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Potential Effects of Climate Change on Agriculture in the Prairie Region of Canada

Louise M. Arthur and Fay Abizadeh

The objective of this paper is to examine the effects of long-term climate change, as a consequence of doubled atmospheric carbon dioxide, on Canadian prairie agriculture. The climate change scenarios are based on regional results from two leading general circulation models (GCMs), the GFDL model and the GISS model. Although both scenarios suggest that average temperatures will increase in all areas of all three provinces by an annual average of 2.6 to 4.6 degrees centigrade, in some areas additional precipitation is enough to compensate for the increased evapotranspiration. Changes in crop revenues under current economic/technological conditions range from a 7% loss in Alberta under one GFDL scenario to an 8% increase in Saskatchewan under a slightly different GFDL scenario.

Key words: agroclimatic models, climate change, greenhouse effect.

Many atmospheric scientists involved in long-term climate forecasting believe that the documented increases in concentrations of atmospheric carbon dioxide (CO_2) and other greenhouse gases will continue (Seidel and Keyes) and will bring about a general warming of the earth's surface (Manabe and Wetherald, Walts). Recent estimates of trends in atmospheric accumulation of the most important greenhouse gas, CO_2, project a doubling in concentrations sometime between 2035 and 2075 (White) and a consequent 3 ± 1.5 degrees centigrade (C) mean global temperature increase (Herbert), with much larger increases in the higher latitudes. Predictions for such dramatic changes in climate raise concerns for the future viability of agricultural sectors already severely constrained by climate. Therefore, despite considerable uncertainty concerning the magnitude and timing of the greenhouse effect, agricultural impact studies are being undertaken in areas that are particularly sensitive to climate, such as the northern prairies or steppes, which are characterized by extreme and variable weather (Parry). The objective of this study is to examine the effects of long-term climate change on crop production in the Canadian prairie provinces of Alberta, Saskatchewan, and Manitoba.

Studies evaluating the economic effects of even current weather on crop production in various regions of Canada are few because of economists' unfamiliarity with both climatology and plant physiology and because of the complexities of physiological models of plant response to weather. Economists' yield models have tended to include simple measures of weather, either aggregate indicators of seasonal temperature and precipitation (Thompson, Waggoner) or a composite index of both (Miranowski, Narayanam and Dyer, Perrin and Heady). Such models have been useful in analyzing extremely aggregate variations in crop production but are not particularly successful in determining weather effects on specific crops and regions. Studies by agrometeorologists, on the other hand, have been directed toward the development of physiological crop growth models and not toward development of models

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which account for the effects of other factors of production, such as fertilizer, management, and variety selection (Blackburn and Stewart; Williams; for an exception see Stewart 1984, 1987). In an effort to emphasize the effects of weather on regional crop production while still recognizing the roles of management and technology, this study employs both physiological and statistical agroclimatic yield models.

The sensitivities of yields to current weather are used to simulate prairie crop yield responses to a new weather regime stemming from doubled CO_2. The economic implications of these yield effects are evaluated in terms of current economic/technological conditions; attempts to forecast an economic environment fifty to ninety years in the future (the expected time frame for a doubling of CO_2) would lead to model components that could not be validated and to the confounding of errors in climatic forecasts with errors in economic forecasts. The objective is to determine the potential impacts of the greenhouse effect on prairie crop production as it is currently structured. Because the prairie provinces are net exporters of all grains and oilseeds, exporting 90% to 95% of production on a value basis (Coffin), changes in production will translate to increases or decreases in excess supply and, hence, exports, which will be priced at world prices.

Methods

The Climate Change Scenarios

Two climate change scenarios were provided by the Canadian Atmospheric Environment Service (AES) based on general circulation model (GCM) experiments for doubled CO_2 ($2 \times CO_2$) conducted by the Geophysical Fluid Dynamics Laboratory (GFDL) and the Goddard Institute for Space Studies (GISS). The results were compared to respective GCM results for $1 \times CO_2$ (i.e., current conditions) in order to provide monthly average changes in precipitation and temperatures (see table 1) for grid points ranging from 4.4 to 8 degrees latitudinally and from 7.5 to 10 degrees longitudinally.[1] Because monthly averages are not adequate for predicting crop response using the models available for the prairie region, monthly average weather changes were distributed to daily changes using two methods: a flat distribution (referred to as GFDL1 and GISS1) and trigonometric distributions of temperatures (scenarios GFDL2 and GISS2) based on sin-curve extrapolations which simulate the distribution of historic monthly averages over historic daily temperatures (Brooks).[2] These daily temperature and precipitation changes were then interpolated to the nearest prairie weather station and added to historic daily weather data for 1961 to 1985 for all 188 prairie weather stations. Based upon the latitudes and longitudes of these stations, thiessen polygon coefficients were calculated to determine the average temperature and moisture regime for each of forty districts or subdistricts (CRDs).

