Crop Yield and Variability under Climate Change and Adaptative Crop Management Scenarios

Final Report for Climate Change Action Fund Project A080

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SUMMARY

The rising trend of global atmospheric carbon dioxide is expected to induce a change in climate. Despite the uncertainty regarding the magnitude of this climate change, assessments of its impacts on agricultural production are needed for both scientific and policy-making purposes. The complexity of climate-crop production interactions makes simulation a very useful and practical approach available for making the needed assessments.

The EPIC simulation model integrates the major processes in the soil-crop-atmosphere-management system, including the beneficial effects of elevated CO_2 levels on crop growth. This model was run to estimate crop yields from daily baseline (1965-1995) maximum- and minimum air temperatures and precipitation data at 29 climate stations across the agricultural region of Canada. Thirty year climate change data, representing a $2xCO_2$ scenario, were constructed by superimposing the output from the Canadian Global Coupled model, which incorporates the effects of aerosols (CGCM1+A1) upon the baseline climate data in such a way that both the mean and the variability of the weather parameters changed. Local soils and crop management practices were used in the simulations.

Under a warmer and slightly wetter $2xCO_2$ climate scenario, the planting dates, simulated as a function of local soil and weather conditions, advanced by approximately 1 to 2 weeks in eastern and central Canada and by approximately 3 weeks in western Canada. Simulated planting dates of winter wheat at Kentville, Harrow and Delhi were delayed by one week.

Compared to the yields simulated with the baseline data, yields of spring planted barley, wheat and canola (the latter simulated only for the prairie region) did not change significantly under the $2xCO_2$ climate scenario. Corn yields in central Canada decreased significantly by 11%, although with increased nitrogen fertility, this yield decrease was reduced to less than 5%. Soybean, potato and winter wheat yields increased by approximately 12, 16 and 18%, respectively. The temporal yield variability of all crops increased under the $2xCO_2$ scenario, from 6% for spring wheat to 50% for soybeans.

Based on the assumption that at least 2400-2500 Crop Heat Units must be available for the crop to mature, corn and soybeans could be grown under the $2xCO_2$ climate scenario at all locations, except some of the most northern ones. When water stress was not a major limiting factor, corn and soybean yields were comparable to those simulated in central Canada where these crops are currently grown.

INTRODUCTION

Concern over climate change has reached global dimensions and concerted international efforts have been initiated in the last decade to address this problem. Based on climate records, the average global earth's surface temperature has increased over the 20th century by about 0.6 ^{0}C, with most of the warming occurring from 1910 to 1945 and from 1976 to 2000. Based on a wide range of scenarios and several current Global Change Models (GCMs), the mean annual global surface temperature is projected to increase by 1.4 to 5.8 ^{0}C over the period 1990 to 2100, with likely precipitation increases over northern mid- to high latitudes and in the Antartica (IPPC 2001). However, regional changes could be quite different from the global ones. For example, Hengeveld (2000), discussing the simulations made with a Canadian GCM, suggests temperature increases for most of Canada in the order of 2 to 4 ^{0}C by the middle-, and 5 to 10 ^{0}C by the end of this century, except in the High Arctic where the temperatures could soar by more than 15 ^{0}C. Projected changes in annual precipitation over Canada remain within 10% of present levels until after 2050 when the precipitation would increase by 10 to 20%, with most of the increases occurring during the winter months.

Global climate change is being attributed, in part, to the increased atmospheric carbon dioxide (CO_2) concentration from 280 ppm at the pre-industrial level to nearly 370 ppm by the end of the 20th century (Hengeveld 2000). Further increases, up to 90 to 250 % above the pre-industrial concentration, are projected by the end of the 21st century (IPPC 2001). However, while CO_2 is an acknowledged significant greenhouse gas which causes global warming, it also, at elevated concentrations, has beneficial physiological effects on plant growth (Wittwer 1995). This fertilizing effect of CO_2 varies with plant species. Under controlled conditions, C4 crops (like corn and many tropical grasses) are more efficient photosynthetically than C3 crops (like wheat, canola and soybeans), but show less response to increasing atmospheric CO2 concentrations (Richard et al. 1990). Recent field Free-Air-CO_2-Enrichment (FACE) studies have found overall positive CO_2 effects under current climate conditions (Wechsung et al. 1999; Garcia et al. 1998; Miglietta et al. 1998; Luscher et al. 1998).

The variability of the climate has been a topic of recent interest. The consequences of changes in variability may be as important as those that arise due to variations in mean climatic variables (Hulme et al. 1999; Carnell and Senior 1998). Most studies of climate change impacts on agriculture have analyzed the effects of mean changes of climatic variables on crop production, but the impacts of changes in climate variability have been studied to a much lesser extend (Alexandrov and Hoogenboom 2000; Mearns et al. 1997; Porter and Moot 1996).

Global and regional climate change will affect all economic sectors to some degree, but the agricultural sector is perhaps the most sensitive and vulnerable because agricultural production remains very dependent on climate resources (Downing 1996; Watson et al. 1996). The combined effects of increased temperatures, elevated atmospheric CO_2 concentrations, increased probability of extreme events (droughts, floods, frosts, etc.) and reduced crop-water availability are expected to cause significant changes in crop yields, cropping systems, scheduling of field operations and pest conditions (Chiotti and Johnston 1995). The overall impact will depend on both the magnitude of the change and how well agriculture will adopt to these changes (Kaiser et al. 1995).

Assessments of the potential impacts of climate change on Canada's society have been carried out at a national scale (Maxwell et al. 1997). At the regional level estimates of potential climate change on agriculture were conducted by McGinn et al. (1999), Brklacich and Stewart (1995), Brklacich and Smit (1992) and Singh and Stewart (1991). However, the methodologies used in the regional studies were not always compatible (e.g. different models and different climate change scenarios were used) and consequently a national agricultural impact assessment on crop yields and yield variability is currently lacking. In this study we examined the impacts of a 2xCO_2 climate change scenario on crop yield and yield variability in the major agricultural regions across Canada. Adaptative soil and crop management techniques to mitigate negative aspects of climate change were also investigated.

METHODOLOGY

Because of the complexity of climate-soil-crop systems, computer simulation techniques are among the most practical approaches available to make assessments of climate change impacts on agriculture. In this study we employed the Environmental Policy Integrated Climate, formerly known as the Erosion Productivity Index Calculator, (EPIC) model (Williams 1995) to compute long-term annual crop yields for the major agricultural regions in Canada using a historic baseline and a 2xCO_2 climate scenario. Further details on data, methods and assumptions are given below.

The Study Area

Seventeen ecoregions with potential for annual crop production (Table 1; Fig. 1) were selected from the National Ecological Framework for Canada (Ecological Stratification Working Group 1995). Currently marginal agricultural regions, like the Lake Timiskaming Lowland (# 97), the Central Laurentians (#101), the Interlake Plain (#155) and the Peace Lowland (#138) were included, because under warmer climatic conditions these areas might become better suited to agricultural production systems. Within each ecoregion, up to three representative climate stations were selected (Table 1; Fig. 2). For most stations a continuous historic 31-year (1965-1995) daily record containing maximum and minimum air temperature and precipitation was available from a computer archive maintained by the Eastern Cereal and Oilseed Research Centre of AAFC in Ottawa. The data were originally obtained from Environmemt Canada (1999) and were reformatted into a daily record. Short-term substitutions from nearby stations were required for Brucefield, Camrose, Winnipeg and Dauphin. At Normandin the weather record ended on August 31, 1992 and no suitable substitute was available.

Soils with an agricultural land use designation were chosen from the Soil Landscapes of Canada (Shields et al. 1991). The percentage that these soils represented within each mapped polygon was determined. Since the Soil Landscape polygons were nested within the ecoregion polygons, it was then possible to calculate the percentage of each agricultural soil for each ecoregion. Soils with the highest percent of cropland were chosen (Table 2.)

Many different crops are currently grown in each of the agricultural ecoregions, but in order to keep the number of simulations within a manageable range, only the most common crops within a region were selected for this study. Current indicator crop rotations (Table 2) were established with the help of local land resource specialists. In addition to continuous barley, a crop which was simulated in each agricultural region, one or two common and typical three-year rotations were selected.

Description of the EPIC Model

EPIC (version 5300), developed by Williams (1995), is a processed based simulation model which can be used to examine the effects of weather and management strategies on agricultural production and soil and water resources. The model integrates the major processes that occur in the soil-crop-atmosphere-management system, including: hydrology, weather, wind and water erosion, nutrient cycling, plant growth, soil temperature, tillage, plant environmental control and economics. It runs on a daily time step at the scale of a single field. Input requirements (see below) include: daily weather data, soil properties and soil and crop management data. EPIC uses a single model for simulating all crops, although each crop has unique values as model parameters (see Table 3). The crop growth model uses radiation-use efficiency in calculating photosynthetic production of biomass. Atmospheric CO_2 concentrations influence photosynthesis through the radiation use efficiency term, i.e. rates are increased by 10 and 25%, respectively for C4 (corn) and C3 crops (barley, wheat, canola, soybeans and potatoes) for the $2xCO_2$ scenario. The computed potential biomass is then adjusted daily for stress from the following factors: water, temperature, nutrients (nitrogen and phosphorus) and soil aeration in proportion to the severity of the most severe stress during that day. Crop yields are estimated by multiplying the above-ground biomass at maturity (determined in this study by specified harvest dates) by a water stress adjusted harvest index for the particular crop.

Stress days, which incorporate both stress duration and stress severity, are calculated during the growing season as the sum of (1. - daily stress factor). Thus on a day when the stress factor is 0. (i.e. no growth) the model calculates 1 stress day. If the stress factor is 1. (i.e. no stress) it calculates 0 stress days. Other days give a partial stress day.

While the EPIC model was developed based on weather, soil and crop management conditions as encountered in the United States, it has been subjected to numerous validation exercises worldwide. In Canada, where EPIC has been tested by Bouzaher et al. (1993), Moulin and Beckie (1993), Toure et al. (1994), Kiniry et al. (1995) and Roloff et al. (1998a and b), the model provides appropriate estimates of long-term yield averages, but it is less precise in following annual yield variability. Although this project was not designed to test and validate the model, a limited comparison between measured yields and those simulated with the baseline climate scenario revealed that the overall performance of the model was satisfactory (see

Appendix A). Underestimates of simulated corn and soybean yields could be partly attributed to significant genetic crop improvements which were not incorporated into the EPIC model.

