does not suggest that 2,4-D is a potent mutagen" (WHO 1984), although the World Health Organization aknowledges this issue has not been adequately tested.

The most serious concern with respect to the use of 2,4-D and 2,4,5-T is due to its possible contamination with dioxins. Dioxins are toxic chlorinated compounds that have been linked to cancer (Holloway 1994). However, 2,3,7,8-TCDD, a highly toxic dioxin contaminant found in 2,4,5 T, has not been found in 2,4-D. Nevertheless, other chlorinated dioxins have been detected in 2,4-D. The U.S. Environmental Protection Agency (EPA) reported that 30 out of 33 samples of 2,4-D produced in the U.S. were free of any contamination by chlorinated toxins and the only dioxins EPA found were traces of four relatively non toxic isomers. The 2,3,7,8-TCDD was never detected (Mullison 1987). In 1985, EPA stated: "Based on our preliminary analysis, we believe that the concentrations of the dioxins found in 2,4-D do not pose a significant health hazard." At the present time, Canada requires 2,4-D to have no 2,3,7,8-TCDD present.

An important consideration related with pesticides is persistence in the environment. It appears that 2,4-D is one of the least persistent herbicides in the environment. It is degraded by physical, chemical and biological action. In soils, although its rate of degradation depends upon soil pH, organic matter content, moisture content, chemical composition and climatic conditions, it usually lasts only one to four weeks in warm, moist soil (Mullison 1987). Therefore, under favourable temperature and rainfall conditions, there is no risk of 2,4-D accumulating in the soil season after season (NRC 1978). Recent studies such as that of Smith and Lafond (1990) examine the mechanisms of degradation in soils and find some evidence that degradation rates are enhanced with repeated treatments with 2,4-D and MCPA. This results from adaptation by soil microorganisms able to metabolize the herbicides and use them as energy sources. But in very dry conditions, the rate of degradation is known to be slowed considerably, although it has not yet been measured with precision. This is of special concern in Western Canada because of the cold temperatures during most of the year. Nevertheless, as Campbell and Zentner (1990), research scientists at Swift Current, conclude, "The effects on soil processes of repeated applications of herbicide have not been fully ascertained, though Biederbeck et al (1987) demonstrated no deleterious effects on soil biota after 40 years of using 2,4-D."

Herbicides used in agriculture can contaminate waters by drift during application to terrestrial systems, by direct application by industrial discharges and by the washout during rainfall of the herbicide contained in the atmosphere. The direct application of this herbicide in water systems or an inadequate disposal practice may lead to environmental pollution that can contaminate drinking water and sources of irrigation. Generally, concentrations of 2,4-D do not exceed 0.1 ppm persisting only 1 or 2 days. Higher concentrations may occur in streams that flow from treated areas and in this case, 2,4-D may persist for several days. 2,4-D presence in the water ecosystem may cause direct effects and also secondary effects. Although direct lethal effects seem to be fairly low, there could be sublethal effects due to continued exposure which are less easily detected. Secondary effects include the change of the water ecosystem in terms of physical and chemical properties due to partial destruction of aquatic plants, which could be more important than direct effects. 2,4-D seems to be relatively nontoxic to fish and does not accumulate in fish sufficiently to pose a threat either to the health of the fish or the consumers. The Alberta Environmental Center in Vegreville monitored the amount of pesticides in fish from Alberta's lakes and rivers without finding 2,4-D. 2,4-D in its amine or salt formulation seems to be harmless to phytoplankton although its esters appear to be deleterious (Brown 1978).

In the US, the FDA has not detected 2,4-D in drinking water, thus indicating that "drinking water is not a significant source of human exposure outside the directly sprayed area." A 1979 study on surface waters of Western Canada (quoted in NRC 1983) showed levels of 2,4-D ranging from 0.004 to 0.235 mg per ml with a mean value of 0.046 mg per ml. As many as 20 different pesticides have been found in groundwater in numerous sites in the US and its widespread occurrence has caused serious concern. In Canada, the extent of groundwater pollution is largely unknown. Wells have been checked for a few pesticides in Canada including the insecticides Temik and Thimet, the herbicides Atrazine, Lasso and Dual and the soil fumigant D-D. 2,4-D was not included as an agricultural pesticide known to pollute groundwater by the Conservation Council of Environment Canada in 1987 (Coon 1987). A recent Farming for the Future study, Chang (1992), measured herbicides residues in southern Alberta groundwater, including 2,4-D, MCPA, dicamba, triallate, bromoxynil and other herbicides. Small amounts of some herbicides, including 2,4-D and bromoxynil, were found in some samples. The findings are significant since the author points out that given the special features of the testing area herbicide leaching should have been minimal. He concludes that "leaching losses of herbicides on agricultural land should be a concern" (Chang 1992, p. 17).

