

# SENSITIVITY OF CROP YIELDS AND LAND RESOURCE POTENTIAL TO CLIMATIC CHANGE IN ONTARIO, CANADA

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**Abstract.** Increasing concentrations of atmospheric CO<sub>2</sub> and other greenhouse gases are expected to contribute to a global warming. This paper examines the potential implications of a climatic change corresponding to a doubling of atmospheric concentrations of CO<sub>2</sub> on crop production opportunities throughout Ontario, a major food producing region in Canada. The climate is projected to become warmer and drier, but the extent of these shifts are expected to vary from region to region within Ontario. The effect of this altered climate on crop yields and the area of land capable of supporting specific crops varies according to region, soil quality and crop type. Most notable are the enhanced opportunities for grains and oilseeds in the northern regions, and the diminished production prospects for most crops in the most southerly parts of Ontario.

## 1. Introduction

Climatic impact assessment is concerned with the sensitivity of environmental and socio-economic systems to current climatic fluctuations and to long-term climatic change, and with providing a more informed basis for public decision making. Recently, the growing consensus that increasing concentrations of atmospheric CO<sub>2</sub> and other infrared absorbing gases are contributing to a global warming (Gates, 1985; Hare, 1985; Wilson and Mitchell, 1987) has stimulated considerable interest in the potential significance of such long-term climatic changes on a wide range of human activities (National Research Council [NRC], 1983).

Agri-food has been identified as an economic sector which could be especially

sensitive to long-term climatic change (Maunder and Ausubel, 1985; Postel, 1986; Schneider, 1977; Warrick and Riebsame, 1981). Earlier studies have examined the impacts of climatic change on agroclimatic properties (Williams, 1985), on crop productivity levels (Bootsma *et al.*, 1984; Liverman *et al.*, 1986; Pittock and Nix, 1986; Stewart, 1986), and on the location of the agricultural frontier (Parry, 1985; Rosenzweig, 1985). There has been some research into the sensitivity of food production opportunities to altered climates (Liverman, 1986; Schneider and Temkin, 1978), but the capability to estimate the adverse and beneficial effects of climatic change on the production prospects for particular regions is still quite limited (Waterstone, 1985).

The broad purpose of this paper is to isolate and assess the sensitivity of agricultural production prospects throughout the Province of Ontario, Canada to changes in average long-term climatic conditions. This study traces the possible effects of change in long-term climate induced by a doubling in the atmospheric concentration of CO<sub>2</sub> on the regional opportunities for food production. More specifically, it

(1) assesses for major food production regions in Ontario the sensitivity of yields for the major crops to climatic change, and

(2) estimates the subsequent regional implications for the agricultural potential of the province's land resources.

Changes in climatic variability, as well as adjustments to other biophysical or socio-economic conditions which may also alter food production prospects, are beyond the scope of this study.

The paper extends previous climatic impact research by developing explicit links amongst climatic change scenarios, crop yield responses to climatic change, and land resource inventories. This inclusion of a spatial dimension via resource inventories provides a consistent geographic context for climatic impact assessment, and thereby facilitates assessments of the differential regional impacts of climatic change. Furthermore, the possible impacts of climatic change on primary agricultural production throughout Ontario have not been examined previously. Ontario agriculture is a major contributor to the Canadian economy and hence, adjustments to Ontario's food production prospects, stemming from changes in climate and other conditions, could cascade throughout the national economy.

## **2. Research Framework, Procedures and Data**

The framework for assessing the impacts of climatic change on land resource potential for food production outlined in Figure 1 draws upon established procedures for rating land-use potential. Evaluating the potential use of land resources for specific activities is widely recognized as one of several prerequisites for effective rural resource assessment (Beek, 1981; Dudal, 1981; Smit *et al.*, 1984). These appraisals usually commence with an inventory of biophysical

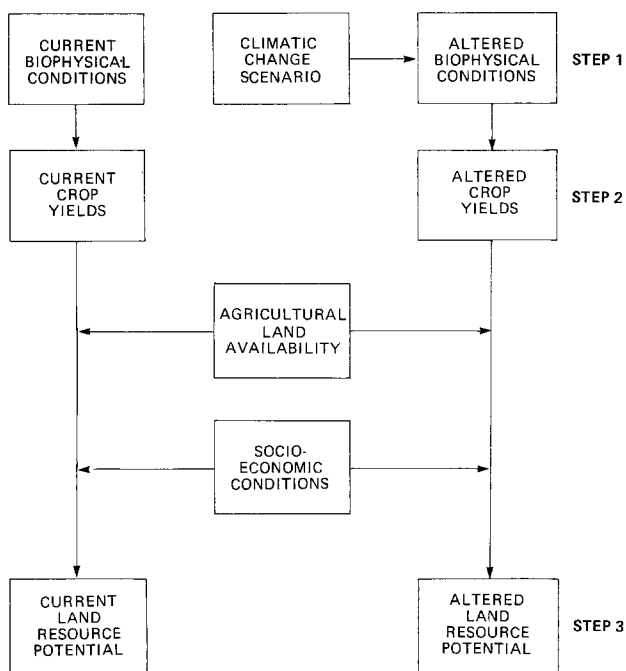


Fig. 1. Assessing the effects of an altered climate on crop yields and land resource potential.

conditions (e.g., climate, soil and water). Interpretative schemes are then employed to assist with rating the performance (e.g., capability, suitability and productivity) of land for particular uses or user groups (Dent and Young, 1981; McRae and Burnham, 1981). More recently, performance ratings have been expanded to include socio-economic as well as biophysical conditions, and to appraise the sensitivity of performance ratings to alternative or changing conditions.