Climate Data

(i) Historic weather data (baseline scenario). Daily maximum and minimum air temperatures and precipitation were obtained for the 1965 to 1995 period from 29 climate stations across the agricultural region of Canada. Solar radiation data, required to estimate crop growth and yield, were not available at many of these locations and were therefore simulated with the EPIC build-in weather generator. Potential evapotranspiration was calculated based on the Baier and Robertson (1965) methodology which requires daily maximum and minimum air temperatures and solar radiation at the top of the atmosphere.

(ii) Climate change scenario. The first version of the Canadian Global Coupled Model (CGCM1), as described by Flato et al. (2000) and Hengeveld (2000) was selected to form the basis of the climate change scenario constructed for this project. Four transient climate change simulations, representing the years 1900 to 2100, have been made (Boer et al. 2000a and b). They consist of three independent simulations with the same greenhouse gas and aerosol forcing (GHG+A), and a fourth simulation with greenhouse gas forcing only (GHG). The greenhouse gas concentrations used in the GHG+A follows the observed CO_2 concentration to 1996 with a 1% $year^{-1}$ compound increase thereafter. The annual average aerosol loading patterns are based on the chemistry model of Langner and Rhode (1991). The three GHG+A simulations differ in the way the model was initialized, but, because daily data was only available on the internet from the first run (GHG+A1), we selected that one for our scenario building exercise.

Daily data from the GHG+A1 run was available for three 21-year time windows: 1975-1995 (present climate), 2040-2060 (approximately CO_2 doubling) and 2080-2100 (approximately CO_2 tripling). De Jong and Li (2000) and Gameda et al. (2000) showed that the simulated GHG+A1 daily temperatures for the period 1975-1995 were significantly higher than observed ones for eight climate stations across Canada. Simulated GHG+A1 precipitation values also exceeded observed ones, mainly because the number of days with precipitation was significantly overestimated. Consequently crop yield and yield variability estimates with EPIC were significantly different when using simulated versus observed weather data. It was therefore decided to use historic observed weather data for the 1965-1995 period and a $2xCO_2$ scenario constructed using the methodology described by McGinn et al. (1999).

Daily data sets of maximum and minimum air temperature and precipitation from the GHG+A1 run for the periods 1975-1995 ($1xCO_2$) and 2040-2060 ($2xCO_2$) were downloaded from the Canadian Centre for Climate Modelling and Analysis (CCCma) website (http://www.cccma.bc.ec.gc.ca) for all grid points covering the entire agricultural region of Canada (Fig. 2). For each grid point and each month of the year we calculated, using the daily data, the ratio of variances for maximum and minimum temperature and precipitation, δ_{TMX}, δ_{TMN} and δ_{PPT} respectively, as:

$$\delta_{TMX} = \sigma^2_{2TMX} / \sigma^2_{1TMX}$$
$$\delta_{TMN} = \sigma^2_{2TMN} / \sigma^2_{1TMN}$$
$$\delta_{PPT} = \sigma^2_{2PPT} / \sigma^2_{1PPT}$$

where σ^2 refers to the variance and the subscripts 1 and 2 refer to the $1xCO_2$ (1975-1995) and $2xCO_2$ (2040-2060) data sets. Also calculated for each gridpoint and each month were the differences between the two periods for maximum and minimum temperature, $\Delta TMX=TMX_{2CO2} - TMX_{1CO2}$ and $\Delta TMN=TMN_{2CO2} - TMN_{1CO2}$ and precipitation ratios of the two periods, (PPT_{2CO2}/PPT_{1CO2}). Using 4 surrounding grid points, the inverse distance square procedure (Isaaks and Srivastava 1989) was used to interpolate the monthly grid point values of δ_{TMX}, δ_{TMN}, $\delta_{PPT,}$ ΔTMX, ΔTMN and (PPT_{2CO2}/PPT_{1CO2}) to the station locations. The time series of daily maximum and minimum temperature under the $2xCO_2$ scenario (TMX_{new}, and TMN_{new}) at each station were then estimated using the methodology described by McGinn et al. (1999):

$$TMX_{new} = (T^B + \sqrt{}\delta_{TMX} (TMX - T^B)) + \Delta TMX$$

$$TMN_{new} = (T^B + \sqrt{}\delta_{TMN} (TMN - T^B))+ \Delta TMN$$

where T^B is the mean daily temperature obtained from the 31-year normal (1965-1995), TMX and TMN are the historical maximum and minimum temperatures for the day and station in question. The above procedure ensured that the $2xCO_2$ scenario incorporated changes in both mean temperature and temperature variability. During the winter months (December through March), ΔTMX was usually less than ΔTMN, which resulted in on average 5% of cases where $TMX_{new} < TMN_{new}$; when that occurred, the maximum and minimum air temperatures were switched around.

The procedure of McGinn et al. (1999) was also used to obtain daily precipitation values under the $2xCO_2$ scenario (PPT_{new}):

$$\chi^* = \chi^B + \sqrt{}\delta_{PPT} (\chi - \chi^B)$$

where χ^* is the log-transformed monthly precipitation, χ^B is the log-transformed mean monthly precipitation obtained from the 31-year normal (1965-1995) and χ is the log-transformed historical monthly precipitation. The mean effect of climate change on precipitation was obtained as:

$$P^* = \exp(\chi^*) (PPT_{2CO2}/PPT_{1CO2})$$

where P^* is the new monthly precipitation due to climate change. Finally, the new daily precipitation (PPT_{new}) was calculated as:

$$PPT_{new} = PPT \ (P^*/P_{mon})$$

where PPT is the daily historic precipitation and P_{mon} is the monthly historic precipitation. While the above equations changed the amount of precipitation, the frequency was not changed.

Soil and Landscape Data

Based on the highest percentage of annual cropland soil, we selected the most representative soil series within an ecoregion (Table 2). Soil profile characteristics, which constitute the minimum EPIC input requirements, including horizon depth, bulk density, sand and silt content, pH and organic carbon content, were extracted from the Soil Layer File of the National Soil Data Base (Tarnocai and Lacelle, 1996). When available, values for organic nitrogen, sum of bases, calcium carbonates, cation exchange capacity and coarse fragments were also extracted. Following Izaurralde et al. (1996), values for field capacity, wilting point and hydraulic conductivity were estimated by EPIC's internal pedotransfer functions because these properties were estimated in the NSDB Soil Layer File by different methodologies in different provinces.

EPIC uses the USDA Curve Number (CN) technique to estimate surface runoff. The curve numbers employed in this study were derived from soil textural data in the uppermost soil layer according to the criteria developed by Bouzaher et al. (1993): $\geq$65 % sand, CN = 63; <65 % sand and $\leq$30 % clay, CN = 75; > 30 % clay <60% clay, CN = 83; $\geq$60 % clay, CN = 87.

The Universal Soil Loss Equation was used to estimate water erosion. Slope length was set to 50 m, slope steepness to 2 %. Wind erosion was not considered because wind speed data were not available. The initial soil water content in 1965 was set to field capacity, except on the prairies were it was set to 75% of field capacity.

Crop Parameters

The crop growth subroutine in EPIC simulates crop growth described by parameters related to radiation-use efficiency and leaf area. Values for barley, spring wheat, winter wheat, canola, corn, soybeans and potatoes (Table 3) were based on previous evaluations of the model, both in Canada and the USA. The radiation-use efficiency was assumed to increase with CO_2 doubling: for corn, C4 crop, the increase was 10%, for the remaining C3 crops the increase was 25%.

Crop and Soil Management

i) Planting dates

Spring wheat and barley were planted when the criteria developed by Bootsma and De Jong (1988) were met for 10 days in ecoregions 138 through 162. In order to obtain better agreement between estimated planting dates and those obtained by expert opinion, as reported by Huffman (2000), the same criteria had to be met for 7 days in ecoregions 97, 101, 117, 120, 126, 130, 132 and 134, and only 3 days were required in ecoregions 135 (Lake Erie Lowland) and 196 (Lower Mainland). The final overall agreement between predicted and estimated planting dates was reasonable good (Table 4).

The planting dates for corn and soybeans were based on the starting dates of Crop Heat Unit (CHU) accumulations as defined by Bootsma and Brown (1995). In ecoregions 117, 120, 126, 130 (the Atlantic Maritime ecozone) and 196 (the Pacific Maritime ecozone), the planting date was advanced by 7 days, thereby ascertaining a reasonable agreement between the predicted planting dates and those obtained by expert opinion and observations by Bootsma (personal communication) (Table 4).

Winter wheat planting dates for the baseline 1965-1995 conditions could be based on the empirical relationships between planting date and average air temperatures in September and October as developed by Bootsma and Suzuki (1986) and Bootsma et al. (1993). However, under a 2xCO_2 climate scenario, one could be extrapolating outside the range of observed data. Therefore the following strategy was developed: winter wheat planting dates were calculated each year (1965-1995) using the criteria of Bootsma and Suzuki (1986) and Bootsma et al. (1993). Also calculated for each year was the ‘freeze-up’ temperature, defined as the first day in the fall when the 5 day running mean daily temperature fell below 0^0C. The 30-year average difference between this freeze-up date and the winter wheat planting date was calculated at each station. The overall average difference was 63 days and therefore winter wheat planting dates were estimated to occur (for both the baseline and the 2xCO_2 scenario) 2 months prior to the day when the 5 day running mean daily air temperature fell below 0^0C. Average 1965-1995 estimated winter wheat planting dates at Earlton, Kentville and Brucefield, respectively Aug. 27 and Sept. 22 and 17, compared well with the recommended winter wheat planting date for northern Ontario (Aug. 22 to Sept. 5), and local expert opinion data, Sept. 20 at Kentville and Sept 15 in Grey and Dufferin county, just north of Brucefield.