Air borne 2,4-D has also been considered. Atmospheric levels of samples taken on the Canadian prairies or the western US ranged from 0.01 to 1.0 mg per cubic meter. A US National Air survey, over a period of three years, found 2,4-D in the air only 5.64% of the time and only in places of direct usage. Although there is no concentration of 2,4-D in air established to be safe for the population, there is a threshold limit value (TLV) established for workers working 40 hours a week of 10 mg. per m^3 which is the same value as for dust. In a study cited by the WHO, workers during herbicide application were exposed to 2,4-D levels up to 0.2 mg per $meter^3$ air. The National Research Council of Canada in its 1982 report quotes a result that the exposure of a person 2.5 or 5 miles from the spray line would be almost negligible. Drifts from aerial spraying of 2,4-D esters may produce crop damage and air pollution. It is recommended to replace these volatile esters by less volatile esters or amine salts, a substitution that has taken place over the last two decades. When less volatile formulations are used following ground spray operation, studies showed that between 3 and 8% of the applied herbicide drifts. When high volatile esters are used or if the herbicide is applied by aircraft, between 25 and 35% of the herbicide sprayed drifts (WHO 1984).

In relation to the exposure of the general public to 2,4-D in food, the WHO reports that "detectable residues of 2,4-D on food plants may be consumed by human beings or animals and may thus contribute to the overall exposure of the human population to this chemical." In 1983, the US FDA and the Association of Official Analytical Chemists (AOAC) reported that for the years 1965-1970, the concentration of 2,4-D in the diet was 15,000 times less than the acceptable daily intake. Results reported for the years 1971-1973 showed 300,000 times less than the acceptable daily intake and from 1974 on, no trace has been found (Mullison 1987). The WHO (1982) also reports that "there is unlikely to be any exposure of the general population to 2,4-D residues in retail food supplies." Regarding its effects on wildlife, 2,4-D does not bio-concentrate through food chains and it does not appear to adversely affect vertebrates, soil micro-organisms or arthropods in a direct way, as shown by numerous studies (see National Research Council of Canada 1982).

Even though normal use patterns of 2,4-D are not expected to have direct toxic effects on animals, secondary effects arising from the change in plant community should also be considered. As a result of 2,4-D application, there is a change in the types of plants dominant in a determined area, thus changing the structure of the plant community. The long term significance of these effects on ecosystems is difficult to evaluate. Spraying of pastures with 2,4-D or drifting of sprays into pastures may present little direct hazard toxicity to livestock, however, some deaths were reported. From a producer's point of view, environmental secondary effects may render pesticide application counterproductive in certain circumstances. For example, scheduled or prophylactic treatments or poor practices may have little effects on yields. Moreover, secondary effects may develop pest resistance and destroy natural predators of certain pests. These problems are aggravated by monoculture, irrigation and fertilization (Osteen and Szmedra 1989).

Overall, the following conclusion appears to be warranted. The continuous usage of 2,4-D in agriculture throughout more than 40 years, the fact that it has not produced any major environmental undesirable effect nor major health problem and its short persistence in the environment, suggest that it poses no major hazards to the general population or to the environment. Areas of concern, however, relate to occupational hazards of farm workers mainly associated with increased risk of cancer, particularly lymphomas, and possible water contamination with herbicides.

The other major group of herbicides are wild oats herbicides. This group includes the following: Trillate, Diallate, Barban, Trifluralin, Diclofop Methyl, Flamprop Methyl, and Asulam. As explained in section I, treatment with wild oats herbicides in the prairies has expanded very rapidly in the seventies and eighties.