The framework outlined in Figure 1 is tailored to address the issue of climatic change and its implications for agri-food, but it could be expanded to consider adjustments to a wider range of socio-economic and biophysical conditions. Output from each step is used as input to subsequent steps, and hence, the framework provides a basis for consolidating independent assessments of climatic change, yield response to climatic change, and land potential for food production. The remainder of this section presents a short discussion of each step, and summarizes the procedures and data employed in the Ontario study.

### 2.1. Step 1: Specify Climatic Change

The initial step specifies the direction and magnitude of change in those climatic parameters which influence crop productivities. The specific parameters are ultimately determined by the procedures used to estimate yield response to an altered climate (Step 2), but usually include spatial variability in growing season

length, temperature, and precipitation, and the interannual variability in these agroclimatic parameters.

Generally speaking, there are three approaches for specifying climatic change. Historical analogues have provided insight into various aspects of the relationships between man and climate, including responses to extreme events and adaptation to climatic change (Parry and Carter, 1984). General circulation models (GCMs) which simulate global atmospheric conditions represent another approach for forecasting future climates (Wilson and Mitchell, 1987). Alternatively, synthetic scenarios specifying incremental adjustments to selected climatic parameters can be used as the starting point for climatic impact assessments (Bootsma *et al.*, 1984; Williams *et al.*, 1975).

This study employs the GCM approach for estimating climatic change as it is well-suited to establishing direct links between increasing levels of CO<sub>2</sub> concentrations and climatic characteristics. The climatic change scenario employed in this study is derived from a CO<sub>2</sub> doubling model trial which utilized a GCM developed and implemented by the Goddard Institute of Space Studies (GISS) (Hansen *et al.*, 1983).

The GISS model is employed to derive adjustments to long-term climatic norms. Output from the model is readily available, and provides an estimate of the effects of a 2 × CO<sub>2</sub> environment on climate, and should not be considered an accurate forecast of future climate. The study is not intended to support or validate current GCMs, but is intended to provide insight into the potential implications of a climatic change on agricultural production prospects throughout Ontario. Furthermore, this approach also demonstrates the opportunities and limitations of using GCM output in the context of climatic impact assessments. It would of course be feasible to employ output from other GCMs and thereby appraise the potential consequences of alternative estimates for long-term climatic change for agriculture (e.g., see Cohen, 1986; Land Evaluation Group, 1985).

The application to climatic impact assessments of output derived from GCMs requires that the macro-climatic properties analyzed by the atmospheric models be transformed and interpreted in a manner consistent with the objectives of the specific study (Cohen, 1986; Gates, 1985). This first step of the Ontario case study is concerned with the broadscale implications of elevated CO<sub>2</sub> concentrations on the long-term agroclimatic parameters listed in Table I. The effects of elevated CO<sub>2</sub> levels on these agroclimatic parameters are estimated for the regions of Ontario identifying major zones of agricultural production (Figure 2).

Agroclimatic data are not directly available for the regions used in the Ontario study. However, it is feasible to infer the required information from existing data sources.

Data on current climatic conditions compiled for the map units delineated on the Soils of Canada map (scale of 1:5 M) (Clayton *et al.*, 1977) were obtained from a computerized data base developed by Agriculture Canada (Kirkwood *et*

TABLE I: Selected agroclimatic parameters

Parameter	Description
Mintemp	Mean daily minimum air temperature (°C)
Maxtemp	Mean daily maximum air temperature (°C)
Meantemp	Mean growing season air temperature – computed by summing the daily values from the GSS to the GSE and dividing by the GSL
GSS*	Growing season start – date on which Mintemp rises above 5 °C
GSE*	Growing season end – date on which Mintemp falls below 5 °C
GSL*	Growing season length – number of days between GSS and GSE
DD	Growing degree days – accumulation of Meantemp values > 5 °C during the GSL
Precip	Total precipitation for the GSL (mm)
PE	Total potential evapotranspiration for the GSL (mm)

\* GSL is based on the frost-free period (days) during the year when the mean minimum temperature is equal to or greater than 5 °C. Use of the 5 °C isotherm for GSS and GSE of the growing period represents, with a 50% probability, the average date of the last spring and first autumn frosts (0 °C), as calculated from the comparison of 30-year climatic normals data with actual yearly data (Sly and Coligado, 1974).

*al.*, 1983). In total, some 93 map units are located either completely or partially within the Province of Ontario. For those map units which traverse the provincial boundary, only the portions of map units within Ontario are included in the case study. Climatic data compiled for the Soils of Canada map units are then aggregated for each region identified in Figure 2. Each of the regions are defined according to existing administrative boundaries and thereby facilitate an eventual link between biophysical data and broadscale socio-economic conditions.

Climatic change is simulated for a doubled CO<sub>2</sub> climate using monthly mean air temperature and precipitation data derived from the GISS model. While GCMs provide estimates of potential changes to long-term norms, they are not appropriate for estimating adjustments to interannual variability or the distribution of climatic properties throughout the growing season. In the absence of information for other climatic parameters, they are held constant at 1951–1980 normals.

The climatic change data were obtained from the Canada Climate Centre of the Atmospheric Environment Service (AES) in the form of point data presented for grid cells measuring approximately 4° latitude by 5° longitude (Hengeveld and Street, 1985). In total twelve data points cover the study area (Figure 2). For this case study, it is assumed that any changes in mean air temperatures result in corresponding changes in maximum and minimum air temperatures.