According to local expert opinion (Table 4), planting dates of canola tend to coincide with cereal planting dates, except in the Mixed Grassland (Brown soil zone) and the Lake Manitoba Plain ecoregion where canola is planted approximately a week later. Potatoes are planted at the same time as cereals at Prince Edward Island, in south-western Ontario and in the Lower Frazer Valley, but 5 to 10 days later in the Annapolis-Minas Lowland and the Saint John River Valley. In this study we assumed that canola and potato planting dates coincided with those for cereals (Bootsma and De Jong 1988).

(ii) Harvest dates

Harvest dates of wheat and barley were determined by the biometeorological time scales developed by Robertson (1968) and Williams (1974a and b). Canola (Argentine type) was harvested at the same time as spring wheat (Kiniry et al. 1995). Potatoes were harvested when 850 (medium to late crop, e.g. Shepody) Potato Heat Units (PHU) were accumulated since planting (Sands et al. 1979). Work by Boons-Prins et al. (1993) suggests that potatoes in warmer Mediterrean climates mature when ≈ 16% more heat units are accumulated as compared to the cooler conditions prevailing north-western Europe. Consequently, a longer growing season potato crop with 975 PHU was selected for the 2xCO_2 climate scenario. If a killing frost ($Tmin \leq -2\ ^0C$) occurred prior to the above described harvest dates for wheat, barley or potatoes, then the harvest date was assumed to coincide with the killing frost date. The harvest dates for corn and soybeans were based on: first date when $Tmin \leq -2\ ^0C$ or when long-term average $Tmin \leq T_{crit}$, whichever was first. For the Maritimes and British Columbia $T_{crit} = 5.8\ ^0C$, for Ontario and Quebec $T_{crit} = 6.5\ ^0C$, and for the prairie provinces, $T_{crit} = 5.0\ ^0C$ (A. Bootsma, personal communication). Any crop grown prior to winter wheat was harvested prematurely if its 'normal' fall harvest date was later than the winter wheat planting date; this crop would be harvested 7 days prior to the winter wheat planting date. Winter wheat itself was harvested after 1800 degree-days above $0\ ^0C$ were accumulated since planting (Kiniry et al. 1995).

iii) Fertilizer applications

Fertilizer recommendations are usually based on site specific soil tests and they vary from one year to the next. In this study we used general recommended nitrogen and phosphorus fertilizer application rates, as obtained from various provincial farm guides and local agronomists (Table 5). All N and P fertilizer was applied on the planting date, except for winter wheat which received 20% of its fertilizer at planting and the remainder the following May 1.

iv) Tillage practices

All tillage dates were linked to the planting and harvesting dates (Table 6), with the exception of 'spring' fertilization of winter wheat on May 1, and tillage operations on fallow land which were assumed to take place on May 15, June 15 and August 15. Spring tillage consisted of three operations prior to planting. All nitrogen and phosphorus fertilizer was applied at planting time, except winter wheat which received 80% of its recommended rate the following spring (May 1). Fall tillage was conducted with a moldboard plow, except in the Prairies and Boreal Plains ecozone where a noble blade was used. EPIC yield estimates are not affected by pesticide and/or herbicide applications and consequently these chemicals were not used.

Adaptation Options

(i) Planting and harvest dates of all crops were adjusted under the $2xCO_2$ scenario according to the above described criteria.

(ii) Some EPIC runs showed that the recommended N application rates (Table 5) for barley, spring wheat and corn caused crop N deficiencies during the growing season. The model was then re-run with automatic N applications whenever this nutrient was the active crop growth constraint. Thus the annual applications varied according to the crop's needs, the soil's ability to supply those needs and the magnitude of the N stress relative to water and temperatures stresses.

(iii) The Crop Heat Unit (CHU) system developed by Brown (1969) was used to delineate locations where corn and soybeans could be grown. A threshold value of 2400 CHU was selected because this is the minimum amount of heat that current hybrids require to mature. CHU's were therefore calculated for the corn and soybean growing season at each location for both the 1965-1995 baseline- and the $2xCO_2$ climate scenario.

(iv) Under a warmer climate, potentially new warm-season crops might be grown in Canada. Cotton and peanuts, currently grown in the southern USA, require 1450 and 1550

Growing Degree Days (GDD) above 10 and 13.5 ^{0}C respectively (J.R. Williams and J.R. Kiniry, USDA, Temple, TX, personal communication). GDD's for cotton and peanuts were calculated between corn planting dates and December 31 at each location using the 1965-1995 baseline- and the 2xCO$_2$ climate scenario.

EPIC Simulation Runs

The EPIC simulation model was run at all 29 stations with the 31 year (1965-1995) baseline weather data and with the 31 year 2xCO$_2$ climate scenario data. In the latter scenario, the direct effects of increased atmospheric CO$_2$ levels were included. The CO$_2$ concentration for the baseline data was assumed to be 340 ppm (Environment Canada 1998; Keeling et al. 1996). The initial year of the simulation was ignored in subsequent analyses. For a 3-year rotation, the model was run three times, with each initial year containing a different crop. The output files, containing crop yields, cumulative stress factors which account for both stress duration and severity, and growing season variables like precipitation, potential evapotranspiration, solar radiation,etc., were sorted in '30-year single crop' files. For each output variable we calculated means, standard deviations and probability values ranging from 5 to 95%, using the procedures described in Spiegel (1961).

RESULTS AND DISCUSSION

Changes in monthly and annual mean temperature and precipitation values as a result of the 2xCO$_2$ scenario are presented in Tables 7 and 8. The projected annual mean temperature increase in eastern and central Canada (ecoregions 97 through 135) was spatially fairly uniform, i.e. approximately 2.5 ^{0}C. In western Canada (ecoregions 138 through 196) the annual mean temperature increase varied from 3.6 ^{0}C in the eastern prairies (Winnipeg and Brandon) to 1.9 ^{0}C at Agassiz. The temperature increases during the winter months (January through March) tended to be considerably higher than those of the remaining part of the year. Annual precipitation changes as a result of the 2x CO$_2$ scenario were small, especially when computed as a percent change from the 1965-1995 baseline data. At most locations annual precipitation would increase by less than 10%, except in the driest region of the country (at Gleichen, Aneroid, Alsask and Foremost) where small decreases were projected. The distribution of changes in precipitation was not uniform during the year: generally the small precipitation increases occurred during the winter and spring months, while the decreases tended to occur during June, July and August.

Barley

Barley growth and yield was simulated at all 29 locations across Canada. The annual planting dates were simulated primarily as a function of weather conditions and consequently, under a warmer 2xCO$_2$ climate all 30-year mean planting dates were advanced (Table 9). At the northern edge of current-day agriculture (Earlton, Normandin, Mont Joli, Beaverlodge and Melfort) the planting dates were less advanced under the 2xCO_2 scenario, (by approximately up to a week), compared to most of the other stations where the simulated planting dates were advanced by 2 to 3 weeks. At Agassiz, the planting date was a full month earlier under the 2xCO_2 climate. Harvest dates were advanced by approximately the same number of days than the planting dates and therefore the barley growing season length at most stations did not change by more than 1 week. Exceptions occurred at Harrow, where the growing season increased by 13 days, and at Beaverlodge and Melfort, where the growing season decreased by 9 and 8 days respectively, under the 2xCO_2 climate.

Temperature stress (Table 9), which was not delineated between heat and cold stress in the EPIC model, increased at some stations and decreased at others under the 2xCO_2 climate: the maximum increase was simulated at Harrow (4 days), while maximum decreases occurred at Beaverlodge (9 days), Melfort (6 days) and Camrose (6 days). Averaged over all stations, the barley temperature stress decreased minimally from 9 to 8 days. While there was little water stress ($\leq$ 3 days) under either the baseline or the 2xCO_2 climate at Earlton, Fredericton , Kentville, Charlottetown and Beaverlodge, the average water stress increased from 14 to 17 days. Simulated nitrogen stress (> 10 days) for both the 1965-1995 baseline data and the 2xCO_2 climate was most significant in ecoregions 97 through 138, and at Agassiz. In the same regions N stress increased on average by 4 days. Small decreases in N stress were observed in the relatively dry ecoregions 157 and 159. Little or no phosphorus stress was observed under either the baseline or the climate change scenario at any of the locations (data not shown).

Despite the fact that average water and nitrogen- stress each increased by approximately 20% under the 2xCO_2 climate, barley yields were most often not significantly different at $P<0.05$ (Table 10). The 25% increased radiation use efficiency and the adaptation to earlier planting dates were sufficient to offset the negative impacts (i.e. increased water and N stress) of the imposed climate change scenario. Small, but significant yields increases were simulated only at the 5 stations with no water stress.

As expected, increased nitrogen fertilization rates would improve barley yields under both climate scenarios. For example, when the EPIC model was run with the automatic N fertilization option (i.e. no N stress) the average baseline (1965 - 1995) barley yields in ecoregion 97 through 135 increased from 3.47 Mg ha^{-1} to 4.55 Mg ha^{-1} (a 31 % increase), while the 2xCO_2 yields increased from 3.52 Mg ha^{-1} to 5.41 Mg ha^{-1} (a 54 % increase). The latter bigger yield increase suggests that fertilizer practices may be able to alleviate some of the negative aspects of climate change.

Spring wheat

Spring wheat was simulated at 25 locations across Canada. The planting dates of spring wheat were the same as those for barley (Table 9). However, unlike barley, the simulated spring wheat growing season length under the 2xCO_2 climate was slightly shorter, on average by 3.5 days, than under the baseline scenario (Table 11). Only at Agassiz did the growing season length increase by 6 days.

The temperature and water stress increased at some stations and decreased at others, but, averaged over all stations, changed by only 1 day under the $2xCO_2$ climate. Compared to barley, where the average temperature stress was about 8 to 9 days, the average temperature stress of wheat was about half that; on the other hand, the average water stress in wheat was almost twice as high as that in barley. High N stress (> 2 weeks) was simulated at Earlton, Lennoxville, Mont Joli, Fredericton, Charlottetown and Agassiz under both climate scenarios (Table 11), but the overall N stress increase was less than 2 days. As with barley, little or no phosphorus stress was observed under either the baseline or the climate change scenario at any of the stations.