Trillate is a selective post-emergence carbamate herbicide which controls wild oats and other annual grasses in all varieties of wheat and barley. It is used mainly on wheat. The World Health Organization (1988) classified it as a slightly hazardous pesticide. Smith (1987) showed it is not carcinogenic to rats at levels up to 200 ppm. Trillate incorporates into the soil to a depth of 5 cm and is degraded by soil microorganism. The half-life in soils is 120 days, and there are losses due to volatilization. Persistence of Trillate in Saskatchewan soils is reported in Smith (1983). If applied in May, 3 to 64 percent of the Trillate was found in the soil at the end of the growing season. No leaching of Trillate was reported.

Diallate is a pre-emergence selective carbamate herbicide useful to control weed such as wild oats, windgrass and foxtail. It is used mainly on wheat, canola and sugar beets. The WHO report quoted above classified it as a moderately hazardous pesticide. It is carcinogenic in rats and it has "..moderate acute toxicity and potential adverse effects in animals chronically exposed." Diallate is not a widely used herbicide which means reduced wildlife exposure to it. In the environment diallate is degraded mainly by microorganisms having a half-life of approximately two weeks.

Asulam is a selective post-emergence carbamate herbicide used to control some grasses and weeds. It is mainly used in sugar cane and reforestation. It has very short persistence in the soil having a half-life of 6-14 days. It has a slight acute oral toxicity to laboratory animals. Both its dermal and oral toxicities seems to be low.

Barban is also a selective post-emergence carbamate herbicide used to control wild oats, mainly on wheat. It is readily degradable by soil microorganisms reducing residues to traces in about three weeks. It has a low acute, dermal and oral toxicity in rats. It seems to have a low chronic toxicity in rats. Trifuralin is a pre-emergence herbicide used to control a variety of grasses and broad leaf weeds. It has a low mammalian toxicity but a moderate to high toxicity to fish. Although it is degraded by soil microorganisms, trifuralin can persist from year to year controlling weeds and damaging sensitive crops.

The use of wild oats herbicides, as with any pesticide, is not without risks. Overall, however, the use of these herbicides in the prairie crop sector appears to be associated with minor, and not major, risks.

IV.3 Recent Developments in Assessing Pesticides

The issues surrounding the assessment of pesticide use are fairly complex and involve a wide range of scientific, technical and conceptual problems, as well as policy issues and options. Pesticide use has also been the subject matter of much debate and public controversy. A key problem is the lack of a clear consensus based on definite scientific evidence. Opinions and positions among actors vary depending on diverse factors such as their scientific discipline, institutional affiliation, theoretical paradigm, value systems, and other factors. We believe this report has provided a flavour of some technical and economic aspects of these issues. However, we know that important elements of a comprehensive treatment of the subject have been left outside the scope of the project. Nevertheless, in this concluding section a critique of some selected issues in the literature on pesticide use and assessment is provided, including a brief commentary on some recent noteworthy developments in that literature.

The likely impact of the withdrawal of agricultural chemicals from production is one area of controversy. The disagreements are not new and are well known, but some recent developments are worth mentioning . One example is the debate published in *Choices* between a team of agricultural economists who produced estimates of costs associated with reduction in pesticides and fertilizers in the United States and their economist critics[8]. In the original Knutson et al study, the reductions in yields estimated to result from discontinuing pesticide use are considerable. If fertilizer use is also discontinued, yield losses in the United States are as high as 38% in wheat, 37% in soybeans, 53% in corn, and up to more than 60% in cotton and rice. In this scenario impacts on food stuff prices would be even higher: real prices would double for corn, increase by 150% for soybeans, and increase by 24% for wheat. The figures used in the previous section (pp. 21/22) for comparison and our own estimations of productivity gains in Prairie agriculture in the period 1971-1991, lead us to believe these are likely upper bounds for yield losses. Important among the criticisms[9] is the lack of consideration of induced research and development and

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[8] The original study is Knutson et al (1990a and b). For the exchange, see *Choices*, Fourth Quarter 1990, including the articles by Ayer and Conklin and the rebuttal by Knutson, Taylor, Penson and Smith.

