IMPLICATIONS OF CHANGES IN CLIMATIC AVERAGES AND VARIABILITY ON FOOD PRODUCTION OPPORTUNITIES IN ONTARIO, CANADA*

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Abstract. This paper explores the implications of changes in climatic averages and a range in precipitation levels on food production opportunities at the farm, regional and provincial levels for the province of Ontario. A doubling in atmospheric CO_2 or its equivalent would contribute to extended frost-free seasons throughout Ontario, and possibly increase year-to-year variability in precipitation. At the farm level, these changes imply greater fluctuations in annual farm profits. The benefits of longer frost-free seasons would be impaired during years with relatively low precipitation, and under these conditions, the security of the province's food supply would be at risk.

1. Introduction

Growing evidence that atmospheric concentrations of carbon-dioxide, methane, nitrous oxide and other 'greenhouse gases' are increasing (Hengeveld, 1987; Moore, 1988) and contributing to a global warming (Hansen *et al.*; 1983; Wilson and Mitchell, 1987) has sparked considerable interest in the relationships among climate, climatic change and society (Clark, 1985; Kellogg, 1987; NRC, 1983; Warrick and Riebsame, 1981). Climatic impact assessment is a relatively new field of scientific investigation, but there is a growing body of literature which appraises the likely impacts of a long-term climatic change on a wide range of human activities. While the activities considered and analytical procedures employed vary from study to study, the use of climatic change scenarios based upon possible alterations to climatic averages is common in many of these recent assessments (Arthur, 1988; Bergthorsson *et al.*, 1988; Cohen, 1986; Marchand *et al.*, 1988; Pitovranov *et al.*, 1988; Rosenzweig, 1985; Smit *et al.*, 1988b and 1989; Wall, 1988; Yoshino *et al.*, 1988).

Two frequently offered suggestions for extending the utility and scope of climatic impact assessments are to consider:

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(1) possible adjustments to interannual climatic variability as well as changes to long-term norms (Clark, 1985; Stewart and Glantz, 1985), and

(2) the impacts of climatic change at different spatial scales (Myers, 1988; Sonka and Lamb, 1987; Waterstone, 1985).

These recommendations reflect concerns that changes in climatic variability, particularly extremes, may well have a greater impact on society than will anticipated changes in long-term averages, and that the effects of climatic change on human activity may vary at the local, regional, national and international levels.

This paper investigates the effects of changes in climatic averages and precipitation range on food production opportunities at the farm, regional and provincial levels for the Province of Ontario, Canada.

The initial step in the analysis estimates the potential effects of increases in infrared absorbing gases on agroclimatic resources throughout Ontario, and estimates a range in precipitation levels during the frost-free season under the current and the altered climatic regime. Estimates of changes to climatic averages are derived from the output of a general circulation model assuming the equivalent of a doubling in atmospheric CO_2. Values reflecting a range in precipitation are estimated by superimposing the current (i.e. 1951–1980) climate range onto the estimated changes for the average climate. Atmospheric models can provide estimates of changes in average climate, but they are not presently able to provide insight into possible adjustments to interannual variability. The approach employed here facilitates an analysis of the sensitivity of agriculture to climatic variability by considering a range in precipitation levels. The analysis is clearly exploratory: sensitivity to other properties of climatic variability and to such factors as the direct effects of CO_2 on yields are beyond the scope of this paper.

At the farm level, the analysis examines the potential impacts of changes in climatic averages on the economic viability of a representative cash grain farm in South Western Ontario, and estimates the extent to which a range in precipitation levels might affect farm profits under the current and altered climatic regimes. The regional analysis estimates the potential influence of changes in climatic averages and precipitation levels on the production opportunities for major field crops in each of six regions in the province. The province-wide assessment appraises the possible effects of three levels of precipitation under present and modified thermal regimes on Ontario's potential for food production. The analysis measures the extent to which losses in production opportunities in one region might be offset by increases elsewhere, and thereby provides an aggregate assessment of the implications of climatic change on the provincial prospects for food production.

This analysis is based upon the integration of separate models of climatic change, crop productivity and production opportunities. The models are integrated in the sense that consistent assumptions are applied throughout the analysis, and one step provides data for subsequent steps. However dynamic linkages among farm, regional and provincial models which could estimate price and farm structure responses to alternative conditions are beyond the scope of this paper.

The analysis commences with an appraisal of the extent to which long-term averages for selected agroclimatic parameters might change given a doubling in atmospheric concentrations of CO_2 (or its equivalent), and then estimates a range of precipitation levels for the frost-free season given current and possible future climates. Subsequent steps assess the implications of these altered climates on food production opportunities, starting with an assessment at the farm level, then an examination at the regional level, and concluding with a province-wide appraisal.

2. Procedures and Data for Agroclimatic Analysis

2.1. *Long-Term Averages*

Estimates of current averages (1951–1980) for monthly temperature and precipitation are derived from Kirkwood *et al.* (1983). The climatic change scenario employed in this study stems from the CO_2 doubling experiments conducted by the Goddard Institute of Space Studies and provides estimates of changes to long-term averages for monthly temperatures and precipitation (Hansen *et al.*, 1983). These estimates of current and altered averages for monthly temperature are converted to daily values using the sine-curve interpolation procedure developed by Brooks (1943). For precipitation, a uniform distribution within each month is assumed. Potential evapotranspiration is estimated using procedures outlined in Selirio and Brown (1979). These data are then used to calculate for the current and altered climate:

- frost-free season start, and length (FSS, FSE, FSL, respectively),
- mean daily temperature during the frost-free season (FSS),
- accumulated corn heat units for the FSS,
- total precipitation for the FSS, and
- total potential evapotranspiration for the FSS.