In general scenarios GFDL1 and GFDL2 show more intra-annual variation in both temperature and precipitation, while scenarios GISS1 and GISS2 show greater annual average temperature increases. The greater variation in scenarios GFDL1 and GFDL2 will result in greater sensitivity to variations in the daily distribution of the monthly average temperatures.

Simulation Models

Figure 1 represents the components of the simulation model used in the analysis. The causal linkages among models are primarily unidirectional and begin with either historical daily weather data for 1961 to 1985 or scenario weather data representing the effects of doubled CO_2.

The models' translation of the meteorological events of weather into agricultural events depends primarily on the moisture stress experienced by various crops under various weather conditions. The "Versatile Soil Moisture Budget" (VSMB, Baier and Robertson) provides a physiological simulation of a crop's response to moisture, based on daily changes in soil moisture content in response to weather (evapotranspiration, precipitation, runoff, snow melt), the crop's rooting pattern, and soil moisture release characteristics. Moisture "deficits" are then defined in terms of the amount of water a given plant would have used in each growth stage had it been available. Timing of

[1] Grid point spacings correspond to approximately 300 to 550 miles and 400 to 500 miles, respectively, varying by GCM.

[2] GCMs can generate daily data for 20 years, but they are not generally saved due to the expense (Schlesinger).

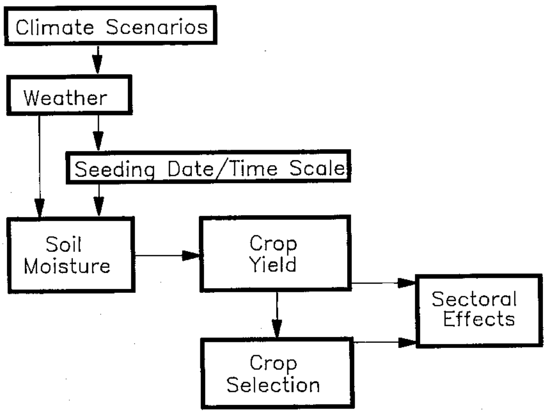


Figure 1. Model flows

growth stages, in turn, is based on purely physical and climatological data which determine both the seeding date (based on risk of frost and field accessibility)[3] and the length of each stage (based on temperature, precipitation, and day length). Moisture deficits are determined for all major grains and oilseeds for each of five growth stages (emergence to maturity), three soil types (light to heavy), forty CRDs, two seedbeds (fallow or stubble), and twenty-five base weather years (1961 to 1985).[4]

The crop yield effects of these varying soil moisture deficits are determined by a series of empirical equations which quantify the effects of soil moistures and technological/management variables on crop yields. With respect to the technological/management variables, yields are assumed to increase, but at decreasing rates. However, the functional form allows marginal products (yields) of the moisture stress variable to both increase and decrease, depending on the actual level of stress:

$$(1) \qquad Y = \alpha CD_i^{\beta_{1i}} V^{\beta_2} F^{\beta_3} M1^{\beta_4} M2^{\beta_5} EX_j^{\beta_{6j}} e^{\beta_7 M1} + {}^{\beta_8 M2} u,$$

where Y is crop yield in bushels per acre; CD, N dummy variables for CRDs, ($i = 1 - n$, n varying across models for different regions due to differing numbers of CRDs); V, varietal improvement index (indicating the relative yield potential of various varieties); F, applications of nitrogen per acre; $M1$, moisture deficit (mm.) from stages 2 and 3 (post emergence) of crop growth; $M2$, moisture deficit (mm.) from stages 4 and 5 (to maturity) of crop growth; EX, dummy variables (j) for extreme weather events (frost, excess moisture) in certain regions and years; α, β, estimated regression coefficients; and u is error.