[9] The criticisms by Ayer and Conklin (1990) include: no allowance for induced R&D; inadequate allowance for nitrogen fixing crops and manures; imports frozen at pre-ban levels; no recognition of price induced conservation; fruits and vegetables ignored; and irrelevance of the scenario of a total ban on agri-chemicals. In a category of its own stands the last criticism: the appearance of conflict of

resulting innovations, and of crop rotations and increased use of organic fertilizer. Probably the most critical assumption is that of a total ban of agricultural chemicals. In the Canadian case, the agri-chemical intensive technology diffused and was adopted, and its effects were felt, over two decades. Withdrawing agri-chemicals from agriculture would not simple reverse the process. In any case, it is clear that there is no agreement or consensus on the magnitude of the reductions in productivity and the resulting effects on output and prices.

Although the estimation of benefits associated with pesticide use is complicated, estimating and valuing the associated costs is not easier. Besides the private costs to farmers of the pesticides, which in our framework are accounted for in the productivity calculations, there remain the eventual damage to farm operators and workers, to the population in general, and to the environment and wild life, resulting from the use of pesticides. Damage assessment includes estimating the relationship between the pesticide residues and/or environmental pollution and the damage produced, the response of the system to such pollution, and the assignment of a value to the damages. Since information is limited and it is not possible to run controlled experimentation, controlled experiments on animals and epidemiological studies to obtain mortality rates are used.[10] Once significant effects are determined they need to be quantified and valued in monetary terms. Several methodologies are used for this purpose such as the contingent valuation method. Implied in all this are severe problems of risk assessment and valuation including the thorny

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interest and alleged biases in research.

[10] These are difficult undertakings. Animal experimentation present the problem of extrapolating the effects to humans. Most of the effects on humans are at low doses of exposure and tend to appear over a lengthy period of time; however, animals are typically exposed to much higher doses for short periods of time. This means extrapolation well beyond the range of experimentation. Epidemiological studies do not present this problem, but then the conditions of experimentation are not controlled. They determine significant correlation at the most, but correlation does not necessarily imply causation. Problems are increased with synergistic effects which occur when the effect of a factor depends on the amount of other factors. The effect of pesticides on agricultural production, which is extensively discussed in this report, is an example.

problem of valuation of human life.[11]

Even if the problem of valuation is satisfactorily resolved, problems of risk assessment are even more difficult and controversial. Such is the case of risk evaluations of the effects of pesticides on human health and the environment. These evaluations are by their nature based on scientific evidence. The evidence linking pollution from different sources, including pesticides, to health has been tenuous and subject to various interpretations. A very recent example is the article by Gold et al (1992).[12] The authors deal with human exposure to natural carcinogens, including natural pesticides, as opposed to exposure to synthetic carcinogens. They claim that little attention has been given to these natural pesticides since studies focus on the oncogenic effects of synthetic pesticides. They use Ames' estimate that 99.99% by weight of the pesticides humans ingest are natural substances.[13] These are chemicals produced by plants to defend themselves from pests such as insects. Only a few natural pesticides have been tested as cancer causing agents, many having been shown to cause cancer in rats.[14] Moreover, risk extrapolation from high dosage bioassays on rodents are increasingly questioned. Although the toxicity of the chemicals at high doses are beyond much doubt, it is argued that the high doses used in the bioassays are a cause of

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[11] Procedures are outlined in Tietenberg (1992) and in Fisher (1981). In the latter, estimates of the value of saving a statistical life (Table 6.1, p. 212), differ widely according to the methodology. The estimates of the "implicit value of human life" in Tietenberg, p. 83, are clustered around a low range of 300,000 $ to 600,000 $ and a high range between one and seven million (in 1981 U.S. dollars).

[12] Gold, L. S., Slone, T. H., Stern, B. R., Manley, N. B., and Ames, B. N. (1992). The authors are bio-scientist from the Lawrence Laboratory in Berkeley and the University of California at Berkeley.

[13] See Gold et al (1992, p. 261). The 99.99 % figure is based on the study by Ames et al (1990).