Next, a link between the point data for climatic change and the map units upon which current climatic conditions are compiled is developed. Rates of change amongst data points employed by the climatic change scenario are not known and hence are inferred using the following guidelines. A change in mean monthly temperature and precipitation is specified for each map unit by con-

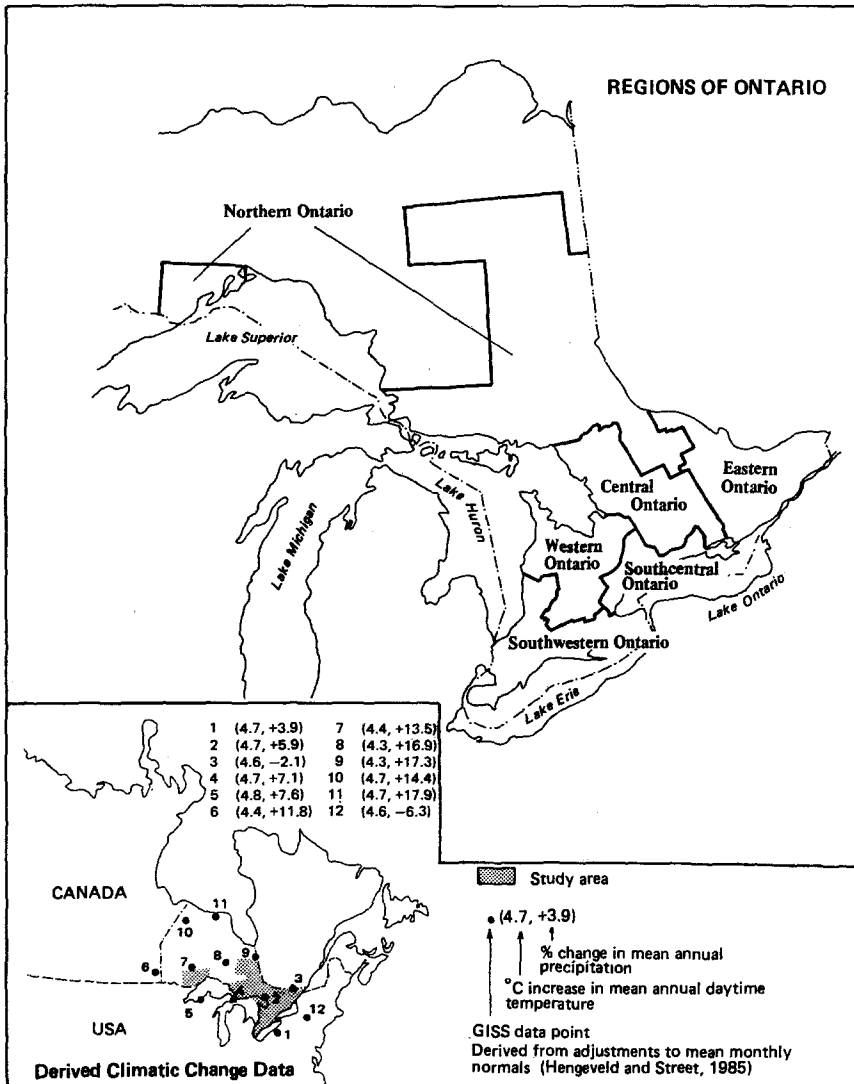


Fig. 2. Regions and GISS reference points used in the Ontario study.

sidering the location of a map unit relative to the nearest grid points. The process is simplified by aggregating the map units into larger contiguous groupings, and by assigning a uniform climatic change to all map units in the group. These map unit groupings are then fit to the regions illustrated in Figure 2, and annual regional values for the macro-climatic properties listed in Table I are estimated.

The estimated changes in mean monthly temperature and precipitation are used to adjust the current climatic records to calculate an altered temperature and precipitation value for each map unit. Procedures employed to infer other

climatic parameters (Table I) from temperature data are identical to those used given current climatic conditions. These adjustments to climate, which are compiled on the basis of map units on the Soils of Canada map, are then aggregated to the regional level (Figure 2) by weighting the data for each map unit by the percentage of the area of the region occupied by each unit, and summing all units for the region.

## 2.2. Step 2: Evaluate Crop Yield Sensitivities

The second step estimates crop yields relative to specified sets of conditions. Crop productivity models are employed to estimate yields for the principal grain, oilseed and forage crops (grain corn and barley, soybeans, and hay forage, respectively) throughout Ontario, given the current and altered climate. The models consider the extent to which agroclimatic and edaphic conditions combine to influence crop yields. Then, the analyses consider crop production costs and prices, and identify yield levels which would be sufficient to generate a profit. Concise accounts of the photosynthetic, agroclimatic-edaphic and socio-economic components of the crop models follow.

The photosynthetic component estimates constraint-free crop yield which indicates the harvestable dry matter for a high producing variety, produced under conditions where water, nutrients, weeds, pests and diseases do not limit crop growth. The procedures employed by Stewart *et al.* (1984), which extend deWit's (1965) approach to crop productivity modelling, are used in the Ontario case study. For all crops, it is assumed that planting occurs at growing season start (GSS), and crop growth terminates on growing season end (GSE) unless the designated crop growing period is reached first. Growing periods of 180 days, 130 days and 100 days are employed for grain corn, soybeans and barley respectively. Constraint-free yields, given current and altered climates, are calculated for each map unit identified on the Soils of Canada map (Clayton *et al.*, 1977) as:

$$YP_i = BN_i \times H_i \quad (1)$$

$$BN_i = 0.36 BGM_i / (1/GSL + 0.25 CT_i), \quad (2)$$

where

$YP_i$  = potential or constraint-free dry matter yield ( $\text{kg ha}^{-1}$ ) for crop  $i$

$BN_i$  = potential net biomass production ( $\text{kg ha}^{-1}$ ) of crop  $i$

$H_i$  = harvest index for crop  $i$  which represents the useable portion of  $BN_i$

$BGM_i$  = gross biomass production of crop  $i$  determined by its photosynthetic response to temperature and radiation

$GSL$  = growing season length (days)

$CT_i$  = maintenance respiration coefficient for crop  $i$ .