All models are pooled across some CRDs as well as across the entire time series. Because of poor individual yield models for Alberta, pooling was performed across similar soil types

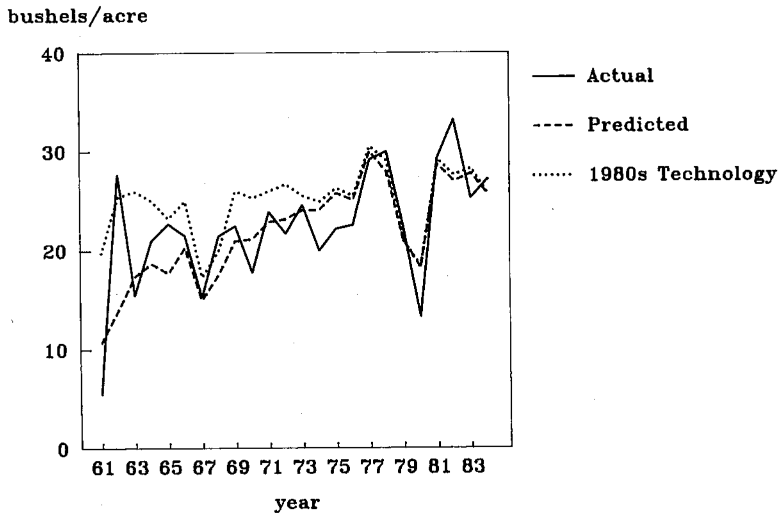
[3] Heavy clay soils in many prairie regions constrain accessibility during wet weather.

[4] Separate models were also run for reduced tillage/snow trapping (versus conventional tillage) but empirical yield data were not available to develop the yield models required for estimation of economic impacts.

Table 1. Climatic Change Scenarios: Descriptive Statistics

	Scenario			
	GFDL		GISS	
	So. Manitoba	No. Alberta[a]	So. Manitoba	No. Alberta[b]
Temperature change (+C)[c]				
Average (annual)	2.57	2.79	4.58	4.64
Standard deviation	1.44	1.46	.96	1.06
Low (month)	0.40 (July)	1.20 (Feb., Nov.)	3.10 (July)	3.30 (June, July)
High (month)	6.00 (April)	6.10 (April)	5.70 (Jan., Dec.)	6.20 (Jan., Dec.)
Precipitation charge (% normal)[c]				
Average (annual)	128.07	114.85	113.87	122.14
Standard deviation	28.62	28.75	8.09	11.58
Low (month)	88.80 (Mar.)	72.40 (June)	95.80 (Sept.)	100.00 (Sept.)
High (month)	171.50 (Apr.)	196.80 (Sept.)	123.50 (Jan., Dec.)	141.20 (Jan.)

[a] Approximately Peace River region.
[b] Approximately Edmonton region.
[c] Change from 1 × CO_2 experiments.



Vertical is bushels/acre, horizontal is year.

Figure 2. Stubble seeded spring wheat yields in Manitoba CRD 1

in Alberta and Saskatchewan for some crops, particularly those with sparse data sets. Because Manitoba is predominantly heavy black soils, all Manitoba crops models were pooled across the entire province.

Table 2 represents a sample of the estimated results for spring wheat in Manitoba, Alberta, and Saskatchewan. For the various models, R^2 values range from .23 for canola on stubble in Alberta to .66 for barley on stubble in Manitoba.[5] All models (with the exception of canola in some areas) showed an initial increase in yields in response to small amounts of moisture stress in the early stages of growth (a maximum of approximately 20 mm.) and declining yields in response to further stress. In most cases the intercepts for fallow equations exceed those for stubble equations, which can be attributed to higher conserved moisture and base nutrient levels as well as reduced weed problems. Elasticities with respect to fertilizer applications tend to be somewhat less than .1%, with slightly higher elasticities in the equations for stubble seedbeds.