Because at most stations the stress variables did not change significantly ($\leq$ 3 days), a linear model would predict significant yield increases because the radiation use efficiency was increased by 25% under the $2xCO_2$ climate. However, in the integrated EPIC model, the increased radiation use efficiency was counterbalanced by relatively high water stress values which negatively affect both total biomass production and the harvest index. For example, at Biggar where the temperature-, the N-, and the high water stress did not change notably among the two climate scenarios, the total biomass production increased by a mere 6% from 7.73 to 8.19 Mg ha^{-1}, considerable less than the 25% increase in radiation use efficiency. Moreover, the harvest index fell by 2%, leading to an overall yield increase of only 3%. Consequently at most stations, wheat yields remained fairly constant among the two climate scenarios (Table 12). Exceptions occurred at Normandin, Mont Joli and Brandon where the yields decreased significantly ($P<0.05$) under the $2xCO_2$ climate scenario because of increased water stress (> 5days). At Earlton, Fredericton and Charlottetown the yields increased significantly because there was no water stress.

The highest (> 20 days) N stress values were encountered at Earlton, Fredericton and Charlottetown. When N stress was eliminated at these three stations the average baseline (1965 - 1995) yields increased from 3.06 Mg ha^{-1} to 4.40 Mg ha^{-1} (a 44 % increase), while the $2xCO_2$ yields increased from 3.12 Mg ha^{-1} to 4.92 Mg ha^{-1} (a 58 % increase). As with barley, the latter bigger spring wheat yield increase indicates that increased N fertilization can diminish negative aspects of climate change.

Canola

Canola was simulated at 12 stations in western Canada only. The planting dates were the same as those for barley and spring wheat (Table 9) and the harvest dates coincided with those of spring wheat. Temperature stress decreased on average by 3 days, while water stress increased on average by 2 days under the $2xCO_2$ climate scenario (Table 13). Canola did not experience any N or P stress under either scenario. At the stations where both canola and spring wheat were simulated, the temperature stress (cold stress, rather than heat stress) was greater for canola than for wheat, especially under the baseline scenario, because the optimum temperature for canola growth was 3 ^{0}C higher than the one for wheat (Kiniry et al. 1995). The water stress values were lower for canola than for wheat.

As with wheat, the 25% increase in radiation use efficiency of canola was largely counter balanced by relative high water- and temperature stress values under the 2xCO_2 climate, resulting in overall small (0.1 Mg ha^{-1}) changes in yield (Table 14). Exceptions occurred at Beaverlodge, Camrose and Dauphin where yields increased significantly, and at Brandon and Yellow Grass were yields decreased significantly. Crop yield variability increased at all stations, on average by 15%, except at Yellow Grass.

Corn

Corn was simulated at 6 stations in central Canada. The annual planting and harvest dates were simulated as a function of air temperature and consequently, under a warmer 2xCO_2 climate, planting dates were advanced (by approximately 9 days) and harvest dates were delayed (by approximately 12 days), leading to a growing season which was on average 20.7 days longer than under the baseline scenario (Table 15). Average temperature stress during the growing saeson decreased from 15.5 to 12.5 days under the 2xCO_2 climate scenario. The average water stress, which was high already under the baseline scenario, increased by 60% (from 36.5 to 57.3 stress days) under the 2xCO_2 climate. This, along with increased N stress, not only reduced the average total biomass production from 14.38 to 13.43 Mg ha^{-1} (a 7% decrease), but it also decreased the harvest index by 6%. The radiation use efficiency of corn was increased by 10% under the 2xCO_2 climate scenario, but this did not offset the negative impacts of the warmer climate: yields decreased on average from 5.65 to 5.01 Mg ha^{-1}, i.e. a decrease of 11% (Table 16).

Increased nitrogen fertilization rates improved corn yields under both climate scenarios. The average baseline (1965 - 1995) corn yields increased from 5.65 Mg ha^{-1} to 5.84 Mg ha^{-1} (a 3 % increase), when N stress was eliminated. For the 2xCO_2 scenario, yields increased from 5.01 Mg ha^{-1} to 5.55 Mg ha^{-1} (an 11 % increase) under no N stress.

Soybeans

Soybeans were simulated at the same stations as corn. Planting and harvest dates were similar to that of corn, except at Harrow and Delhi were harvesting took place earlier because otherwise it would interfere with winter wheat planting dates. The average temperature stress during the growing season decreased from 18.5 to 14.8 days under the 2xCO_2 climate scenario (Table 17). The average water stress increased from 25.7 to 45.2 stress days under the 2xCO_2 climate, but the soybeans did not experience any N or P stress. The radiation use efficiency of soybeans increased by 25% under the 2xCO_2 climate scenario and this, along with the increased growing season length, caused an average increase in total biomass production of 13%. Yields at all stations increased significantly, on average by 12 %, from 1.99 to 2.23 Mg ha^{-1} (Table 18).

Potatoes

Potato yields were simulated at only five locations, namely Normandin, Fredericton, Kentville, Charlottetown and Agassiz. Under the 2xCO$_2$ scenario planting dates were advanced ranging from 5 days at Normandin to 30 days at Agassiz (Table 19). The average growing season length increased fairly uniformly by 16 days in response to higher air temperatures and the fact that a later maturing potato variety was used in the 2xCO$_2$ climate scenario. Temperature stress did not change by more than 2 days at any of the locations, but water stress increased significantly (>10 days) at Normandin, Fredericton and Kentville. There was no water stress at Charlottetown and high water stress (>30) days at Agassiz, but at either location water stress did not change among the climate scenarios. N stress remained generally fairly low ($\leq$ 6 days), except at Agassiz where it increased from 13 to 20 days under the 2xCO$_2$ scenario. Significant yield increases under the 2xCO$_2$ scenario ranged from 30% at Normandin to 11% at Kentville (Table 20). At Agassiz the yield increase was not significant.

Winter wheat

Winter wheat was simulated at only three locations: Kentville, Harrow and Delhi. In contrast to all other crops, average fall planting under the 2xCO$_2$ scenario was delayed by 7 days (Table 19). Harvest dates were advanced on average by 25 days, because under both climate scenarios the crop needed the same number of degree-days to mature. Average temperature stress decreased by 21 days, water stress by 4 days, but N stress more than doubled from 7 to 16 days. The radiation use efficiency of winter wheat increased by 25% under the 2xCO$_2$ climate scenario and this, along with the adjusted planting and harvest dates, caused a significant yield increase at all three locations, averaging 18% (Table 20).

Temporal Yield Variability

Average crop yields were computed over the 30 year period. While average yields give an overall impression of the regional potential, for risk analysis year-to-year variation caused by weather conditions is relevant (Dumanski and Onofrei 1989). The simulated yields of the individual years make it possible to compare yield stability under the two climate scenarios. Some typical examples for each of the crops are presented in Figs. 3 to 7. Generally, the temporal yield variability was higher under the 2xCO$_2$ scenario. For example, at Swan River under the baseline climate scenario, in 80% of the years barley yields were found to range from 2.75 to 5.18 Mg ha^{-1} (Fig. 3a). However, under the 2xCO$_2$ scenario climate differences were estimated to cause a greater range in yield from 1.88 to 5.43 Mg ha^{-1} in 80% of the years.

Temporal yield variability, as expressed by its standard deviation, increased under the 2xCO$_2$ climate scenario at most stations for all the investigated crops (Tables 10, 12, 14, 16, 18 and 20). Averaged over the stations were the crops were grown, the standard deviation increased by 6, 15, 16, 17, 22, 24 and 48% for respectively spring wheat, winter wheat, canola, corn, barley, potatoes and soybeans. It should be noted that the yield variability of barley and spring wheat, which are both grown in all ecoregions, are generally higher in western Canada as compared to eastern Canada.

Crop adaptation

Under current conditions, i.e. the baseline scenario, and based on the assumption that on average at least 2400 CHU must be available for the crop to mature, corn and soybeans could be grown at Lennoxville, Fredericton, Kentville, Kemptville, St Hyacinthe, Peterborough, Brucefield, Harrow, Delhi and Agassiz (Table 21). However, there would be a 30% risk that the crops would not mature at Lennoxville, Fredericton and Peterborough due to a shortage of heat units. Cotton, which requires a minimum of of 1450 GDD’s above 10 ^{0}C, might be grown only at Harrow with a 50% probability that it would mature. Peanuts, which require 1550 GDD’s above 13.5 ^{0}C, could not be grown at any of the locations under the baseline climate scenario.

Based on available CHU’s under the 2xCO_2 scenario, corn and soybeans could be grown at most locations, except at Normandin, Mont Joli and Beaverlodge. At Earlton, Melfort and Gleichen the probability that these crops would mature was less than 40%. Cotton could be grown at St Hyacinthe, Harrow and Delhi, and possibly, with an approximate 50% chance of success, at Kemptville, Brucefield , Winnipeg and Agassiz. As in the baseline scenario, peanuts could not be grown under the 2xCO_2 scenario either.

Corn and soybean yield distributions under the 2xCO_2 climate scenario at 5 locations where these crops were not simulated with the baseline climate, are shown in Figs 8, 9 and 10. Despite the fact that on average sufficient CHUs would be available (i.e. >2400) to mature the crop, corn and soybean yields at Gleichen and Aneroid were less than 50% of the average simulated yields in central Canada under the baseline scenario (Tables 16 and 18). At both locations water stress in excess of 60 days during the growing season was the most limiting yield factor. Yields at the remaining 3 locations were approximately the same as those reported in Tables 16 an 18. When extra N fertilizer was applied to corn, the yields increased by 22% at Earlton and by 52% at Charlottetown, but by less than 3% at Gleichen, Winnipeg and Aneroid.

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REFERENCES

Alexandrov, V.A. and Hoogenboom, G. 2000. The impact of climate variability and change on crop yield in Bulgaria. Agric. Forest Meteorol. 104: 315-327.

Baier, W. and Robertson, G.W. 1965. Estimation of latent evaporation from simple weather observations. Can. J. Plant Sci. 45: 276-284.

Boer, G.J., Flato, G.M., Reader, M.C. and Ramsden, D. 2000a. A transient climate change simulation with historical and projected greenhouse gas and aerosol forcing: experimental design and comparison with the instrumental record for the 20th century. Climate Dynamics16: 405-425.