TABLE II: Data inputs for estimating effects of climatic change on crop yields

Parameter	Equation	Comments and data sources
Harvest Index	1	Standard values for H reported in FAO (1978) are adapted to Canadian conditions. Constant values used under each climatic scenario.
Gross Biomass Production	2	Estimated using procedure outlined by Stewart (1981) and FAO (1978) for current and altered climate.
Growing Season Length	2	Estimated for current and altered climates using procedures outlined in Table I.
Respiration Coefficient	2	Estimated for current and altered climates using procedures outlined in Stewart (1981).
Workability Parameter	3	WP estimates likelihood for a successful harvest. For the current climate, WP values for map units identified on Soils of Canada map (Kirkwood <i>et al.</i> , 1983) are aggregated to regional level using procedures outlined in Section 2.1. Under the altered climate, drier conditions during a longer harvest period would enhance prospects for a successful harvest, and hence, WP values are adjusted.
Dry Matter to Dry Weight Conversion Coefficients	3	Constraint-free dry matter yields are converted to dry weight, the standard units employed by crop production statistics. Representative values of 15% moisture for grains and oil-seeds, and 21% for hay forage are used under both climatic scenarios.
Soil Aeration	3	Excess soil moisture which characterizes land types D and E (Table III) contributes to poor soil aeration which reduces yields. Procedures for estimating yield reduction coefficients are summarized in McBride (1983a), and employed under both climatic scenarios. Poor soil aeration is not a limitation to crop growth on other land types (i.e., coefficient = 1.0).
Seasonal Yield Response to Deficit Water Stress	4	Estimates reported by Dumanski and Stewart (1981) applied to current and future climates.
Normalizing Coefficients for Moisture Stress	4	Estimates reported by McBride (1983b) applied to current and future climates.
Plant-Available Water	5	Current levels of precipitation during the winter season are usually sufficient to fully recharge soil moisture prior to the onset of the growing season in Ontario. Winter precipitation levels under the climatic change scenario tend to be greater than current levels and therefore no adjustment to plant-available water is required.
Precipitation	5	Total precipitation for the growing season under the current and altered climates is estimated by converting monthly precipitation values to daily values, and summing the daily values between GSS and GSE. When the GSL exceeds the maximum growing season for the crop, precipitation available for crop growth is estimated by summing daily values from GSS to the

		end of the maximum growing period. Otherwise, the estimate of precipitation for the growing season is used to approximate precipitation available for crop growth.
Potential Evapotranspiration	5	PE is estimated for the crop growing period under the current and altered climates using the Priestly and Taylor (1972) approach modified by Selirio and Brown (1979).

Table II summarizes the data sources used in the Ontario case study. Yields are estimated for individual map units. These estimates, along with data on the area of each polygon in each region, are employed for estimating a regional constraint-free yield ( $YP_{ir}$ ) for each region illustrated in Figure 2.

For hay forage, constraint-free yield response to climatic change is estimated using a crop productivity model developed for the Crop Insurance Commission of Ontario (McBride and Brown, 1984). The model employs similar principles to the model used to estimate constraint-free yields for grain corn, soybeans and barley. However, the growing season start is adjusted to reflect the onset of the growing period for perennial crops, and the total number of cuts increases with growing season length.

The agroclimatic-edaphic component estimates the extent to which factors such as moisture stress and poor soil aeration combine to reduce constraint-free yields to levels that would be expected under optimal management conditions. Implementation of this component requires the disaggregation of each region into the seven land types described in Table III. This partitioning reflects

TABLE III: 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.

the variability in soil qualities which affect agricultural productivity throughout each region. Attainable yields are estimated as:

$$YA_{ijr} = YP_{ir} \times MSF_{ijr} \times WP_{ir} \times D_i \times Z_j \quad (3)$$

$$MSF_{ijr} = 1 - [KY_i \times (SMDS_{ijr} + A_i)/B_i] \quad (4)$$

$$SMDS_{ijr} = AW_{jr} + PREC_{ir} - PE_{ir}, \quad (5)$$

where

$YA_{ijr}$  = attainable dry weight yield (kg ha<sup>-1</sup>) for crop *i* on land type *j* in region *r*

$YP_{ir}$  = constraint-free dry matter yield (kg ha<sup>-1</sup>) for crop *i* in region *r*

$MSF_{ijr}$  = moisture stress factor for crop *i* on land type *j* in region *r*

$WP_{ir}$  = workability parameter for crop *i* in region *r*

$D_i$  = dry matter to dry weight conversion coefficient for crop *i*

$Z_j$  = deflation coefficient for poor soil aeration on land type *j*

$KY_i$  = seasonal yield response coefficient for crop *i* to water stress

$SMDS_{ijr}$  = soil moisture deficit or surplus (cm) for crop *i* on land type *j* in region *r*

$A_i$  and  $B_i$  = coefficients to normalize for excess or deficit moisture stress conditions for crop *i*

$AW_{jr}$  = plant-available water (cm) at the onset of the growing season for land type *j* in region *r*

$PREC_{ir}$  = total precipitation (cm) during crop *i*'s growing period in region *r*

$PE_{ir}$  = potential evapotranspiration (cm) during crop *i*'s growing period in region *r*.