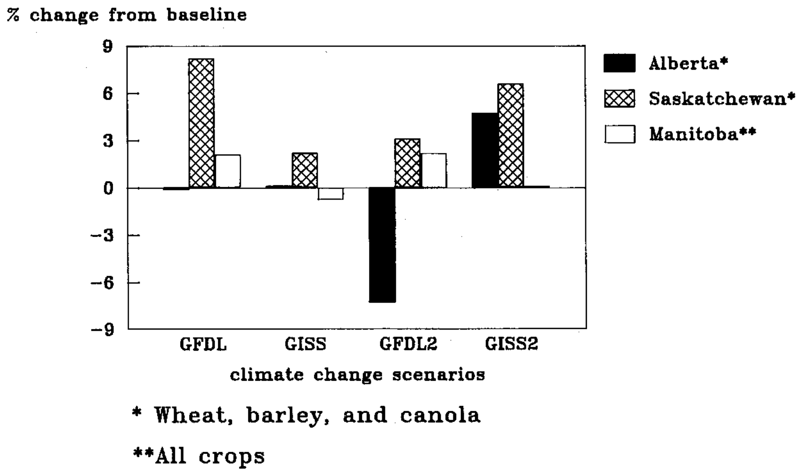
Based on the results of the regression equations, yields are predicted for each weather year (1961–85) of each scenario. Using the regression coefficients and the average fertilization rates and crop variety selections of the 1980s, the yields are then adjusted to reflect the latest technology, with results as illustrated in figure 2. For example, predicted yields for 1961 are the yields that would have occurred with 1961 weather but technology of the 1980s. Predicted yields under both historic and scenario weather are then averaged over the entire 1961 to 1985 baseline period.

Economic effects for the prairie region can be extrapolated from the yield results based on established seeding patterns and current prices. In the case of Manitoba yields are entered into a linear programming model (LP) which uses the expected yields under the various weather scenarios to adjust CRD cropping patterns and fertilization rates to maximize net crop revenues, given physical, biological, and economic constraints on the sector (see Arthur and Freshwater). Seeding and fertilization decisions are based on expectations for long-term normal weather, either average 1961–85 weather or with the new long-term averages expected from doubled CO_2.[6]

For Alberta and Saskatchewan economic impacts on the agricultural sector were extrapolated directly from the provincial yield effects multiplied by current crop prices and

[5] Canola is edible rapeseed with less than 5% erucic acid and less than 30 micromoles of glucosinolates per gram of meal. There are fewer data points in terms of both time (available only since 1976) and place than for other crops.

[6] Unfortunately, the yield effects of various fertilizer-moisture interactions at time of seeding are not well understood. Research is currently underway (see Josephson and Zbeetnoff).



Vertical is % change from baseline, horizontal is climate change scenarios.

Figure 3. Percentage change in crop receipts by scenario

seeded acreage for each province (1985 to 1986). The majority of Saskatchewan and Alberta farmers have fewer dryland cropping alternatives than many Manitoba farmers, resulting in reduced need for an LP-type framework.

Data

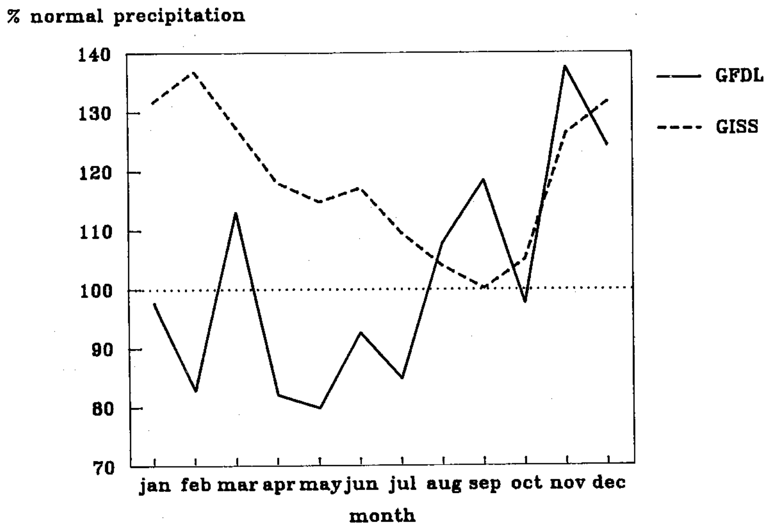
Historical daily weather data were obtained from AES for 1961 to 1985 for all prairie weather stations. Field-level data concerning selected crop varieties, seeding dates, yields, and fertilization rates were obtained from provincial crop insurance corporations. Genetic potential indices for crop varieties (V) were developed by agronomists at the University of Manitoba. Commodity prices are from the Canada Grains Council and input prices (for the LP) from input suppliers and Statistics Canada.[7] Primarily because Canada's crop production represents only a small proportion

[7] Detailed description of all data sources for the LP can be found in Arthur and Freshwater.