Boer, G.J., Flato, G.M. and Ramsden, D. 2000b. A transient climate change simulation with historical and projected greenhouse gas and aerosol forcing: projected climate for the 21st century. Climate Dynamics 16: 427-450.

Boons-Prins, E.R., De Koning, G.H.J., Van Diepen, C.A. and Penning de Vries, F.W.T. 1993. Crop specific simulation parameters for yield forecasting across the European Community. Simulation Report CABO-TT, no. 32, CABO-DLO, Wageningen, The Netherlands.

Bootsma, A., Andrews, C.J., Hoekstra, G.J., Seaman, W.L. and Smid, A.E. 1993. Estimated optimum seeding dates for winter wheat in Ontario. Can. J. Plant Sci. 73: 389-396.

Bootsma, A. and Brown, D.M. 1995. Risk analyses of crop heat units available for corn and other warm-season crops in Ontario. Tech. Bull. 1995-1E, CLBR, Research Br., AAFC.

Bootsma, A. and De Jong, R. 1988. Estimates of seeding dates of spring wheat on the Canadian prairies from climate data. Can. J. Plant Sci. 68: 513-517.

Bootsma, A. and Suzuki, M. 1986. Zonation of optimum seeding period of winter wheat based on autumn temperatures. Can. J. Plant Sci. 66: 789-793.

Bouzaher, A., Shogren, J.F., Holtkamp, D., Gassman, P., Archer, D., Lakshminarayuan, P., Carriquiry, A., Reese, R., Furtan,W.H., Izaurralde, R.C. and Kiniry, J. R. 1993. Agricultural Policies and Soil Degradation in Western Canada: An Agroecological Economic Assessment (Report 2: The Environmental Modelling System). Tech. Rep. 5/93, Policy Branch, Agic. Canada, Ottawa, ON.

Brown, D.M. 1969. Heat units for corn in southern Ontario. Ont. Min. Agric. Food Tactsheet Agdex 111/30, 4 pp.

Brklacich, M. and Smit, B. 1992. Implications of changes in climatic averages and variability on food production opportunities in Ontario, Canada. Clim. Change 20: 1-21.

Brklacich, M. and Stewart, R.B. 1995. Impacts of climate change on wheat yield in the Canadian prairies. *In*: Climate Change and Agriculture: Analysis of Potential International Impacts. ASA Special Publication no. 59, Amer. Soc. of Agron., Madison, WI.

Carnell, R.E. and Senior, C.A. 1998. Changes in mid-latitude variability due to increasing greenhouse gases and sulphate aerosols. Clim. Dynamics 14: 369-383.

Chiotti, Q.P. and Johnston, T. 1995. Extending the boundaries of climate change research: a discussion on agriculture. J. of Rural Studies 11: 335-350.

De Jong, R. and Li, K.Y. 2000. Simulating crop yields with weather data from the Canadian Global Coupled Model. In: 2000 Annual meetings abstracts, Amer. Soc. of Agron., Minneapolis, MN.

Downing, T.E. (ed.). 1996. Climate change and world food security. NATO ASI Series I: Global Environmental Change37, Springer, Berlin, 662 pp.

Dumanski, J. and Onofrei, C. 1989. Techniques of crop yield assessment for agricultural land evaluation. Soil Use and Management 5: 9-16.

Ecological Stratification Working Group. 1995. A national ecological framework for Canada. Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch, Ottawa/Hull.

Environment Canada 1998. Climate Change. National Environmental Indicator Series, State of the Environment Bull. No. 98-3.

Environment Canada. 1999. Canadian Daily Climate Data Temperature and Precipitation. Environment Canada, Meteorol. Serv. of Canada, Downsview, Ontario. CD-Rom Database.

Flato, G.M., Boer, G.J., Lee, W.G., McFarlane, N.A., Ramsden, D., Reader, M.C., and Weaver, A.J. 2000. The Canadian Centre for Climate Modelling and Analysis Global Coupled Model and its Climate. Climate Dynamics 16: 451-467.

Gameda, S., R.de Jong and A. Bootsma. 2000. The challenge of developing agroclimatic scenarios from general circulation models. In: Proc. Intern. Forum of Climate Prediction, Agriculture and Development. Intern. Research Inst. for Climate Prediction, Washington, DC.

Garcia, R.L., Long, S.P., Wall, G.W., Osborne, C.P., Kimball, B.A., Nie, G.Y., Pinter Jr.,P.J., LaMorte, R.L. and Wechsung, F. 1998. Photosynthesis and conductance of spring wheat leaves: field response to continuous free-air atmospheric CO_2. Plant, Cell and Environment 21: 659-669.

Hengeveld, H.G. 2000. Projections for Canada’s climate future. A discussion of recent simulations with the Canadian Global Climate Model. CCD 0001, Environment Canada.

Hengeveld, H.G. 2001. An assessment of new research developments relevant to the science of climate change: 1999 in review. CO_2/Climate Report, spring 2001 issue. Environment Canada, Downsview, ON.

Hulme, M., Barrow, E.M., Arnell, N.W., Harrisson, P.A., Johns, T.C. and Downing, T.E. 1999.Relative impacts of human-induced climate change and natural climate variability. Nature 397: 688-691.

Huffman, E. 2000. Soil cover by crops and residue. Pages 33 - 39 in McRae,T., C.A.S. Smith and L.J. Gregorich (eds). 2000. Environmental Sustainability of Canadian Agriculture: Report of the Agri-Environmental Indicator Project. Agric. and Agri-Food canada, Ottawa, ON.

Intergovernmental Panel on Climate Change (IPCC).2001. Summary for policymakers. Report of Working Group I. Climate Change 2001: the scientific basis.
http://www.meto.gov.uk/sec5/CR_div/ipcc/wg1/WGI-SPM.pdf

Isaaks, E.H. and Srivastava, R.M. 1989. Applied geostatistics. Oxford Univ. Press, Oxford.

Izaurralde, R.C., Gassman, P.W., Bouzaher, A., Tajek, J., Laksminarayan, P.G., Dumanski, J. and Kiniry, J.R. 1996. Application of EPIC within an integrated modeling system to evaluate soil erosion in the Canadian Prairies. In: D. Rosen, E. Tel-Or, Y. Hadar and Y. Chen (eds.) Modern Agriculture and the Environment. Kluwer Acad. Publ., Lancaster, UK, pp. 267-283.

Kaiser, H.M., Riha, S.J., Wilks, D.S. and Sampath, R. 1995. Adaptation to global climate change at the farm level. *In*: H.M. Kaise and T.E. Drennen (eds.), Agricultural Dimensions of Global Change. St. Lucie Press, FL, pp. 136-152.

Keeling, C.D., Chine, J.F.S. and Whorf, T.P. 1996. Increased activity of northern vegetation inferred from atmospheric CO_2 measurements. Nature 382: 146-149.

Kiniry, J.R., Major, D.J., Izarraulde, R.C., Williams, J.R., Gassman, P.W., Morrison, M., Bergentine, R. and Zentner, R.P. 1995. EPIC model parameters for cereal, oilseed and forage crops in the northern Great Plains region. Can. J. Plant Sci. 75: 679-688.

Langner, J. and Rhode, H. 1991. A global three-dimensional model of the tropospheric sulphur cycle. Atmos. Chem. 13: 225-263.
Luscher, A., Hendrey, G.R., and Nosberger, J. 1998. Long-term responsiveness to free air CO_2 enrichment of functional types, species and genotypes of plants from fertile permanent grassland. Oecologia 113: 37-45.

Maxwell, B., Mayer, N. and Street, R. 1997. The Canada Country Study: Climate Impacts and Adaptation, National Summary for Policy Makers. Environment Canada, Ottawa, On.

McGinn, S.M., Toure, A., Akinremi, O.O., Major, D.J. and Barr, A.G. 1999. Agroclimate and crop response to climate change in Alberta, Canada. Outlook on Agric. 28: 19-28.

Mearns, L.O., Rosenzweig, C. and Goldberg, R. Mean and variance change in climate scenarios: methods, agricultural applications and measures of uncertainty. Clim. Change 35: 367-396.

Miglietta, F., Magliulo, V., Bindi, M., Cero, L., Vaccri, F.P., Loduca, V. and Peressotti, A. 1998. Free Air CO2 Enrichment of potato (solanum tuberosum L.): development, growth and yield. Global Change Biol. 4: 163-172.

Moulin, A.P. and Beckie, H.J. 1993. Evaluation of the CERES and EPIC models for predicting spring wheat yields. Can. J. Plant Sci. 73: 713-719.

Porter, J.R. and Moot, D.J. 1996. Research beyond the means.....climatic variability and plant growth. *In*: N.R. Dalezios (ed.) Intern. Symp. on Applied Agrometeorology and Agroclimatology. Office for Official Publ. of the EC, Luxembourg, pp. 13-23.

Robertson, G.W. 1968. A biometeorological time scale for a cereal crop involving day and night temperatures and photoperiod. Int. J. Biometeor. 12: 191-223.

Roloff, G., De Jong, R. and Nolin, M.C. 1998a. Crop yield, soil temperature and sensitivity of EPIC under central-eastern Canadian conditions. Can.J. Soil Sci. 78 : 431-439.

Roloff, G., De Jong, R., Zentner, R.P, Campbell, C.A. and Benson, V.W. 1998b. Estimating spring wheat yield variability with EPIC. Can. J. Soil Sci. 78: 541-549.

Sands, P.J., Hackett, C. and Nix, H.A. 1979. A model of the development and bulking of potatoes (Solanum Tuberosum L.). Field Crops Research 2: 309-331.

Shields, J.A., Tarnocai, C., Valentine, K.W.G. and MacDonald, K.B. 1991. Soil Landscapes of Canada. Procedures manual and user's handbook. Agriculture Canada, Land Resource Research Centre, Ottawa, ON.

Singh, B. and Stewart, R.B. 1991. Potential impacts of a CO2 induced climate change using the GISS scenario on agriculture in Quebec, Canada. Agric., Ecosystems Environ. 35: 327-347.

Spiegel, M.R. 1961. Schaum's outline of theory and problems of statistics. Schaum's Publishing Co., New York, 359 pp.