[14] These chemicals are present in many common foods; for example, caffeic acid is contained in lettuce, apples, coffee, celery and potatoes, d-limonene in mango and oranges, safrole in species, and hidrazines and hidrazinobenzoate in mushrooms. Their ranking carcinogenic hazards by means of indexes shows many natural pesticides above the mean of exposure index of the set tested which includes natural and synthetic pesticides (Gold et al, 1992, Table 2, p. 263). A case in point is coffee which contains more than a thousand chemicals. According to the authors only 26 have been tested for cancer with 19 positive results in at least one test.

increased cell deaths resulting in high rates of cell replacement which favours cancers.

The authors caution against interpreting their results as asserting that natural pesticides produce cancer. Nor do they seem to indicate that many synthetic chemicals such as pesticides are not harmful substances, at least at certain high levels of exposure or that we can become complacent in their use and handling. Rather, they point out that "...widespread exposure to naturally occurring rodent carcinogens may cast doubts on the relevance to human cancer of far lower exposure to synthetic rodent carcinogens" (Gold et al, 1992, p. 264).[15] According to the authors' interpretation of their results, the previous experimental evidence linking exposure to chemicals, including pesticides, to cancer is to be doubted. Perceived economic trade-offs emanating from their assessment are not left implicit but specifically addressed. If such views gain widespread acceptance, they would certainly influence opinions and assessments of both pesticide use and regulatory policy. We quote extensively from the Gold study since it is representative of a series of similar pieces and editorial comments, for example, Corliss (1993), Garfield (1989), Spencer (1993) and Josephson (1993).[16]

The implication of these types of arguments can be better understood in view of recent criticisms in the United States of America of the so-called Delaney Clause first introduced in 1958 as an amendment of the 1938 Foods and Drugs Act. The Delaney Clause bans agricultural

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[15] Furthermore Gold et al (1992) argue that (their arguments) "...undermine many assumptions of current regulatory policy..." and "...the enormous amount of money spent trying to prevent "one in-a-million risks" can be counterproductive and involve economic and health trade-offs." "In the case of synthetic pesticides, the concern with minuscule residues makes fruit and vegetables more expensive and thus serves to decrease consumption of foods that help to prevent cancer..." Ames is very explicit regarding the relationship between pesticide exposure and cancer: "Unless you wade around in the stuff, pesticides don't cause cancer. That's the bottom line." (quoted in Spencer, 1993).

[16] Corniss (1993) for instance, quotes M. Kroger, professor at Pennsylvania State University, who "maintains that the benefits of pesticides...justify their use...The anti-cancer benefits from vitamins C and beta carotene in fresh fruits and vegetables far outweigh any tiny increased cancer risk from pesticides..."; he also quotes J.H. Hotchkiss, professor at Cornell University, as saying that "...risks from dietary pesticide exposure are minimal compared with exposures to cigarette smoke, radon, and sunshine."

products which leave any residue in food of any substance causing cancer in animals; it is therefore regarded as a zero risk environmental regulation. The Clause, now under review after 35 years, has been criticized as an anachronism.[17] All these signs increasingly point to a reopening or new round of debate on the environmental and health consequences of pesticide use in agriculture which suggests that a lack of consensus continues to divide opinions in the scientific community.[18] The likely outcome of the whole debate will undoubtedly influence opinion, assessment, and policy making which may have considerable economic consequences. These developments are very likely to impinge on the topic of our report in the near future and they are also likely to have considerable influence on the perception of it in Canada. They also are likely to have some consequences for Canadian agriculture, including the areas of regulation, policy making, public and private research policies and agricultural practices.

V. Summary and Conclusions

The use of agricultural chemicals has increased greatly in the prairie region. Pesticide use increased 7.6 percent per year from 1948 to 1991, slowing down only after 1985 with depressed conditions in the grain economy. The relatively rapid growth in agricultural chemical use in prairie agriculture over the past four decades is clearly evident, especially in the period from 1971 to 1985. However, since 1985, pesticide use has been relatively stagnant.

The average productivity of pesticides has generally declined over time, particularly since

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[17] See Winter (1993) and Hoyle (1993). What appears to have prompted the review is a ruling based on the Delaney Clause in 1992 by a Californian appeal court reversing a 1988 judicial decision to allow trace amounts of pesticides in foods. The head of the Environmental Protection Agency declared: "We do not believe that consumption of these pesticides as residues in processed-food products is a threat..."(as quoted in Hoyle, 1993).