Procedures employed to fit climatic data derived from Kirkwood *et al.* (1983) and Hansen *et al.* (1983) to the six regions identified for Ontario (Figure 1) and to estimate the additional climatic properties from monthly averages for temperature and precipitation are presented in Smit *et al.* (1989).

General circulation models are designed for broadscale applications, and do not presently generate outputs at a resolution matching climate station coverage within the study area. For this investigation, climate stations closest to the grid points in the general circulation model (Figure 1) were used as benchmarks from which known interregional differences in climatic parameters, related to local topography and so on, were transposed.

2.2. *Precipitation Variability*

Despite considerable consensus on temperature changes for the mid-latitudes, there is little agreement about the implications of an enriched CO_2 atmosphere for

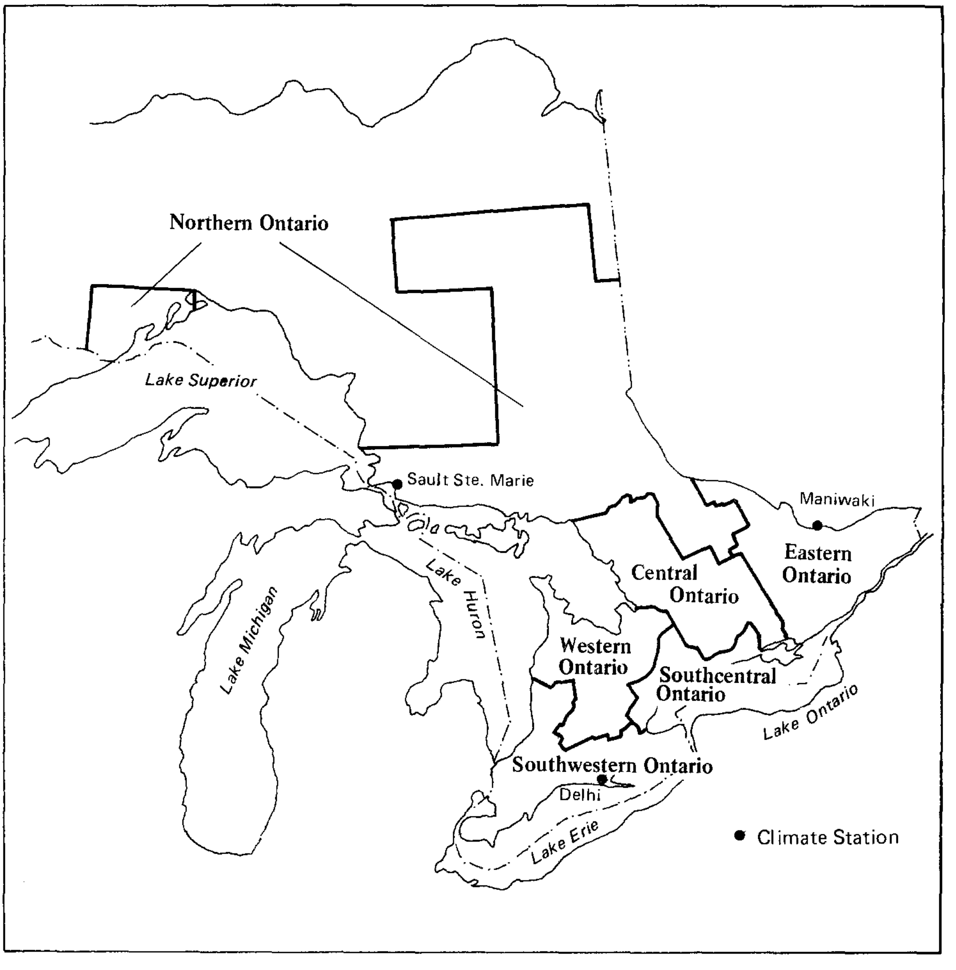

Fig. 1. Regions of Ontario.

precipitation (Hengeveld, 1989). Given this and the importance of moisture for crop growth, precipitation is a useful attribute to vary in scenarios for long-term climatic change.

A distribution of precipitation levels in the frost-free season for the current climate was derived for each region from monthly data for the period 1951 to 1980. High and low precipitation scenarios were selected as simple indicators of variability. The extreme 10 per cent of the observations (i.e. 5 per cent from each tail) were discarded to exclude extremely rare events. The precipitation values defining the limits of this truncated distribution, in effect the 95 and 5 precentile values respectively, represent the high and low precipitation levels used in subsequent analyses. In other words, under current conditions the high and low precipitation levels might each be expected approximately one year in twenty.

The effect of CO_2 doubling on year-to-year variation is unknown. In the absence

TABLE I: Specification of climatic scenarios

Precipitation	Thermal regime	
	Current	Future
Average	Scenario 1	Scenario 2
High	Scenario 3	Scenario 5
Low	Scenario 4	Scenario 6

of such information, it was assumed that the relative distribution of precipitation about the seasonal average would not change. Precipitation for the frost-free season under a changed climate was derived from the general circulation model output using the altered start and end dates for each region. The proportional deviations of high and low values from the current averages were then applied to these changed averages to generate high and low seasonal precipitation levels for the changed climate for each region.

Considering the thermal and precipitation levels together, six climatic scenarios are specified (Table I) for use in subsequent analyses.

3. Estimated Changes to Ontario's Agroclimatic Resources

3.1. *Changes in Long-Term Averages*

Climatic changes stemming from elevated concentrations of atmospheric carbon dioxide would have a considerable impact on agroclimatic resources throughout Ontario (Table II). The frost-free season in Northern Ontario would approach the current period for South Western Ontario. In the southern half of the province, the frost-free season would extend beyond 200 days and be comparable to the current season for southern Illinois.