Tarnocai, C. and Lacelle, B. 1996. Soil Organic Carbon of Canada Database. Eastern Cereal and Oilseed Research Centre, Agriculture and Agri-Food Canada, Research Branch, Ottawa, ON.
Toure, A., Major, D.J. and Lindwall, C.W. 1994. Comparison of five wheat simulation models in southern Alberta. Can. J. Plant Sci. 75: 61-68.

Watson, R., Zinyowera, M. and Moss, R. (eds.). 1996. Climate Change 1995 - Impacts, adaptation and mitigation of climate change. Contribution of Working Group II to the Second Assessment Report of the IPCC, Cambridge Univ. Press, Cambridge.

Wechsung, G., Wechsung, F., Wall, G.W., Adamsen, F.J., Kimball, B.A., Pinter, P.J., LaMorte, R.L., Garcia, R.L. and Kartschall, Th. 1999. The effects of free-air CO2 enrichment and soil water availability on spatial and seasonal patterns of wheat root growth. Global Change Biol. 5: 519-529.

Williams, J.R. 1995. The EPIC model. *In*: V.P. Singh (ed.) Computer models of watershed hydrology. Water Resources Publ., Littleton, CO, pp 909-1000.

Williams, G.D.V. 1974a. Deriving a biophotothermal time scale for barley. Int. J. Biometeor. 18: 57-69.

Williams, G. D. V. 1974b. A critical evaluation of a biophotothermal time scale for barley. 1974. Int. J. Biometeor. 18: 259-271.

Williams, J.R., Dyke, P.T., Fuchs, W.W., Benson, V.W., Rice, O.W. and Taylor, E.D. 1990. EPIC-Erosion/Productivity Impact Calculator: 2. User Manual. USDA Tech. Bull. No. 1768. 127 pp.

Wittwer, S.H. Food, climate and carbon dioxide - The global environment and world food production. Lewis Publishers, New York, USA.

APPENDIX A

The results from long-term, well managed, experimental crop rotation studies in the prairies were summarized by Campbell et al. (1990). Representative of the Brown soil zone (ecoregion # 159) are the Swift Current rotation studies: the average 18-year (1967-1984) fallow wheat yield, with N and P fertilizer applied, was 1.91 Mg ha^{-1}. This was in excellent agreement with the 30-year average baseline simulated yields of 1.95, 2.15 and 1.91 Mg ha^{-1} at respectively Aneroid, Alsask and Foremost. In the Dark Brown soil zone (ecoregion # 157), stubble wheat yields, with N and P fertilizer applied, at Lethbridge averaged 1.91 Mg ha^{-1} (1972-1984), while at Scott they averaged 2.03 Mg ha^{-1} (1966-1984). Simulated yields with the baseline scenario at Yellow Grass, Biggar and Gleichen averaged respectively 2.26, 2.25 and 1.66 Mg ha^{-1}, well within acceptable limits (arbitrarily set to ± 20%) of the measured yields. In the Black soil zone (mostly located within ecoregion # 156) measured stubble wheat yields varied from 1.84 Mg ha^{-1} at Indian Head (thin Black zone) to 2.44 Mg ha^{-1} at Melfort (thick black zone). Simulated yields at Melfort averaged 2.69 Mg ha^{-1}, close to the measured 1960-1984 average.

Average barley yields simulated with the baseline climate data at Biggar (3.08 Mg ha^{-1}) compared well with long-term (1980-1991) experimental yields of barley grown on stubble at nearby Scott (2.98 Mg ha^{-1}) as reported by Brandt and Zentner (1995). The barley plots at Breton (located in the Boreal Transition ecoregion # 149 in Alberta) were established in 1930, but till 1980 were under fertilized. Nevertheless, Campbell et al. (1997) state that 'above-ground yield for fertilized barley at Breton, when currently accepted technologies and N fertilizer rates are used, is 7.25 Mg ha^{-1} '. Assuming a harvest index of 0.54 (Table 3), one would then estimate a barley yield of 3.91 Mg ha^{-1}. Simulated baseline barley yields at the northern fringes of agricultural areas on the prairies (ecoregions 138,149 and 155) averaged 4.29 Mg ha^{-1}.

Average barley yields from variety trials conducted between 1994 and 2000 in central and eastern Canada In eastern Canada were compiled by Bootsma et al. (2001). Average baseline simulated yields of 3.89, 3.60 and 3.67 Mg ha^{-1} at Fredericton, Kentville and Charlottetown, respectively, compared well with average yields of 2-row barley in the Maritime provinces (4.1 Mg ha-1). At Normandin simulated (4.56 Mg ha^{-1}) and measured (5.3 Mg ha^{-1}) yields were within 15%. Also, the simulated barley yields at Earlton (4.39 Mg ha-1) compared well with measured ones from New Liskeard in northern Ontario (4.4 Mg ha^{-1}). However, the simulated yields in ecoregion # 132, 134 and 135 were underestimated by approximately 25% as compared to measured yields.

Yields of Polish canola grown on fallow plots at Scott in the Dark Brown soil zone averaged (1980-1991) only 1.46 Mg ha^{-1}, partly because of insufficient weed control (Brandt and Zentner 1995). Simulated yields of Argentine canola, and assuming no weed and pest investations at nearby Biggar were 64% higher. The simulated 30-year average canola yield over 12 stations on the Prairies (2.46 Mg ha^{-1}) compared well with the various short-term (2 to 3 years) measured canola yields (approximately 1.8 to 3.1 Mg ha^{-1}) as reported by Kiniry et al. (1995).

Drury and Tan (1995) reported experimental 35-years corn grain yields in south-western Ontario to be 5.12 Mg ha^{-1} for fertilized continuous corn and 6.59 Mg ha^{-1} for fertilized corn grown in rotation with oats and alfalfa. The simulated corn yields at Harrow (5.88 Mg ha-1) were in excellent agreement with these long-term measurements. However, the average 1990-2000 yields from corn hybrid trials reported by Bootsma et al. (2001) were considerable higher than the yields reported by Drury and Tan (1995) and the simulated yields. This was not unexpected, because there have been significant increases in grain yield over the past 30 to 40 years . Dwyer and Tollenaar (1989) suggest that such yield increases may, at least partly, be accounted for by higher leaf net photosynthesis rates. Such genetic improvements of corn hybrids could possibly be mimicked with the EPIC model by increasing the radiation use efficiency.

Compared to average soybean yields from 1996-2000 variety trials (Bootsma et al. 2001), EPIC substantially underestimated the yields using the baseline climate scenario from 1966-1995. But not unlike corn, soybean yields have improved by about 0.5% per year since 1934, with evidence that since 1976 the rate of genetic improvement of seed yield is accelerating (Voldeng et al. 1997). Subsequent work by Morrison et al. (1999; 2000) disclosed that the yield increase was significantly correlated with an increase in number of seeds per plant, harvest index, photosynthesis and stomatal conductance and a decrease in leaf area index and foliar desease index. Such information could be used to make the EPIC model more responsive to new evolving soybean cultivars.

Bootsma, A., Gameda, S. and McKenney, D.W. 2001. Adaptation of agricultural production to climate change in Atlantic Canada. Final Report for Climate Change Action Fund Project A214. http://res2.agr.ca/ecorc/staff/bootsma/report.pdf

Brandt, S.A. and Zentner, R.P. 1995. Crop prodeuction under alternate rotations on a Dark Brown Chernozemic soil at Scott, Saskatchewan. Can. J. Plant Sci. 75: 789-794.

Campbell, C.A., Janzen, H.H. and Juma, N.G. 1997. Case studies of soil quality in the Canadian prairies: long-term field experiments. *In:* E.G. Gregorich and M.R. Carter (eds.) Soil Quality for Crop Production and Ecosystem Health. Developments in Soil Science, Elsevier, Amsterdam.

Campbell, C.A., Zentner, R.P., Janzen, H.H. and Bowren, 1990. K.E. Crop rotation studies on the Canadian prairies. Agric. Canada, Res. Br. Publ. 1841/E, Ottawa, ON.

Drury, C.F. and Tan, C.S. 1995. Long-term (35 years) effects of fertilization, rotation and weather on corn yields. Can. J. Plant Sci. 75: 355-362.

Dwyer, L.M. and Tollenaar, M. 1989. Genetic improvement in photosynthetic response of hybrid maize cultivars, 1959 to 1988. Can. J. Plant Sci. 69: 81-91.

Morrison, M.J., Voldeng, H.D. and Cober, E.R. 1999. Physiological changes from 58 years of genetic improvement of short-season soybean cultivars in Canada. Agron. J. 91: 685-689.

Morrison, M.J., Voldeng, H.D. and Cober, E.R. 2000. Agronomic changes from 58 years of genetic improvement of short-season soubean cultivars in Canada. Agron. J. 92: 780-784.

Voldeng, H.D., Cober, E.R., Hume, D.J., Gillard, C. and Morrison, M.J. 1997. Fifty-eight years of genetic improvement of short-season soybean cultivars in Canada. Crop Sci. 37: 428-431.

Table 1. Agricultural ecoregions with representative climate stations.

Ecoregion		**Climate station**		
Name	**# in Fig.1**	**Name**	**Latitude Longitude (degrees minutes)**	**# in Fig. 2**
Lake Timiskaming Lowland	97	Earlton	47 42 79 51	1
Central Laurentians	101	Normandin[1]	48 51 73 32	2
Appalachians	117	Lennoxville	45 22 71 51	3
		Mont Joli	48 36 68 12	4
Saint John River Valley	120	Fredericton	45 55 66 37	5
Annapolis-Minas Lowlands	126	Kentville	45 04 64 29	6
Prince Edward Island	130	Charlottetown	45 15 63 08	7
St. Lawrence Lowlands	132	St Hyacinthe	45 38 72 57	8
		Kemptville	45 00 75 38	9
Manitoulin -Lake Simcoe	134	Peterborough	44 14 78 21	10
		Brucefield[2]	43 33 81 33	11
Lake Erie Lowland	135	Delhi	42 52 80 33	12
		Harrow	42 02 82 54	13
Peace Lowland	138	Beaverlodge	55 11 119 22	14
Boreal Transition	149	Melfort	52 49 104 36	15
Interlake Plain	155	Arborg	50 55 97 20	16
		Swan River	51 59 101 11	17
Aspen Parkland	156	Brandon	49 52 99 58	18
		Wynyard	51 46 104 12	19
		Camrose[3]	52 57 112 48	20
Moist Mixed Grassland	157	Yellow Grass	49 48 104 10	21
		Biggar	52 04 107 59	22
		Gleichen	50 53 113 03	23
Mixed Grassland	159	Aneroid	49 42 107 18	24
		Alsask	51 21 109 50	25
		Foremost	49 29 111 27	26
Lake Manitoba Plain	162	Winnipeg[4]	49 54 97 14	27
		Dauphin[5]	51 06 100 03	28
Lower Mainland	196	Agassiz	49 15 121 46	29

[1] Normandin weather data end on 31/8/1992; no suitable substitute is available.
[2] Brucefield: 1994 and 1995 weather data from Exeter.
[3] Camrose: from 1/7/1994 to 1995 weather data from Edmonton.
[4] Winnipeg: 1995 weather data from Stony Mountain.
[5] Dauphin: 1995 weather data from Gilbert Plains.