Table 2. Estimated Coefficients for Spring Wheat

	Manitoba		Saskatchewan and Alberta, Brown Soils		Saskatchewan and Alberta, Black Soils	
Variable	Fallow	Stubble	Fallow	Stubble	Fallow	Stubble
Intercept	2.48[b]	2.31[b]	1.506[b]	2.425[b]	1.876[b]	1.167[b]
Ln V[c]	1.00[b]	1.00[b]	1.00[b]	1.00[b]	1.000[b]	1.000[b]
Ln F	.08[b]	.12[b]	.138[b]	.197[b]	.117[b]	.222[b]
Ln $M1$	.19[b]	.21[b]	.425[b]	.221	.364[b]	.433[b]
Ln $M2$	−.02	−.02	.101	−.068	.059	.127
$M1$	−.01[b]	−.01[b]	−.007[b]	−.004[b]	−.007[b]	−.009[b]
$M2$	−.00	−.00	−.005[b]	−.004[b]	−.004[b]	−.005[b]
Frost 74					−.343[b]	−.307[b]
Frost 79					−.411[b]	−.122[b]
R^2	.51	.60	.553[b]	.492	.611	.640
Restriction[d]	−.06	−.00	.191[b]	−.230[b]	.082	−.122[b]

[a] Intercept shifters (CDs) are excluded.
[b] Significant at the 5% level.
[c] The value of this parameter is restricted =1. V is an index of the actual genetic potential for yield of the crop grown relative to a baseline variety and is developed so that the coefficient value should equal one.
[d] λ is the coefficient for restriction; H_0 is restriction reflected in data set ($\lambda = 0$).



Vertical is % normal precipitation, horizontal is month.

Figure 4. Precipitation changes in Southern Alberta

of U.S. or world production, Canada is recognized to be a price taker in world markets; nearly 70% of Canadian agricultural products are priced on world markets and prairie grown crops represent the bulk of these commodities (Coffin).

Results

Results vary considerably by region and scenario due to the variations in both baseline conditions (relative prices and yields of various crops, soil types, average normal weather, etc.) and scenario changes (figure 3). While temperatures rise under all the climatic change scenarios, in some areas the increases are small during the crop-growing season (e.g., .8°C in June and .4°C in July for the GFDL scenario in central and southern Saskatchewan). In such areas slight increases in precipitation can offset increased evapotranspiration, or earlier seeding (e.g., due to 6.4°C increases in April in the same region and scenario) can result in enhanced production volumes.

Because Manitoba's arable lands are not generally moisture deficient and small increases in precipitation are predicted by the GCM models, the LP results suggest that some small net gains in overall production volumes and revenues could be expected under many of the climatic change scenarios. Furthermore, even when yield losses are expected for several crops in several CRDs, the results show that the aggregate provincial sector can adjust to offset these losses by seeding more drought resistant crops (such as barley and canola) in dry areas and special crops that respond better to the higher temperatures (e.g., corn). Such adjustments will make a major difference to individual farmers and will stabilize the sector's performance as a whole.

As indicated in figure 3, in Saskatchewan all climate change scenarios result in a net in-

Table 3. Change in Crop Yields by Scenario

Provinces	GFDL1	GFDL2	GISS1	GISS2
Manitoba	increase all crops	increase all crops	decrease all crops except wheat	increase all crops
Saskatchewan	increase wheat	increase all crops	decrease all crops except wheat	increase all crops
Alberta	not sensitive	decrease all crops except barley	not sensitive	increase all crops

crease in crop receipts (relative to baseline); although only wheat shows a yield increase under GISS1 (table 3), 70% of improved land is seeded to spring wheat or durum. Declines in yields of other crops attenuate the total yield impact. In Alberta, on the other hand, scenario results are more variable. Under GISS1 and GISS2 yields improve somewhat due to increased precipitation in all months in all but the most northern regions (fig. 4). Under the GFDL1 and GFDL2 scenarios, precipitation decreases in most months of the growing season (fig. 4), resulting in reduced dryland yields.[8]