It is anticipated that average per day levels of precipitation during the frost-free season would not change to any great extent under the altered climate, but the extended frost-free season would increase total seasonal precipitation. The altered climate would also be marked by considerable increases in potential evapotranspiration, and this increase would more than offset the estimated increases in rainfall. Overall, changes in climatic averages would contribute to longer, warmer and drier crop growing seasons in all regions of Ontario.

3.2. *Changes in Precipitation*

The combination of anticipated increases in precipitation and a longer growing season would result in substantial increases in average levels of total precipitation during the cropping season (Table II). The altered climatic regime would also be characterized by a considerable increase in the range of precipitation levels around

TABLE II: Effects of a CO_2 doubling on selected climatic averages

Property	Region in Ontario	Current average	Estimated change	
			Absolute	%
Frost-free season (days)	Northern	115.0	+48.0	+42.0
	Eastern	138.0	+49.0	+36.0
	Central	146.0	+60.0	+41.0
	South Central	152.0	+61.0	+40.0
	Western	154.0	+57.0	+37.0
	South Western	166.0	+57.0	+34.0
Mean temperature (°C)[a]	Northern	15.2	+1.9	NA[b]
	Eastern	16.4	+1.9	NA[b]
	Central	16.7	+1.6	NA[b]
	South Central	16.7	+1.5	NA[b]
	Western	16.4	+1.7	NA[b]
	South Western	16.8	+1.6	NA[b]
Precipitation (mm day^{-1})[a]	Northern	2.8	0.0	0.0
	Eastern	2.8	+0.7	+25.0
	Central	2.5	0.0	0.0
	South Central	2.5	0.0	0.0
	Western	2.5	+0.1	+4.0
	South Western	2.5	0.0	0.0
Potential evapotranspiration (mm day^{-1})[a]	Northern	3.1	+1.7	+55.0
	Eastern	3.1	+1.9	+61.0
	Central	3.2	+1.3	+41.0
	South Central	3.2	+1.2	+38.0
	Western	3.1	+1.6	+52.0
	South Western	3.2	+1.7	+53.0

[a] Mean temperature, precipitation and potential evapotranspiration are for the current and altered frost-free season.
[b] Not applicable.

the future averages (Table III). Future seasonal precipitation levels would be expected to be greater than current lows and highs, with the range between these extremes increasing also under the future thermal regime. The subsequent analyses explore implications of such possible changes in thermal conditions, precipitation during the frost-free season, and changes in the interannual precipitation range.

4. Procedures and Data for Farm, Regional and Provincial Assessments

4.1. *Farm Level Assessments*

The analyses at the farm level is undertaken for a typical cash grain enterprise in the Southwestern Ontario region, where this type of farming dominates primary production (OMAF, 1982). A reliable and widely used model for cash grain farms developed by Pfeiffer (1976) is employed to estimate the effects of climatic change

TABLE III: Frost-free season precipitation estimates

Region	Thermal regime	Precipitation (mm)			
		Low	Average	High	Range
Northern Ontario	Current	218	325	432	214
	Future	340	460	635	295
Eastern Ontario	Current	296	385	481	185
	Future	371	489	606	235
Central Ontario	Current	277	360	454	177
	Future	393	510	576	183
South Central Ontario	Current	268	378	457	189
	Future	354	528	639	285
Western Ontario	Current	277	390	476	199
	Future	354	529	640	286
South Western Ontario	Current	284	406	491	207
	Future	374	550	666	292

on maximum net returns at the farm level, and on the optimal allocation of land, labour and capital resources available to the farm enterprise.

Land resources available for crop production are limited to approximately 200 ha, of which 160 ha are owned by the operator while the remaining 40 ha could be rented. All of the land is assumed to be well-drained loamy soils and level. Production costs on this typical farm include fixed and variable costs such as land, hired labour, machinery operations, on and off-farm crop drying and so on. The major source of farm income is crop sales. All economic data are calibrated relative to conditions in the late 1970s and early 1980s, and model output is reported in 1981 Canadian (CAD) dollars.

The farm model employs linear programming procedures to estimate maximum returns and the optimal allocation of resources. It is run under two sets of conditions. The first approximates current climatic averages and economic conditions in South Western Ontario, whereas the second assumes altered climatic averages owing to a doubling in CO_2, *ceteris paribus* (Table I). The crop productivity model described in Smit *et al.* (1989) is employed to estimate the impacts of the specified adjustments in climatic averages upon yields for grain corn, soybeans and wheat. The model is employed as it is the only seasonal crop model which has been calibrated for conditions throughout Ontario and is applicable to all major crops currently produced in the province. The model begins by estimating a photosynthetic potential or constraint-free yield which is then adjusted for precipitation levels, edaphic conditions and socio-economic factors. The resulting yield estimates correlate well with those obtained by Ontario's better farmers, and are reduced by 25 per cent to approximate yields consistent with average management practices. All other conditions, such as production costs and crop prices, are maintained at levels consistent with conditions in 1981. Hence the analysis isolates the extent to which climatic change would induce a change in the profitability of this typical cash grain farm and its efficient allocation of resources (i.e., use of available land for crops, labour, etc.).

The farm level assessment also includes an examination of the implications of a range of precipitation levels for crop production and profitability for the cash grain farm. Given that decisions regarding crop selection are made well in advance of a particular growing season, it is assumed that decisions regarding farm operations are based upon economic conditions comparable to 1981, and current and altered climatic averages. Under each thermal regime, precipitation levels were allowed to deviate from the average to account for possible high and low levels of precipitation. The crop productivity model was then used to estimate the effects of these deviations in precipitation on yields for each grain crop, assuming the farmer had planted expecting average conditions. This provides a basis for gauging the impacts of alternative levels of precipitation in combination with climatic change on crop production, on farm income, and on profitability.