Table 2. Agricultural ecoregions and climate stations with the most common soil and crop rotations.

Ecoregion	**Station**	**Soil**	**Surface**	**Crop rotation**
97	1	New Liskeard	Clay	Wheat-Barley-Barley
101	2	Herbertville	Loam	Wheat-Wheat-Barley Wheat-Potato-Potato
117	3, 4	Du Creux	Loam	Wheat-Barley-Barley
120	5	Caribou	Loam	Wheat-Potato-Potato Wheat-Barley-Potato
126	6	Queens	Loam	W wheat-Potato-Barley
130	7	Charlottetown	Sandy loam	Wheat-Wheat-Potato Wheat-Barley-Potato
132	8, 9	St Rosalie	Clay	Corn-Corn-Soybean Wheat-wheat-Barley
134	10, 11	Harriston	Silty clay loam	Corn-Soybean-Wheat Wheat-Wheat-Barley
135	12, 13	Brookston	Clay loam	Corn-Soybean-W wheat Corn-Soybean-Soybean
138	14	Hubalta	Clay loam	Barley-Fallow-Canola
149	15	Whitewood	Loam	Wheat-Barley-Canola Wheat-Wheat-Barley
155	16, 17	Pelan	Loamy sand	Wheat-Canola-Barley
156	18, 19, 20	Oxbow	Loam	Wheat-Barley-Canola Wheat-Wheat-Barley
157	21, 22, 23	Weyburn	Loam	Wheat-Fallow-Canola Wheat-Wheat-Barley
159	24, 25, 26	Ardill	Loam	Wheat-Wheat-Fallow
162	27, 28	Red River	Clay	Wheat-Canola-Barley
196	29	Whatcom	Silt loam	Wheat-Barley-Potato

Table 3. EPIC crop parameters selected for the study.

Variable	Description	Barley	Spring wheat	Winter wheat	Canola	Corn	Soybean	Potato
WA	Biomass-energy ratio at 340 ppm CO_2 (kg/ha/MJ)	35	28	30	34	40	25	30
RUEC2	2nd point on RUE-CO_2 curve. Number before decimal is high CO_2 level of the future (ppm). Number after the decimal is the resulting RUE value.	680.44	680.35	680.38	680.43	680.44	680.31	680.38
HI	Harvest index (kg/kg)	0.54	0.42	0.4	0.3	0.55	0.3	0.95
TB	Optimal temperature for plant growth (^{0}C)	25	18	18	21	25	25	18
TG	Minimum temperature for plant growth (^{0}C)	0	0	0	5	8	10	7
DMLA	Maximum potential leaf area index	5	5	5	4.5	6.5	5	5
DLAI	Fraction of growing season when leaf area starts declining	0.6	0.58	0.5	0.5	0.7	0.9	0.6
DLAP1	Two points on optimal leaf area development curve (%). Numbers before decimal are percent of growing season. Numbers after decimal are fractions of maximum leaf area index	15.01	20.1	5.05	15.02	15.05	15.01	15.01
DLAP2	As above for DLAP1	45.95	49.95	45.95	45.95	50.95	50.95	50.95
RLAD	Leaf area decline rate parameter	1	1	0.5	0.15	1	1	2
RBMD	Biomass-energy ratio decline rate parameter	1	1	1	0.3	1	1	10
CAF	Critical aeration factor	0.85	0.85	0.85	0.9	0.85	0.85	0.85
HMX	Maximum crop height (m)	1.3	1.2	1.2	0.9	2.3	0.8	0.8
RDMX	Maximum root depth (m)	1.3	1.3	1.3	1.4	2	1.5	1
CVM	Minimum value of C factor for water erosion	0.01	0.03	0.005	0.2	0.2	0.2	0.2
CNY	Fraction of nitrogen in yield (kg/kg)	0.021	0.025	0.025	0.038	0.023	0.065	0.013

CPY	Fraction of phosphorus in yield (kg/kg)	0.0017	0.0022	0.0022	0.0079	0.0016	0.0091	0.002
WCY	Fraction of water in yield (kg/kg)	0.12	0.12	0.12	0.12	0.15	0.13	0.8
PST	Pests (insects, weeds, desease) factor	1	1	1	1	1	1	1
WSYF	Lower limit of harvest index	0.19	0.2	0.2	0.01	0.01	0.22	0.75
IDC	Crop category number (see Williams et al. (1990))	5	5	5	5	4	1	4
BN1	Nitrogen uptake parameter (N fraction in plant at emergence)	0.059	0.0663	0.0663	0.044	0.06	0.0524	0.055
BN2	Nitrogen uptake parameter (N fraction in plant at 0.5 maturity)	0.0226	0.0255	0.0255	0.0164	0.025	0.0265	0.02
BN3	Nitrogen uptake parameter (N fraction in plant at maturity)	0.0131	0.0148	0.0148	0.0128	0.02	0.0258	0.01
BP1	Phosphorus uptake parameter (P fraction in plant at emergence)	0.0057	0.0053	0.0053	0.0074	0.0048	0.0074	0.006
BP2	Phosphorus uptake parameter (P fraction in plant at maturity)	0.0022	0.002	0.002	0.0037	0.0018	0.0037	0.003
BP3	Phosphorus uptake parameter (P fraction in plant at maturity)	0.0013	0.0012	0.0012	0.0023	0.0014	0.0035	0.002
FRST1	Two points on frost damage curve. Numbers before decimal are minimum daily temperature (^{0}C) Numbers after decimal are fractions of yield loss for given minimum temperature	5.001	5.001	15.05	5.05	5.15	5.01	5.01
FRST2	As above for FRST1	15.01	15.01	30.1	15.1	15.95	15.95	15.95

Table 4. A comparison of 31 year averaged predicted and ‘observed’ planting dates (month/day).

Climate station	**Eco region**	**Predicted**		**Observed (from local ‘expert opinion’ (Huffman’s data))**					**Bootsma**
		Cereals	**Corn and soybean**	**Cereals**	**Canola**	**Corn**	**Soybean**	**Potatoes**	**Corn and soybean**
Earlton	97	5/ 7	5/ 27	5/ 10					5/ 27
Normandin	101	5/ 12	6/ 2						6/ 5
Lennoxville	117	5/ 9	5/ 20	5/ 10					5/ 20
Mont Joli	117	5/ 16	6/ 9						6/ 6
Fredericton	120	5/ 7	5/ 19	5/ 10				5/ 20	5/ 17
Kentville	126	5/ 8	5/ 18	5/ 10				5/ 15	5/ 18
Charlottetown	130	5/ 18	5/ 28	5/ 15		5/ 25	5/ 25	5 /15	5/ 25
Quebec	132	5/ 9	5/ 24						5/ 24
St Hyacinthe	132	5/ 6	5/ 16	5/ 5	5/ 5	5/ 15	5/ 25		5/ 12
Kemptville	132	5/ 6	5/ 17	4/ 25	4/ 25	5/ 10	5/ 17		5/ 17
Peterborough	134	5/ 2	5/ 18						5/ 19
Brucefield	134	5/ 4	5/ 15	5/ 5	4/ 25	5/ 20	5/ 25		5/ 16
Guelph	134	5/ 6	5/ 19	5/ 10		5/ 10	5/ 25		5/ 19
Delhi	135	4/ 27	5/ 13	4/ 19		5/ 11	5/ 25	4/ 15	5/ 13
Harrow	135	4/ 26	5/ 7	4/ 19		5/ 11	5/ 25	4/ 15	5/ 8
Beaverlodge	138	5/ 7	6/ 1	5/ 15-30	5/ 22				
Melfort	149	5/ 13	5/ 23	5/ 15-25	5/ 22				
Arborg	155	5/ 12	5/ 27	5/ 13-20	5/ 25				
Swan River	155	5/ 14	5/ 24	5/ 13-20	5/ 25				5/ 11
Brandon	156	5/ 10	5/ 21	5/ 10-20	5/ 20				
Wynyard	156	5/ 9	5/ 24	5/ 10-20	5/ 20				
Vegreville	156	5/ 7	5/ 24	5/ 10-20	5/ 20				5/ 9
Regina	157	5/ 7	5/ 19	5/ 3-6	5/ 7				5/ 6
Biggar	157	5/ 6	5/ 20	5/ 3-6	5/ 7				
Lethbridge	157	5/ 6	5/ 25	5/ 3-6	5/ 7				5/ 5
Aneroid	159	5/ 2	5/ 18	4/ 17-24	5/ 3				
Alsask	159	5/ 1	5/ 20	4/ 17-24	5/ 3				
Foremost	159	5/ 2	5/ 18	4/ 17-24	5/ 3				5/ 2
Winnipeg	162	5/ 9	5/ 15	5/ 3-10	5/ 15				5/ 5
Dauphin	162	5/ 11	5/ 25	5/ 13-20	5/ 25				5/ 9
Agassiz	196	4/ 30	5/ 6			4/ 30		5/ 1	

Table 5. Nitrogen and phosphorus fertilizer application rates (kg N and kg P per ha) by ecoregion and crop as used with EPIC simulation runs.