Conclusions

Initial responses to expectations of global warming were that agricultural patterns would change dramatically and that the prairie regions could suffer substantial crop losses (Williams). However, early speculations and models were based on hypothetical scenarios of temperature increases, without accounting for the monthly distribution of those temperature increases or the accompanying changes in precipitation. Results from GCMs now suggest that the temperature increases will be about 50% greater in the winter than summer months and that global average annual precipitation will increase by 7% to 11%, with even larger increases predicted for some regions (Sinha, Rao, and Swaminathan). With some notable exceptions, the regional predictions of the GCMs used in this study appear to produce conditions that are slightly more favorable to northern prairie agriculture if certain adjustments are made, primarily with regard to earlier seeding to take advantage of the longer growing season (increased by 30 to 60 days by some estimates; Williams et al.). These results are consistent with a major study of the U.S. response to climate change (Wilks). Using daily weather results from GCM experiments for doubled CO_2 and a biological crop simulator similar to that used to generate the crop moisture stresses for this study, Wilks found that corn output actually increases with the increased temperatures because of changed seeding dates, allowing seeding of later maturing varieties.

Possible adjustments that could not be accommodated by the models could further attenuate crop losses or enhance revenue gains. For example, in the Alberta results, losses under GFDL2 could be reduced somewhat by shifting cropping patterns among the current major crops, by adding higher valued crops that become feasible under the new climate (e.g., corn, soybeans, and winter wheat), or by increasing irrigated acreage. However, net losses may still accrue because of limited cropping options and irrigation water sources. Similar adjustments could increase the benefits of climate change in some regions of Manitoba and Saskatchewan.

Some scientists believe that the most devastating effects from increased CO_2 concentrations would be from an increase in the probability of severe prairie droughts (Williams et al.). For the whole region a drought similar to that of 1961 could result in up to ten times the magnitude of crop losses predicted for the most pessimistic greenhouse effect scenario (Arthur and Freshwater). Conversely, some climatologists contend that the weaker circulation patterns under the greenhouse effect will result in reduced temperature and precipitation variability (Sinha, Rao, and Swaminathan), but this is by no means certain.

While GCMs have increased considerably our understanding of the climatic changes that may occur under the greenhouse effect, various GCMs produce varying results, particularly at the regional level. Therefore, studies of the impacts of climate change should consider more than one possible climatic result. The GCMs tested in this study are the two most often used for impact analysis, but they have been revised since the time of this study and will continue to change as modeling efforts continue. There is no basis on which to have more confidence in one of the scenarios than another, so all are treated with equal degrees of confidence or nonconfidence.

This study has clarified the importance of more carefully defining the precise nature of the climatic changes under the greenhouse effect. The various GCMs produce regional predictions which have contradictory implications for agriculture. Furthermore, the detail generally provided in the GCM scenarios is not sufficient to support rigorous agricultural impact assessment. While the authors of this study attempted to define appropriate daily distributions of temperature and precipitation,

[8] Irrigated yields are not modeled.

because these distributions are of critical importance in determining yield effects, it is recommended that climatic modelers direct their efforts to providing these distributions. Furthermore, GCM models can produce soil moistures (Schlesinger), provision of which could further enhance and expedite impact estimation.

This analysis examined only the climatic effects of increased atmospheric CO_2. The direct effects of CO_2 enrichment are known to include increases in photosynthetic rates (particularly in C_3 species such as small grains, legumes, and root crops), reduced transpiration (particularly in C_4 plants such as corn and sorghum), and reduced impacts of water stress and salinity on photosynthetic rates (Rosenberg). Efforts have been made to quantify yield increases due to CO_2 enrichment, primarily under controlled greenhouse conditions (Acock and Allen, Cure, Kimball), but the yield effects are not well understood under average field conditions; in excellent field conditions, prairie wheat yields may increase by 7% to 36% under doubled CO_2, depending on available nutrients and with no accompanying climate changes (Cure, Kimball). While these effects could not be quantified for inclusion in the yield models, the direct effects of CO_2 will likely improve yields beyond those predicted by the current models.

Based on the results of this analysis, one could conclude that anticipation of a looming greenhouse effect need not spell doom to an already drought stricken prairie agricultural sector. Many areas could see beneficial changes in climate, and in those areas in which negative effects are expected, needed adjustment tools are already available or under development (alternative crops and technologies), and required adjustments will likely be small. However, this analysis addresses only the Canadian prairie impacts of the greenhouse effect. The international effects of global warming are expected to be more profound (Jaeger) and will greatly affect world grain prices and hence Canadian farm revenues. Given the number of factors other than weather which affect world grain prices, the price effects of climate change will likely remain indeterminant.

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