4.2. *Regional Assessments*

The regional assessments examine the influence of changes to climatic averages and variability on the long-term opportunities for crop production in each of the six regions of Ontario identified in Figure 1. The relevant data and models on crop productivity, on yield levels required to provide a positive return to investment, and on the availability of land for field crop production in each region of Ontario are presented in Smit *et al.* (1989). These are employed to trace the impacts of climatic change and alternative precipitation levels on production opportunities in each region for the principal grain, oilseed and forage crops (grain and fodder corn, wheat, oats, barley, soybeans and hay) currently grown in Ontario.

Initially, yield responses to changes in climatic averages are estimated. This involves adjusting the input parameters of the crop productivity model which are sensitive to an altered climate (i.e., constraint-free yield, growing season length, mean daily temperature, accumulated corn heat units, precipitation and potential evapotranspiration). The analysis also takes into account the effects on crop yields of variations in land qualities (Table IV) within each region. Soil moisture and aeration are estimated for each of the land types, and the crop productivity model considers the degree to which these edaphic conditions influence yield. Other factors influencing productivity, including location of the ground water table, crop moisture requirements, and levels of farm management and technology, are held constant at current levels.

The crop productivity model is also employed to estimate the impacts of alternative levels of precipitation on field crop yields. These analyses are conducted given the current and an altered thermal regime, and given identified extremes in precipitation levels (Section 2.1). Once again, other factors affecting productivity

TABLE IV: Land types

Land type	Biophysical characteristics
A	well-drained loamy soils relatively level topography
B	fine-textured clays moderately well to well-drained
C	coarser-textured sand and gravel, or shallow soils (less than 1 m to bedrock) well to excessively well-drained
D	imperfectly drained soils which have been tile drained
E	imperfectly drained soils which have not been tile drained, and all poorly to very poorly drained soils
F	extremely stony or shallow soils
G	well-drained loamy soils rolling to hilly topography

Note: Within a particular region Land Types A and G will have identical yields for individual crops. However topographic limitations associated with Land Type G reduces its overall capability for long-term row crop production.

are held constant. Estimates of each region's suitability under each climatic scenario are obtained by overlaying an inventory of the area of land available for crop production and the crop yield estimates.

4.3. *Provincial Assessments*

The provincial assessments examine the effects of the altered climatic regime and variability in precipitation on Ontario's potential for food production. A macro-scale food production potential model employing linear programming techniques and described in Smit *et al.* (1988a) is the principal analytical procedure used for this analysis. Food production potential is used here to represent the maximum levels of crop production which would be feasible for the province of Ontario, given the availability of resources for agriculture, crop productivity levels, crop production requirements and restrictions on land use. The analyses measure the aggregate implications of alternative climatic regimes on the provincial prospects for food production, indicating the extent to which losses in productivity in one region might be offset by higher yields elsewhere.

Ontario's potential for food production is estimated for the six scenarios presented in Table I. Each of the scenarios represents an alternative climatic regime, and the crop productivity model described in Smit *et al.* (1989) is employed to estimate yields for the seven principal grains, oilseeds and forages on each land type in each region of the province. For all six scenarios it is assumed that:

(1) land available for crop production is limited to current levels;

(2) minimum crop production levels are set equal to current provincial levels; and

(3) only land-use practices which will maintain or enhance soil quality are considered.

Overall, this step in the analysis isolates the impacts of climatic change and precipitation levels on Ontario's food production capacity, and other conditions which could influence agricultural potential (e.g. alternative market demands, adjustments in availability and price of production inputs) are beyond the scope of this investigation.

5. Effects of Climatic Change on Crop Production and Economic Opportunities at the Farm Level

5.1. *Farm Implications of Changes in Climatic Averages*

Given the specified economic conditions, resource limitations and current climatic averages for South Western Ontario, the maximum net profit feasible for this typical cash grain farm is estimated at \$22 000 yr^{-1} (Table V). This profit level would only be feasible given the full utilization of all available land resources, and by planting 134 ha to grain corn, 58 ha to soybeans and 10 ha to winter wheat. Total sales of crop products would generate almost \$122 000 of gross income.

Maximum profit levels and the optimal allocation of available resources would be expected to change considerably given the specified changes in long-term climatic normals for the region (Table V). The longer growing season would be expected to expand planting and harvesting windows for grain crops, and thereby allow for a more efficient use of available production inputs. Assuming the same 1981 economic conditions, maximum net returns could increase to \$27 000 per year, or by 24%. Attaining these profit levels would require a further reliance upon grain corn production. Once again, all available land resources would be required, with 187 ha devoted to grain corn and 15 ha to winter wheat. The reduced yields for soybeans means their inclusion in the production mix would reduce profits. Income from the sales of grain corn and winter wheat would approach \$130 000.