Attainable yields are estimated for each land type in each region given current and altered climates. Table II summarizes the input data used in the Ontario case study. McBride and Mackintosh (1984) have noted that productivity estimates from these types of models are consistent with yields obtained by Ontario's better farmers. Average yields for the province tend to track at approximately 75% of these estimates (OMAF, 1983). For all subsequent steps in the analyses, yields estimated by Equation (3) are reduced by 25% to reflect provincial averages.

In this study, the socio-economic implications of climatic change on agriculture are determined using yield thresholds which identify crop productivity levels sufficient to provide a positive return to investment. Haslett (1983) has

compared current costs of crop production (1981 CDN dollars ha<sup>-1</sup>) to current prices for most field crops (1981 CDN dollars tonne<sup>-1</sup>) produced in the province. These analyses provide a basis for screening out yields which would be insufficient to generate a profit over the long term, and to identify yield levels which would provide a modest or high return to investment (Table IV). The focus of this study is to isolate the effects of climatic change on Ontario's opportunities for agriculture and hence economic conditions deviating from the current are not considered. However, the framework employed in this paper is sufficiently flexible to consider the cumulative effects of specified adjustments to parameters in the economic and biophysical environment.

TABLE IV: Crop yield levels required to obtain alternative rates of return

	Threshold Yield Levels (kg ha <sup>-1</sup> ) given current economic conditions		
	High return	Modest return	Not profitable
Grain corn	>6230	5190–6229	<5190
Soybeans	>2060	1130–2059	<1130
Barley	>3220	2900–2219	<2900

Derived from Haslett (1983).

### 2.3. Step 3: Effects on Land Resource Potential for Crop Production

The third step assesses the implications of a climatic change on the land resource potential for crop production. It extends the analyses conducted under Step 2 in that it considers not only the effects of climate change on crop yields, but also the area of land affected.

For the Ontario study land resource potential is estimated by overlaying an inventory of the land area available for crop production and crop yield estimates for their current and altered climates. This process provides a basis for identifying the area and the production activities in each region which might benefit or suffer from the specified climatic changes.

Land available for agriculture includes all land which is presently used for crop production, as well as other lands which are cleared but not committed to irreversible uses. Lands on which the current use effectively removes the land from agricultural production are excluded.

Land availability is estimated for each land type (Table III) in each region (Figure 2). These estimates are calculated by matching geocoded information obtained from Environment Canada's Geographic Information System on land use, land area, and capability for agriculture with information on administrative boundaries (Statistics Canada, 1977 and 1979). The total estimate of land currently cleared and available for agriculture in Ontario is 5 183 000 ha.

In this paper, land resource potential refers to the area of land capable of

supporting the production of particular crops or crop groups. Once data on crop yields and land availability are compiled for spatially consistent units (i.e., the land types and regions identified in Table III and Figure 2 respectively), land resource potential is estimated readily by overlaying these two data sets. Initially, the current potential for individual crops is estimated given current crop yields, current economic conditions, and the current availability of land. Then, crop yields are adjusted to reflect the climatic change, and the sensitivity of each region's land resource potential is estimated, *ceteris paribus*. A comparison of land resource potentials given the current and an altered climate provides a basis for identifying the regional sensitivity of the biophysical and economic opportunities for crop production to climatic change.

### 3. Sensitivity of Agroclimatic Properties to Climatic Change

#### 3.1. *Frost-Free Growing Season*

Estimated increases in frost-free season length range from 48 days to 61 days (Table V). The available growing period in Northern Ontario under the altered climatic regime would approach the current period in Southwestern Ontario. In the Central, Southcentral, Western and Southwestern Ontario regions the growing season would exceed 200 days, and be comparable to the present season in southern Illinois.

#### 3.2. *Temperature*

A doubling in atmospheric concentrations of CO<sub>2</sub> implies a considerable increase in mean temperatures during the growing season throughout Ontario (Table V). Temperatures in Northern Ontario would be in the order of 17 °C, or higher than the current norm in Southwestern Ontario. In other regions, the mean temperature would exceed 18 °C. It is estimated that the altered climatic regime would tend to reduce the temperature gradient from south to north from the present 1.6 °C to 1.3 °C.

#### 3.3. *Precipitation*

Average per day levels of precipitation during the growing season would not be expected to change considerably with increases in CO<sub>2</sub> levels (Table V). However the extension of the frost-free season implies increases in total precipitation for the growing period. Precipitation increases for the entire frost-free period would range from 80 mm to about 90 mm.