[18] The debate continues while we are writing this. At the recent Annual Meeting of the American Association for the Advancement of Science in San Francisco, a panel discussion on breast cancer, one of the fast rising types of cancers, ended in disarray. Scientists strongly disagreed on the issue of pollution by chemicals, including pesticides, as a source of breast cancer.

the early 1970s, as pesticide use accelerated and diminishing returns in pesticide use occurred. Estimated aggregate production functions for prairie agriculture and the prairie crop sector provide crop output elasticities with respect to pesticide use. They range from 0.43 to 0.89 under different production function specifications over the time period from 1971 to 1991. The estimates in general imply a relatively high degree of responsiveness of output to pesticide use. However, it is difficult to accurately separate the effects of pesticides from the effects of other inputs, especially when pesticides are part of a wider and more intensive technological package.

The major social benefits associated with pesticide use relate to gains in agricultural production and productivity. Gains in productivity resulting from intensification are evaluated in the study in the 20 percent range. Estimates in the literature indicate that considerable yield reductions would result from herbicide removal. Even if such yield losses are over-estimated, they appear to be significant. Among the social costs of pesticides are the private costs incurred by farm producers but also the possible external or spillover costs inflicted on humans and the environment. Our qualitative assessment of these external costs tends to suggest that the agricultural sector in Western Canada has a level of pesticide use that is low in comparison with intensive agriculture in other parts of the world and a mix of herbicides with which minor, rather than major, health and environmental concerns are associated.

Nevertheless, the debate on the cost and benefits of pesticide use is far from settled. Recent developments in the literature cast doubts on the validity of traditional bioassays used to assess synthetic pesticide hazards. Possible areas of concern which emerged in recent literature is the suggested increased risk of lymphomas for farmers and farm workers who may be exposed to 2,4-D for longer periods of time. These issues should be monitored. At the least, guidelines for protective clothing should be considered for farm workers who are engaged in extensive spraying.

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Appendix I

Table A.1. Pesticide Use in the Prairies: Implicit Quantities

Year	Manitoba	Saskatchewan	Alberta	Prairies
1948	1.095	3.333	2.671	7.099
1949	1.401	4.117	3.348	8.866
1950	1.607	4.653	3.804	10.064
1951	1.489	4.300	3.521	9.310
1952	1.404	4.110	3.347	8.861
1953	1.345	4.043	3.257	8.645
1954	1.357	4.147	3.315	8.819
1955	1.417	4.339	3.469	9.224
1956	1.495	4.526	3.637	9.658
1957	1.476	4.468	3.589	9.533
1958	1.438	4.425	3.532	9.395
1959	1.776	5.676	4.321	11.772
1960	2.138	6.724	5.177	14.039
1961	2.498	7.339	5.565	15.402
1962	2.727	7.140	5.660	15.527
1963	2.859	6.838	5.462	15.160
1964	2.993	6.352	5.265	14.609
1965	3.166	6.240	5.245	14.651
1966	4.037	8.290	6.945	19.272
1967	4.469	9.075	7.609	21.152
1968	5.232	10.758	9.010	25.000
1969	4.491	8.205	6.940	19.636
1970	3.916	6.149	5.276	15.340
1971	4.001	7.070	5.538	16.609
1972	4.877	9.118	6.842	20.838
1973	7.727	14.006	10.146	31.879
1974	7.765	15.155	10.706	33.626
1975	9.514	17.515	12.971	40.000
1976	9.801	19.016	13.212	42.029
1977	12.388	23.538	14.454	50.379
1978	16.868	30.383	18.690	65.941
1979	20.756	34.642	21.648	77.047
1980	17.433	29.023	22.050	68.506
1981	22.960	36.321	27.706	86.987
1982	22.234	36.542	29.218	87.994
1983	23.121	41.485	30.039	94.645
1984	25.213	46.270	33.091	104.574
1985	25.554	50.681	34.265	110.500
1986	23.540	50.382	33.046	106.968
1987	23.434	46.076	28.807	98.317
1988	26.131	48.024	31.218	105.372
1989	25.475	51.645	34.817	111.937
1990	25.398	50.037	34.638	110.073
1991	24.566	48.886	34.698	108.150