The 1980s has been characterized by a decline in economic prospects for many types of farming in Ontario, and that trend may well continue into the next century. While this analysis does not cover the full range of farming practices comprising the South Western Ontario agricultural economy, it is important to note that a climatic warming may improve economic efficiency for some types of farming and thereby help offset other factors contributing to diminishing economic opportunities. However, for this typical cash grain farm, improved economic efficiency under the altered climate scenario is heavily dependent upon an increasing reliance on corn monoculture, which in turn is vulnerable to market fluctuations, pest infestations and disease outbreaks. In addition, there is concern regarding the implications of corn monoculture on long-term environmental quality. The degree to

TABLE V: Effects of changes in climatic averages on crop production and economic opportunities at the farm level

	Land use (ha) given		Production (tonnes) given	
	Current averages	Future averages	Current averages	Future averages
Resource use and production				
Grain corn	134	187	892	1264
Soybeans	58	0	141	0
Winter wheat	10	15	35	45
Total	202	202	–	–
	Current averages	Future averages	Change	
	1981 CAD $		Absolute $	Relative %
Economic implications				
Income from crop sales	121702	129782	8080	6
Net profit	22024	27207	5183	24

which the economic benefits of a climatic warming may offset these potentially negative influences is certainly beyond the scope of this study, but assessments of these sorts of tradeoffs are required in order to gain a full understanding of the impacts of an altered climate on farming opportunities.

5.2. *Farm Implications of Changes in Precipitation*

The optimum allocation of resources under current average conditions would generate an annual profit of $22 000 for the typical cash grain farm on a well-drained soil in Southwest Ontario. In years with relatively high levels of precipitation, during the frost-free season, crop moisture stress would be relieved somewhat, and yields and production levels would increase. Income from crop sales would increase to about $144 000 (Figure 2). These sales would be sufficient to increase annual profits to about $45 000, or about double the profit level associated with current averages. Relatively dry years however would result in considerable declines in crop yields and total sales would be reduced to $65 000. Under these conditions, the typical cash grain farm on well-drained land would suffer a loss of about $34 000 for that year.

The analysis suggests that trends in profitability associated with variation in precipitation would be similar under the altered climate, but the effects of a relatively dry or wet year on farm profits would be more pronounced (Figure 2). Given the estimated changes in long-term climatic averages, crop sales and farm profits are calculated to be $130 000 and $27 000 respectively. Higher levels of seasonal

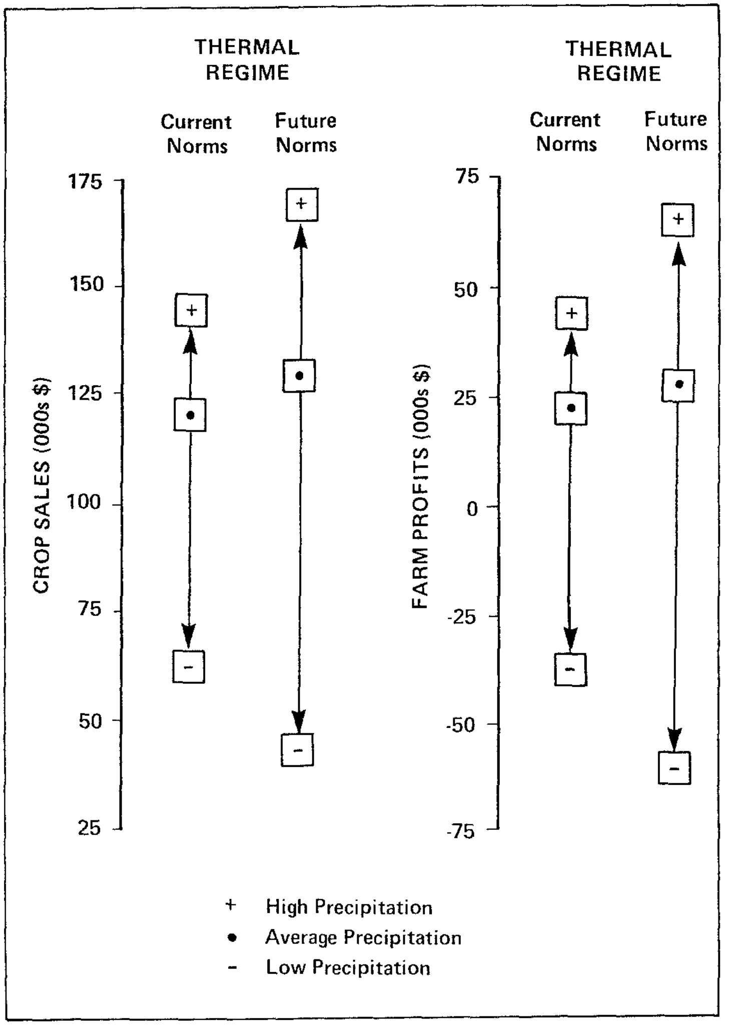

Fig. 2. Effects of climatic change and variability on economic opportunities at the farm level.

precipitation would reduce crop moisture stress and thereby increase yields and crop production levels. Total crop sales would generate an income of $168 000, realizing an annual profit of more than $65 000. In the dry years moisture stress would result in drastic reductions in crop yields and total income from crop sales would be reduced to $43 000. Farm losses would approach $60 000 for the year.

Overall, fluctuations in annual farm profits stemming from variations in seasonal precipitation would be expected to increase under the altered climatic regime. Assessments of the extent to which long-term financing might be affected by a climatic warming would require additional information on the frequency of precipitation extremes and on an annual variability in seasonal weather patterns. While this is beyond this particular study, the results do suggest the altered climate would contribute to a greater range in economic returns, with implications for farm level decision-making and risk.

6. Effects of Climatic Change on Regional Crop Production Opportunities

6.1. *Regional Implications of Changes in Climatic Averages*

The estimated changes in climatic averages would have a considerable impact on the regional opportunities for crop production (Table VI). Lands with relatively high moisture storage capacity (i.e. land types A, D and G from Table IV) predominate in South Western Ontario, and on these lands, the potential impacts of longer but drier frost-free seasons would be tempered. However, lands with low moisture reserves (i.e. land types B and C) account for a considerable portion of the region. On these lands, the longer drier frost-free seasons would be expected to contribute to increases in crop moisture deficits, and thereby effect a considerable decline in the prospects for grain and oilseed production. The region is currently a major contributor to the Ontario agricultural economy, and hence these losses could result in substantial economic and social adjustments in the region and throughout the province.