TABLE V: Estimated impacts of a CO<sub>2</sub> doubling on selected agroclimatic properties

Property	Region in Ontario	Current norm	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
	Southcentral	152.0	+61.0	+40.0
	Western	154.0	+57.0	+37.0
	Southwestern	166.0	+57.0	+34.0
Mean Temperature (°C)*	Northern	15.2	+ 1.9	NA**
	Eastern	16.4	+ 1.9	NA**
	Central	16.7	+ 1.6	NA**
	Southcentral	16.7	+ 1.5	NA**
	Western	16.4	+ 1.7	NA**
	Southwestern	16.8	+ 1.6	NA**
Precipitation (mm day <sup>-1</sup> )*	Northern	2.8	0.0	0.0
	Eastern	2.8	+ 0.7	+25.0
	Central	2.5	0.0	0.0
	Southcentral	2.5	0.0	0.0
	Western	2.5	+ 0.1	+ 4.0
	Southwestern	2.5	0.0	0.0
Potential Evapotranspiration (mm day <sup>-1</sup> )*	Northern	3.1	+ 1.7	+55.0
	Eastern	3.1	+ 1.9	+61.0
	Central	3.2	+ 1.3	+41.0
	Southcentral	3.2	+ 1.2	+38.0
	Western	3.1	+ 1.6	+52.0
	Southwestern	3.2	+ 1.7	+53.0

\* Mean temperature, precipitation and potential evapotranspiration are for the current and altered frost-free season.

\*\* Not applicable.

### 3.4. Potential Evapotranspiration

An altered climate characterized by longer growing periods and higher temperatures would also imply marked increases in potential evapotranspiration (Table V). When accumulated over the frost-free season, these increases would range from approximately 230 mm to 280 mm, with the lowest increases in Northern and Eastern Ontario. Overall, these increases in potential evapotranspiration would more than offset the estimated increases in rainfall, and hence, the altered climate would be characterized by a longer, warmer and drier growing season.

## 4. Sensitivity of Crop Yields to Climatic Change

### 4.1. Grain Corn

The climatic change scenario would have considerable impacts on grain corn

yields throughout Ontario (Table VI). The most profound effects are anticipated in Northern Ontario where it is not presently feasible to produce the crop. Under the climatic change scenario, yields would increase to such an extent that it would be feasible to obtain a high return to investment on well-drained loamy soils (land types A and G), and on lands that have a low drought tolerance (land types B and C). On lands where artificial land drainage has lessened the limitations imposed by excessive moisture conditions (land type D) yields would be sufficient to obtain a modest return.

TABLE VI: Effects of climatic change on crop yields (t. ha<sup>-1</sup>)

Region in Ontario	Land Type	-- Grain Corn --		---- Barley ----		--- Soybeans ---		----- Hay -----	
		Current	Altered	Current	Altered	Current	Altered	Current	Altered
Northern	A,G	0.0	9.1**	3.5**	4.1**	0.0	2.4**	9.9	9.9
	B	0.0	6.8**	4.0**	4.3**	0.0	1.7*	6.7	6.7
	C	0.0	7.0**	4.0**	4.3**	0.0	0.0	6.8	6.8
	D	0.0	5.7*	1.5	1.9	0.0	1.6*	8.8	9.0
	E	0.0	2.7	0.6	0.8	0.0	0.8	5.9	6.1
Eastern	A,G	5.4*	8.8**	4.7**	4.1**	1.9*	1.8*	9.9	10.7
	B	3.5	5.2	4.9**	3.8**	1.4*	1.1	6.8	7.4
	C	3.8	5.7*	4.9**	3.9**	0.0	0.0	7.3	8.0
	D	3.7	7.3**	2.1	2.1	1.2*	1.6*	9.2	10.2
	E	1.8	4.1	0.9	1.0	0.6	0.9	6.2	6.9
Central	A,G	6.6**	8.1**	3.8**	4.0**	2.1**	1.8*	9.1	8.6
	B	4.6	4.6	3.6**	3.5**	1.3*	1.0	5.9	5.5
	C	5.0	5.2*	3.7**	3.7**	0.0	0.0	6.4	6.0
	D	4.3	7.2**	1.9	2.2	1.5*	1.5*	8.4	8.0
	E	2.0	4.2	0.9	1.1	0.8	0.9	5.8	5.5
South- central	A,G	6.9**	6.7**	4.9**	4.0**	1.9*	1.7*	10.8	12.1
	B	4.0	3.2	4.5**	3.6**	1.2*	1.0	7.4	8.4
	C	4.1	3.4	4.6**	3.7**	0.0	0.0	7.6	8.6
	D	5.9*	6.9**	2.5	2.1	1.5*	1.5*	9.3	10.4
	E	3.4	4.3	1.1	0.9	0.8	0.9	6.3	7.1
Western	A,G	6.9**	7.1**	4.9**	4.0**	2.3**	1.7*	9.8	9.5
	B	4.1	3.6	4.6**	3.6**	1.5*	1.0	6.3	6.0
	C	4.4	3.9	4.7**	3.8**	0.0	0.0	6.6	6.3
	D	5.4*	6.8**	2.4	2.0	1.8*	1.6*	8.9	8.5
	E	2.8	4.2	1.1	1.0	0.9	0.9	6.1	5.8
South- western	A,G	7.3**	6.1*	4.9**	3.9**	2.2**	1.7*	11.2	9.5
	B	4.2	2.8	4.5**	3.7**	1.3*	0.9	7.6	9.5
	C	4.2	2.8	4.5**	3.7**	0.0	0.0	7.7	9.5
	D	6.4**	6.8**	2.6	2.0	1.8*	1.5*	9.5	9.5
	E	3.7	4.3	1.2	0.9	1.0	0.9	6.5	9.5

Note: For grains and oilseeds, the \* and \*\* identify yields sufficient to generate a modest and high economic return respectively, whereas no asterisk indicates lands which are unprofitable. For hay forage, suitable economic information on crop production costs and prices are unavailable, and hence, the analysis is confined to assessment of yield sensitivity to be altered climate.

In the Eastern and Central Ontario regions, where grain corn is presently an unprofitable crop on most land types, the altered climate would imply considerable improvements in the economic opportunities for grain corn production. Yield increases on land types C and D would be sufficient to make these lands economically suitable for grain corn, and profit margins would be expected to increase on well-drained lands in Eastern Ontario.