Appendix I

Table A.2. Indexes of Output, Inputs and Total Factor Productivity (TFP) Prairie Agriculture, 1971=1

YEAR	OUTPUT	INPUT	TFP
1948	0.544	1.045	0.521
1949	0.462	1.038	0.445
1950	0.553	0.977	0.566
1951	0.642	1.000	0.642
1952	0.759	1.149	0.660
1953	0.707	1.012	0.698
1954	0.503	0.973	0.517
1955	0.677	0.978	0.692
1956	0.755	0.978	0.772
1957	0.596	0.944	0.631
1958	0.630	0.924	0.682
1959	0.644	0.921	0.699
1960	0.701	0.941	0.745
1961	0.504	0.940	0.536
1962	0.741	0.916	0.809
1963	0.844	0.947	0.891
1964	0.748	0.968	0.773
1965	0.878	0.954	0.920
1966	0.992	0.957	1.036
1967	0.804	0.970	0.829
1968	0.876	0.925	0.947
1969	0.902	0.952	0.947
1970	0.841	0.942	0.893
1971	1.000	1.000	1.000
1972	0.940	1.000	0.939
1973	0.980	1.018	0.963
1974	0.860	1.063	0.809
1975	1.092	1.098	0.994
1976	1.085	1.102	0.985
1977	1.120	1.080	1.037
1978	1.191	1.104	1.079
1979	1.022	1.129	0.906
1980	1.062	1.084	0.980
1981	1.203	1.095	1.099
1982	1.296	1.093	1.185
1983	1.224	1.113	1.100
1984	1.164	1.117	1.042
1985	1.244	1.102	1.129
1986	1.416	1.113	1.272
1987	1.299	1.141	1.139
1988	1.121	1.120	1.001
1989	1.281	1.088	1.178
1990	1.483	1.118	1.326
1991	1.482	1.127	1.315

Appendix II

Table B.1. Transcendental Logarithmic Production Functions

	Prairie Agriculture			Prairie Crop Sector		
Period	1948-91	1958-91	1971-91	1948-91	1958-91	1971-91
Ln Pesticide	-0.38	-0.85*	-2.08*	-0.85*	-1.45**	-2.70*
Ln Fertilizer	0.23*	0.45**	2.15*	0.46*	0.79**	2.56*
Ln Capital	1.64**	9.60**	15.70*	2.17**	14.4**	19.4*
Ln F x Ln P	0.08*	0.28**	0.24*	0.12*	0.42**	0.36
Ln F x Ln K	-0.65	-3.33**	-7.67**	-1.57	-5.6**	-9.6*
Ln P x Ln K	0.50	0.61	4.35	1.86	1.8	5.4
R^2	0.87	0.87	0.77	0.83	0.85	0.76
D.W.	2.10	--	2.04	2.07	--	1.92
Procedure	OLS	C-O	OLS	OLS	C-O	OLS

*, ** significance at the 10% and 5% (or less) levels, respectively.

Appendix II

Table B.2. Transcendental Logarithmic Production Functions II

	Prairie Agriculture			Prairie Crop Sector	
Period	1958-71	1968-91	1968-91	1968-91	1971-91
Ln Pesticide		16.7**			
Ln Fertilizer		13.2*			
Ln Capital	16.0*	-71.1*		2.2	
Ln F x Ln P	2.0**	-8.2*	-1.21**	-1.6*	-0.7*
Ln F x Ln K	-4.1**	3.5	-31.2**	-37.9**	-22.1**
Ln P x Ln K	19.2*	-28.5*	8.0**	9.1*	
$(\text{Ln F})^2$	-0.2	4.4*	2.0**	2.5**	1.3**
$(\text{Ln P})^2$	-4.8**	4.8**	0.4*	0.6*	0.6*
$(\text{Ln K})^2$	-51.2*	181.**	130.**	156.**	110.**
R^2	0.80	0.87	0.82	0.81	0.73
D.W.	--	2.17	2.27	2.11	2.13
Procedure	C-O	OLS	OLS	OLS	OLS

*, ** significance at the 10% and 5% (or less) levels, respectively.