The Central, Western, Eastern and South Central Regions represent a transition zone given changes in long-term climatic norms. That is, with the exception of fodder corn in Western Ontario, and grain corn and wheat in Eastern Ontario, the estimated adjustments to climatic averages would be expected to have only a minor impact on regional opportunities for crop production in these regions.

For Northern Ontario, the changes in climatic averages considered in this analysis imply new opportunities for agriculture. The current climate for the region is characterized by a short, cool frost-free season (Table II), and agricultural opportunities are limited to a few short-season grain crops. The longer and warmer growing season associated with the altered climate would expand crop production prospects for Northern Ontario, and the regional resource base would have the potential to support a wide range of grains and oilseeds (Table VI). It is important to note that soil conditions in the region place severe restrictions on the availability of land for agriculture and hence these new opportunities in Northern Ontario may not offset anticipated losses in South Western Ontario.

6.2. *Regional Implications of Changes in Precipitation*

Overall, it would appear that estimated changes in precipitation levels would have significant implications on regional crop production prospects, relative to those associated with changes to climatic averages (Figure 3). For example, in South Western, South Central and Western Ontario current seasonal moisture supplies fall within the optimal range for many crops, and therefore relatively dry years have only a modest impact on production opportunities for soybeans and wheat. It is

TABLE VI: Effects of changes in climatic averages on regional opportunities for crop production

Regions from (land avail.)[a]	Crop	000s ha economically suitable for crop production given		% Change current
		Current averages	Altered averages	
Northern Ontario (343)	Fodder corn	0	211	NA[b]
	Grain corn	0	235	NA[b]
	Soybeans	0	199	NA[b]
	Wheat	0	141	NA[b]
	Barley	211	211	0
	Oats	211	211	0
Central Ontario (380)	Fodder corn	203	181	−11
	Grain corn	203	214	+5
	Soybeans	204	181	−11
	Wheat	170	170	0
	Barley	247	247	0
	Oats	247	247	0
Western Ontario (1185)	Fodder corn	0	825	NA[b]
	Grain corn	825	825	0
	Soybeans	888	825	−7
	Wheat	859	785	−9
	Barley	947	947	0
	Oats	987	947	−4
Eastern Ontario (920)	Fodder corn	179	224	+25
	Grain corn	179	478	+167
	Soybeans	305	305	0
	Wheat	433	179	−58
	Barley	433	433	0
	Oats	433	433	0
South Central Ontario (595)	Fodder corn	429	431	0
	Grain corn	431	431	0
	Soybeans	468	431	−8
	Wheat	438	429	−2
	Barley	510	510	0
	Oats	511	510	0
South Western Ontario (1761)	Fodder corn	929	338	−63
	Grain corn	1268	1268	0
	Soybeans	1433	1268	−12
	Wheat	1271	929	−27
	Barley	1250	1250	0
	Oats	1588	1250	−21

[a] 000s ha available for crop production.
[b] Not applicable.