In Southcentral and Western Ontario, profit margins would be expected to increase on lands with relatively large moisture reserves (land type D). On other lands in these regions, yield responses to the altered climate would not imply a change in the economic outlook for grain corn.

The economic potential for grain corn production in Southwestern Ontario would suffer under the specified changes in climate. Drier soil conditions would result from the imbalance between evapotranspiration and precipitation, and would contribute to yield declines on well to excessively well-drained lands (land types A, B, C and G), and losses in profitability on land types A and G. Moisture reserves on land types D and E would be sufficient to offset the negative effects of increases in moisture deficits, but these yield increases would not enhance the economic prospects for corn on these lands.

#### 4.2. *Barley*

In Northern Ontario, the altered climatic conditions would result in a more favourable moisture regime for barley production and increases in the likelihood of a successful harvest. Considerable increases in barley yields could be expected throughout the region, but lands suffering from excessive moisture would continue to be economically unsuitable for the small grains (Table VI).

The impacts of increases in temperatures and moisture stress that would stem from an increased CO<sub>2</sub> environment become apparent in Eastern and Central Ontario. Barley yields would be reduced on lands with a low tolerance to droughtiness (land types B and C), but these losses would not be large enough to reduce the economic prospects for the crop in these regions. Yields would increase on lands which have sufficient moisture reserves to offset the effects of higher temperatures and increases in evapotranspiration (land types D and E), but these increases would not be sufficient to create new economic opportunities for barley.

In the Southcentral, Western and Southwestern Ontario regions, crop moisture stress stemming from elevated CO<sub>2</sub> levels would be very pronounced and yield reductions for barley would be in the order of 20% across these regions. Relative to existing conditions however these declines would not contribute to a loss in economic opportunities for barley production in these three regions.

### 4.3. *Soybeans*

A CO<sub>2</sub>-induced climatic change would have a marked effect on the production opportunities for soybeans throughout the province (Table VI). The longer growing season and warmer temperatures would create new opportunities for the crop in Northern Ontario. Land which is well-drained would be especially well-suited for soybeans, and a modest return to investment could be expected on those lands where moisture imposes moderate limitations on crop production.

In other regions, the moisture stress associated with warmer summers in an increased CO<sub>2</sub> atmosphere would tend to impinge upon the opportunities for soybean production. These losses would be greatest on lands with low tolerance to droughty conditions (land type B), and result in considerable declines in the biophysical and economic potential for soybean production in all regions south of Northern Ontario.

### 4.4. *Hay Forage\**

The impacts of a CO<sub>2</sub>-induced climatic change on the regional opportunities for hay production would be considerably smaller than the effects on other field crops. In Eastern, Southcentral and Southwestern Ontario, the longer growing season would permit an extra growth cycle, resulting in considerable increases in production opportunities for hay (Table VI). Elsewhere in Ontario, the number of cutting periods would not change under the altered climate and the production prospects for hay would not differ appreciably from the present.

## 5. Sensitivity of Land Resource Potential to Climatic Change

### 5.1. *Grain Corn*

The potential of Ontario's land resources to support grain corn production is quite sensitive to the specified changes in long-term climate (Figure 3). In Northern Ontario, grain corn would become an economically viable crop on about 70% of the land base that is cleared and available for agriculture. Prospects for corn production in Eastern Ontario would also improve from the specified changes in climate, but not to the extent estimated for Northern Ontario. In the Central, Southcentral and Western Ontario regions, the altered climate would imply little change in the production opportunities for grain corn.

Southwestern Ontario's potential for grain corn would be degraded under the

\* Information on hay yields required to attain a return to investment are not available and hence these analyses pertain only to the biophysical opportunities for production.