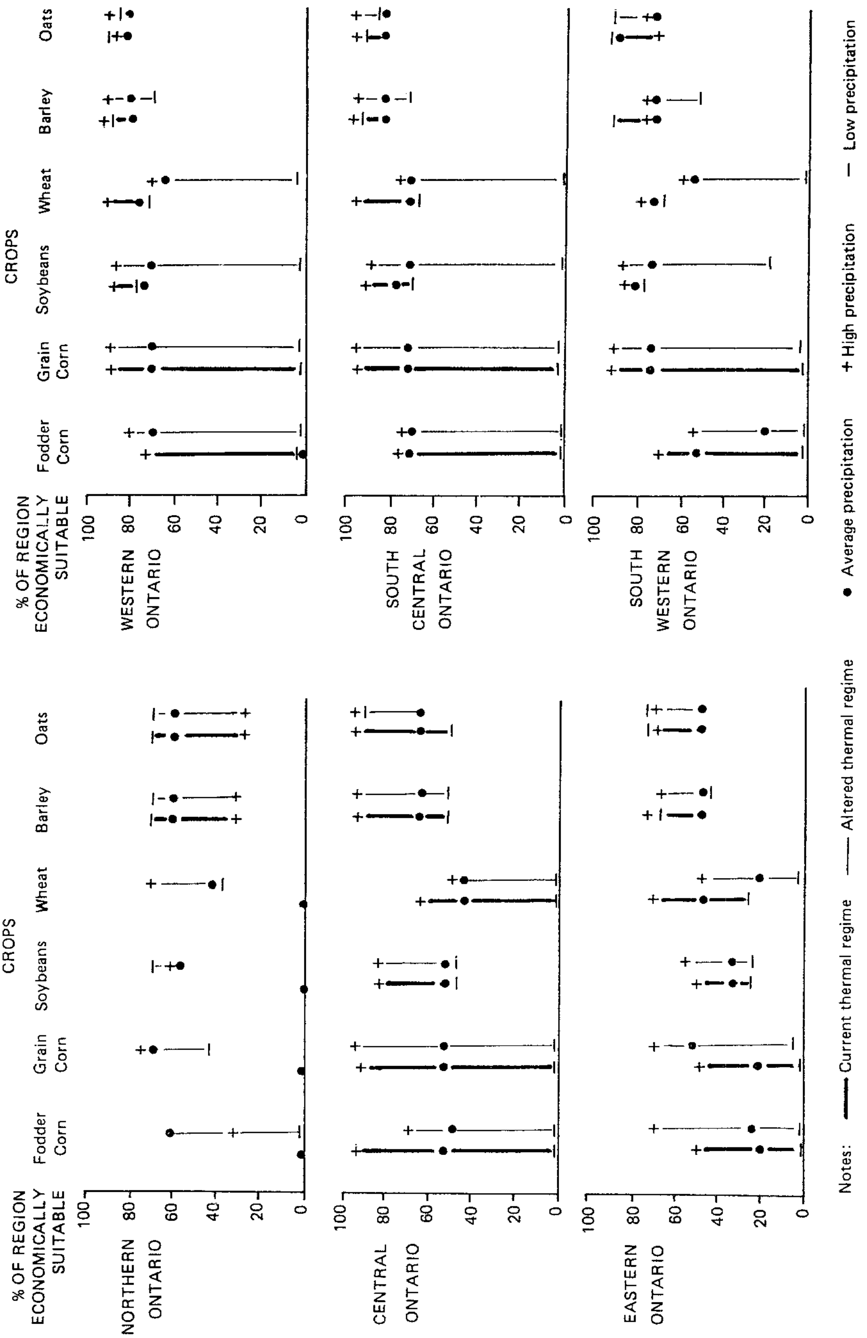

Fig. 3. Effects of climatic change and variability on regional crop production opportunities.

estimated that more than 70 per cent of these regions are economically capable of supporting these crops under these conditions. However, under the altered climate, moisture supplies would be tending towards the lower limit of the optimal range for many crops, and hence dry years would be characterized by relatively severe moisture deficits and crop failures over most of these three regions. Under these conditions, soybean potential would be reduced to 19 per cent of South Western Ontario, and would not be viable in Western and South Central Ontario. These three regions would not be capable of supporting wheat during the relatively dry years under the altered climate. For other crops in these regions, the implications of relatively wet and dry years on regional crop production opportunities would be similar under the altered and current climates.

In Northern Ontario, changes in precipitation levels would also imply considerable risks for crop production. Under the altered thermal regime and average precipitation levels, about 61 per cent of the region would be capable of supporting fodder corn, but these opportunities would be eliminated during relatively dry years. These moisture conditions would also impose considerable restrictions on production prospects for grain corn under the altered thermal regime. For barley and oats, two crops which are currently grown in Northern Ontario, the changes in precipitation levels under the altered climate would not imply a considerable change in regional production opportunities.

7. Effects of Climatic Change on Ontario's Food Production Potential

7.1. *Provincial Implications of Changes in Climatic Averages*

The effects of changes in climatic averages on Ontario's potential for food production are summarized in Table VII. Scenario 1 is the base scenario and representative of present environmental and socio-economic conditions in Ontario. Under these conditions it is estimated that Ontario's potential for food production surpasses current levels of production by about 66 per cent. This does not suggest that it would be advisable to increase production in the province, or that the production potential for individual crops is not greater than 166 per cent of current levels, but it does provide a measure of surplus production capacity in the provincial food production system as a whole. Under the conditions and from a physical production perspective, Ontario's land resources could support a substantial increase in food production.

Scenario 2 differs from Scenario 1 in that it is assumed that the equivalent of a doubling of atmospheric concentrations of CO_2 has resulted in a considerable change in climatic averages with concomitant changes in crop yields. The estimated adjustments to the average climate implies considerable increases in crop stress stemming from moisture deficits, and lower yields would be expected on lands with low tolerance to droughty conditions. Other conditions relating to land availability, base production levels, etc. are identical under the two scenarios. The changes in

TABLE VII: Ontario's potential for food production given changes in climatic averages

Crop	Current (1981) production	Production potential given	
		Current averages (SCEN 1)	Future averages (SCEN 2)
	000s t	000s t	000s t
Grain corn	4693	7804	7485
Barley	1059	1761	1689
Oats	664	1104	1059
Winter wheat	639	1063	1019
Soybeans	707	1176	1127
Hay	5165	8590	8238
Fodder corn	7022	11678	11200
Potatoes	369	614	589
Improved pasture	4729	7865	7543
Unimproved pasture	331	550	528
Production potential relative to current production (% change)		+66	+60

average climatic conditions imply a decline in Ontario's potential for food production, but the overall prospects for crop production would continue to exceed current levels of production (Table VII). Under Scenario 2, it is estimated that the productive capacity of Ontario's land resources would be approximately 60 per cent greater than present levels of provincial production, compared with +66 per cent under the base scenario.

7.2. *Provincial Implications of Changes in Precipitation*

Deficits or surpluses in the seasonal supply of water available for crop growth presently occur throughout much of Ontario and impose constraints on the opportunities for food production. Relative to current averages for temperature and precipitation (Scenario 1), it is estimated that Ontario's crop production potential exceeds current levels of production by 66 per cent. However, this potential is sensitive to existing fluctuations in seasonal levels for precipitation (Figure 4). Precipitation levels above current averages tend to relieve moisture deficits somewhat (Scenario 3) and thereby contribute to a modest increase in food production prospects throughout Ontario. Crop moisture stresses are aggravated considerably in years with low levels of precipitation during the growing season. Under these conditions, Ontario's potential for food production would be reduced by about one-third, and the productive capacity of the province's agricultural land resources would only just exceed current averages for crop production (Scenario 4).