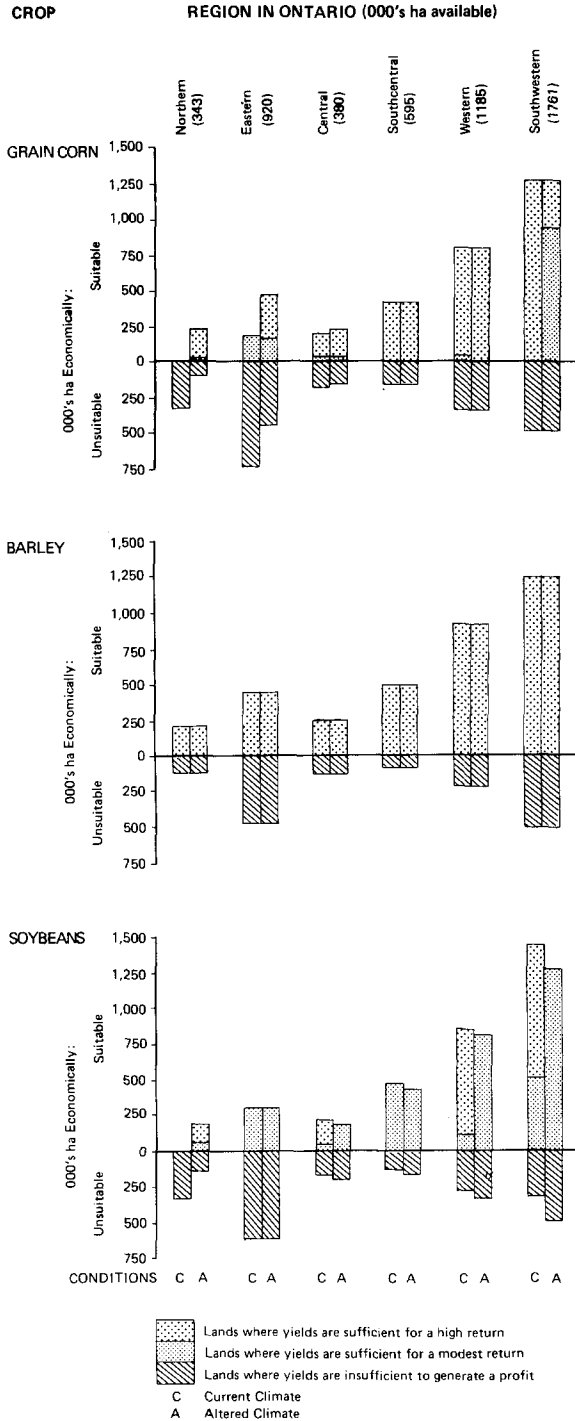


Fig. 3. Effects of climatic change on the agricultural potential of Ontario's land resources.

altered climate. The total area which could support the crop would not be affected to a large degree, but the portion of the regional land base which is especially well-suited to grain corn under rain-fed conditions would be reduced from the present 72% to 21%.

From a provincial perspective, the specified climatic changes would imply an overall reduction in the prospects for grain corn. An increase in the total area of land which could economically and physically support the crop would be expected, but these modest increases would be more than offset by the substantial decline in lands with a high economic potential for grain corn production.

### 5.2. *Barley*

The opportunities for barley production appear to be relatively insensitive to the specified changes in climatic conditions (Figure 3). That is, the altered climate would have little impact on the resource potential for this crop in each of the regions. Overall, about 70% of the 5.2 million ha of cleared land throughout Ontario is, and would continue to be under the altered climate, economically well-suited for barley.

### 5.3. *Soybeans*

The effects of the altered climate on production prospects for soybeans would be expected to vary from region to region (Figure 3). In Northern Ontario, where current climatic conditions prohibit the crop's production, soybeans would be a profitable crop on approximately 58% of the regional resource base. In the Eastern and Southcentral Ontario regions, the altered climate would have little impact on either the total area capable of supporting the crop, or the expected economic returns.

For the Central, Western and Southwestern Ontario regions however the specified changes in climate would be sufficient to contribute to diminished opportunities for soybeans. The total area capable of supporting the crop would be reduced somewhat, but more importantly, would be the elimination of lands with a high economic potential for soybean production.

From a provincial perspective, the specified changes in climate imply fewer opportunities for soybean production. The area of land capable of supporting the crop would be restricted slightly, and lands capable of providing a high return to investment would be confined to a small portion of Northern Ontario.

## 6. Conclusions

This paper indicates that it is feasible to conduct regional assessments of the implications of climatic change on land resource potential for crop production.

The research framework has facilitated the consolidation of information on climatic change, and its effects on crop yields with land inventories, and provides estimates of the impacts of climatic change on crop production opportunities.

The findings summarized in this paper are preliminary and should be viewed as approximations because of the uncertainties regarding climatic change, the scales at which the steps in the analysis are undertaken, and the early stage of development of such impact studies. Nevertheless, it is appropriate to draw some conclusions regarding implications of climatic change for the agri-food sector. First, it would appear that the impacts of a climatic warming would extend across relatively broad regions, and that the direction and magnitude of these impacts are likely to vary from region to region, soil to soil, and crop to crop. Clearly, production prospects for grain corn and soybeans would be more affected by the sorts of climatic changes contemplated in this Ontario study than the prospects for barley and hay forage. Furthermore, these altered climates imply more favourable opportunities in the northern parts of the province and poorer conditions for crops in the more southerly reaches of Ontario. Soils with a relatively low moisture holding capacity appear to be especially sensitive to the specified climatic changes. Clearly, any contemplation of policies relating to climatic change should be cognizant to these differential sensitivities.

The Ontario case study also provides some insight for agricultural research. Many crop breeding programs in Ontario currently focus upon existing climatic conditions, and are to a large extent devoted to developing crops which mature over shorter time spans. However under a warmer climate characterized by longer, hotter and drier growing seasons, moisture deficiencies become a critical constraint to production. Hence, an adjustment to crop breeding programs which would promote the development of crops capable of tolerating drier conditions could alleviate some of the potential negative socio-economic consequences from a climatic warming in Ontario.

Increases in the moisture stress associated with a warmer climate will in all likelihood also influence the demand and use of water for irrigation. This study has assumed rainfed agriculture, but irrigation could alter the physical opportunities for crop production as well as production economics. This is an important consideration for future studies, not only because of its implications for agriculture, but also because climatic change may influence the supply of water available for food production and other economic activities.

This paper has contributed to the modest but growing field of assessing the implications of climatic change on agriculture. Nevertheless, there is a need to expand the analysis to consider the effects of changes in interannual variability and seasonal distribution of climatic properties, direct affects of CO<sub>2</sub> on crops, a wider range of crops including horticultural crops, behavioural responses at the farm level, and impacts on comparative advantages.

## Acknowledgments

The authors gratefully acknowledge support from the Atmospheric Environment Service, Environment Canada, the Research and Agriculture Development Branches of Agriculture Canada, the Social Sciences and Humanities Research Council, the Ontario Ministry of Agriculture and Food, and the Land Evaluation Group. This paper has also benefitted from suggestions from three reviewers.

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(Received 5 November, 1987; in revised form 13 July, 1988)