The analysis suggests that the risks to the provincial potential for agricultural production which are imposed by variations in seasonal precipitation would be increased under the altered climatic regime. High precipitation levels under the

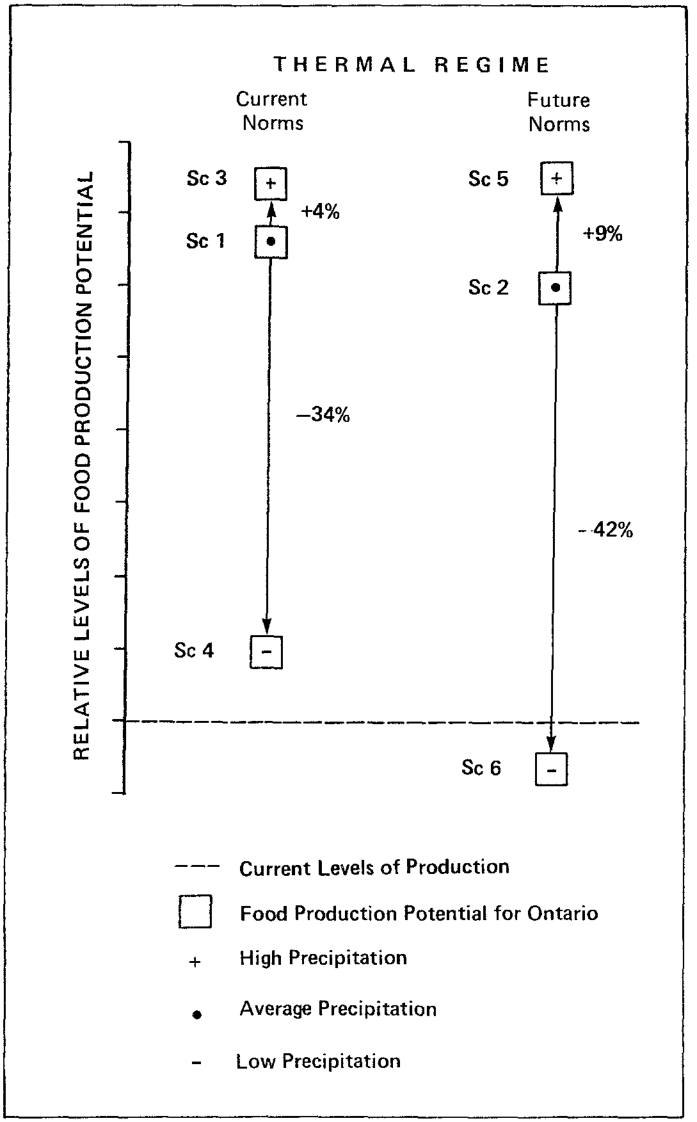

Fig. 4. Effects of climatic change and variability on Ontario's food production potential.

altered climate would reduce crop stress and thereby increase total provincial food production capacity (Scenario 5). Ontario's potential for food production under these conditions is estimated to be 9 per cent greater than under Scenario 2. Crop moisture stress would be accentuated in the dry years under the altered climate (Scenario 6), and the effects of dry years on provincial opportunities for food production would be considerably greater under these future conditions than under the existing climate for Ontario (Figure 4). Low precipitation levels combined with a climatic warming would reduce Ontario's overall potential for crop production below current levels of production, and thereby threaten the future security of the province's food supply.

This analysis has isolated the impacts of a possible climatic change on Ontario's food production potential. It is intended to improve understanding of the relationships among climate, climatic change and an important socio-economic activity. It does not aim to predict what is likely to occur. Other factors influencing the agricultural sector (e.g. accessibility to international markers, availability and costs of production inputs, rates of environmental degradation) will also change, and perhaps more rapidly and to a greater extent than global climate. Analysis similar to the research reported in this paper will need to be considered in this broader context before it is possible to draw firm conclusions regarding the overall implications of climatic change for an agricultural production system.

8. Conclusions

This paper has indicated that, in the context of agriculture in Ontario, changes in long-term climatic variability, or simply shifts in extremes because of changes in averages, may well have a greater impact on socio-economic activity than anticipated changes in the climatic averages themselves. At the farm level, a future climate characterized by longer warmer growing seasons and increases in seasonal precipitation suggests greater fluctuations in annual farm profits. The farm community in Ontario already experiences considerable economic stress given 'abnormally' wet or dry years, and its capacity to manage this potential increase in risk is questionable. An altered climate certainly implies new opportunities for crop production in Northern Ontario, but it is doubtful that this enhanced potential could offset possible declines in South Western Ontario. An altered thermal regime coupled with relatively low precipitation levels would imply a less favourable environment for agriculture in southern Ontario. In Northern Ontario, the benefits of a longer warmer growing season would be impaired during relatively dry years. It is anticipated that changes in climatic averages would have only a modest impact on Ontario's food production potential, but a changed thermal regime coupled with relatively low precipitation levels may well threaten the security of the province's food supply.

The scientific basis for examining policy initiatives in response to climatic change is still in the early stages of development. While extending impact research to consider a range of precipitation levels as well as changes in average climatic conditions and to alternative scales of analysis, this study also employs the standard approach of assuming a limited set of scenarios for climatic change and assessing their implications for a specific activity *ceteris paribus*. There is a need to consider sensitivities of agricultural systems to a wider array of possible futures, including scenarios of extreme events and different transient effects. Current understanding of the implications of climatic change along with or relative to other changes, whether atmospheric, social, economic or political, is limited. Similarly, there is a need for an improved understanding of the behavioural response to various climatic conditions and of the likelihood of particular climatic events occurring. Overall, this emphasizes the need for integrating frameworks incorporating physical, economic and behavioural relationships. This approach would enhance the understanding of climate-human activity interactions, and provide a basis for developing effective responses to climatic change.

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