Ecoregion	**Barley**		**Spring wheat**		**Canola**		**Potato**		**Corn**		**Soybean**		**Winte wheat**	
	N	*P*	*N*	*P*	*N*	*P*	*N*	*P*	*N*	*P*	*N*	*P*	*N*	*P*
97	70	10	70	10	80	10	100	75	110	20	0	10	85	10
101	70	15	90	15	80	20	135	70					90	15
117	70	15	90	15	80	20	135	70	120	25	5	25	90	15
120	75	50	75	50	90	15	135	60	130	20	10	25	100	30
126	75	50	75	50	90	15	135	60	130	20	10	25	100	30
130	75	50	75	50	90	15	135	60	130	20	10	25	100	30
132	45	10	70	10	100	10	120	75	130	20	0	10	85	10
134	45	10	70	10	100	10	120	75	185	20	0	10	85	10
135	45	10	70	10	100	10	120	75	185	20	0	10	85	10
138	75	12	75	12	80	15	70	20	100	15	0	15	100	15
149	80	15	80	15	85	20	70	20	100	15	0	15	100	15
155	80	15	90	15	90	20	85	25	110	15	0	15	105	15
156	70	15	70	15	75	20	70	20	100	15	0	15	100	15
157	45	15	45	15	45	20			80	15				
159	30	15	30	15	25	20			60	15				
162	80	15	90	15	90	20	85	25	110	15	0	15	105	15
196	80	15	80	15			70	60	120	20	0	20	100	20

Table 6. Tillage dates and operations as used in the EPIC simulation runs.

Crop	**Date**	**Tillage**	**EPIC tillage code**
Barley Wheat Canola Soybean	Planting - 7	Field cultivator[1]	20322531010514130
	Planting - 2	Sweep chisel	
	Planting - 2	Harrow	
	Planting	Drill planter	
	Planting	N spreader	
	Planting	P spreader	
	Harvest	Harvester	
	Harvest	Kill	
	Harvest + 14	Moldboard plow[1]	
Corn	Planting - 7	Field cultivator[1]	20182521010514130
	Planting - 2	Culti packer	
	Planting - 2	Harrow	
	Planting	Row planter	
	Planting	N spreader	
	Planting	P spreader	
	Harvest	Harvester	
	Harvest	Kill	
	Harvest + 14	Moldboard plow[1]	
Potato	Planting - 7	Tandem disk	2.93025210102e+20
	Planting - 2	Point chisel	
	Planting - 2	Harrow	
	Planting	Row planter	
	Planting	N spreader	
	Planting	P spreader	
	Planting + 14	Row cultivator	
	Planting + 28	Potato hiller	
	Harvest	Potato harvester	
	Harvest	Kill	
	Harvest + 14	Moldboard plow[1]	
Winter wheat	Planting - 7	Moldboard plow[1]	2.81825310101e+20
	Planting - 2	Culti packer	
	Planting - 2	Harrow	
	Planting	Drill planter	
	Planting	N spreader (20% of N)	
	Planting	P spreader (20% of P)	
	May 1	N spreader (80% of N)	
	May 1	P spreader (80% of P)	
	Harvest	Harvester	
	Harvest	Kill	
	Harvest + 28	Moldboard plow[1]	
Fallow	June 15	Noble blade	242424
	July 15	Noble blade	
	August 15	Noble blade	

[1] On the Prairies use a noble blade (24).

Table 7. Increase in monthly and annual mean temperature (^{0}C) as a result of the 2xCO_2 scenario.

	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Year**
Earlton	3.4	6.1	2.6	0.6	1.9	2.2	1.9	1.5	2.0	2.5	2.2	1.1	2.3
Normandin	3.3	4.1	2.5	1.4	1.8	2.2	2.1	1.6	1.8	2.2	1.7	1.8	2.2
Lennoxville	3.1	4.5	2.7	1.9	1.6	2.3	2.0	1.7	2.0	2.0	2.0	0.5	2.2
Mont Joli	3.0	4.0	3.0	2.1	2.3	2.3	2.0	1.4	1.9	2.0	1.5	1.8	2.3
Fredericton	2.0	4.2	2.3	2.6	1.8	2.2	1.8	1.4	2.1	1.9	1.6	0.9	2.1
Kentville	1.8	3.1	2.3	2.8	1.6	1.9	1.6	1.4	1.9	1.8	1.5	1.4	1.9
Charlottetown	2.0	3.4	2.7	3.4	1.7	2.1	1.8	1.5	2.1	2.1	1.5	1.5	2.2
Kemptville	3.2	5.5	2.8	1.8	1.7	2.3	2.0	1.8	2.0	2.4	2.2	0.6	2.4
St Hyacinthe	3.1	4.7	2.8	1.9	1.7	2.3	1.9	1.6	2.0	2.1	2.0	0.4	2.2
Peterborough	3.4	6.3	3.2	2.3	1.8	2.3	2.0	1.8	2.0	2.4	2.3	1.0	2.6
Brucefield	3.6	6.5	3.9	1.8	2.0	2.4	2.0	1.8	2.1	2.5	2.5	1.4	2.7
Harrow	3.6	6.2	4.3	1.7	1.9	2.4	2.1	2.0	2.2	2.5	2.5	1.6	2.7
Delhi	3.7	6.5	3.8	2.2	1.9	2.4	2.0	1.9	2.1	2.4	2.5	1.4	2.7
Beaverlodge	4.1	3.2	2.5	1.8	4.0	2.4	1.8	1.7	1.9	1.5	1.1	2.3	2.4
Melfort	3.8	4.5	2.4	2.2	2.8	2.8	1.9	2.3	2.6	1.8	1.5	3.7	2.7
Arborg	5.1	5.3	3.4	5.3	2.6	3.1	2.8	3.3	3.1	2.3	1.5	3.7	3.4
Swan River	4.0	5.1	3.2	3.0	2.6	3.0	2.3	2.8	2.8	2.1	1.6	3.5	3.0
Brandon	4.8	6.1	4.8	5.3	2.7	3.0	2.9	3.4	3.1	2.5	1.7	3.2	3.6
Wynyard	4.2	5.3	3.8	3.6	2.8	2.9	2.5	2.9	2.8	2.2	1.6	3.2	3.2
Camrose	4.7	3.9	3.0	4.4	5.1	2.3	1.8	1.8	2.0	1.8	1.3	2.1	2.8
Yellow Grass	4.6	6.0	5.2	5.1	2.9	3.0	2.9	3.3	2.9	2.7	1.7	2.5	3.6
Biggar	4.3	5.0	3.8	4.2	3.4	2.6	2.1	2.4	2.5	2.1	1.6	2.4	3.0
Gleichen	2.9	4.1	3.8	4.5	3.5	2.3	2.0	2.0	2.0	2.3	1.3	1.2	2.7
Aneroid	3.4	5.3	4.5	4.8	3.2	2.7	2.5	2.9	2.7	2.6	1.6	1.9	3.2
Alsask	3.6	4.7	3.9	4.6	3.6	2.5	2.1	2.3	2.3	2.3	1.5	1.6	2.9
Foremost	2.8	4.5	4.3	4.8	3.4	2.5	2.2	2.3	2.2	2.5	1.5	1.3	2.8
Winnipeg	5.3	5.5	3.8	6.2	2.6	3.1	2.9	3.5	3.2	2.4	1.5	3.7	3.6
Dauphin	4.6	5.6	4.1	4.5	2.7	3.1	2.8	3.3	3.1	2.3	1.5	3.5	3.4
Agassiz	1.4	2.0	2.0	2.8	2.4	2.5	1.6	1.3	2.1	2.0	1.4	1.5	1.9

Table 8. Changes in monthly and annual mean precipitation (mm) as a result of the 2xCO_2 scenario.

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Earlton	14.7	5.8	14.4	1.9	8.9	-2.8	-4.8	-5.6	-2.8	7.1	7.3	-4.2	39.9
Normandin	2.3	4.8	7.4	5.9	13.0	-8.6	-0.2	-4.1	-3.8	3.1	0.8	-9.4	11.0
Lennxville	13.9	2.5	-0.2	7.5	16.1	-3.7	-25.1	-3.6	1.4	-11.0	4.4	3.3	5.4
Mont Joli	-1.6	0.6	4.8	5.8	12.4	-2.0	-7.6	0.7	-3.7	9.9	-2.5	-8.5	8.3
Fredericton	15.7	9.4	3.0	6.7	1.8	9.1	-22.9	-10.4	-3.2	1.5	-16.9	7.9	1.7
Kentville	13.5	17.9	7.5	3.8	-0.1	13.5	-18.3	-6.7	-0.2	1.4	-22.7	3.5	13.1
Charlottetown	11.8	18.8	10.9	4.7	0.6	21.3	-19.8	-6.1	0.8	6.3	-26.5	8.1	30.8
Kemptville	11.6	2.1	5.0	10.7	18.0	-0.9	-13.5	-6.4	-3.1	-5.2	9.3	-3.4	24.1
St Hyacinthe	15.5	1.6	0.5	8.3	16.4	-4.8	-22.3	-3.2	0.1	-9.3	7.5	1.5	12.0
Peterborough	8.4	7.1	8.6	11.1	12.8	7.9	-4.5	-12.7	-1.1	-5.6	7.3	-3.4	36.0
Brucefield	17.6	6.9	18.5	11.0	5.7	9.5	3.4	-9.7	9.4	0.6	21.5	-10.4	84.1
Harrow	9.7	5.2	19.7	10.5	3.1	8.8	10.6	-10.4	13.9	-0.7	20.0	-11.6	78.7
Delhi	11.8	8.1	19.1	14.6	8.3	13.2	2.5	-14.2	5.5	-4.9	17.1	-7.4	73.7
Beaverlodge	0.8	1.5	3.5	4.0	14.4	-4.5	-11.7	7.8	8.0	5.8	3.2	2.9	36.0
Melfort	1.2	-0.2	6.2	23.3	3.6	14.4	-17.1	1.9	-2.0	6.0	2.1	1.5	40.9
Arborg	-0.8	0.9	-0.6	6.9	1.8	-0.7	-9.9	-20.9	13.4	16.6	1.6	0.0	8.3
Swan River	0.2	0.3	7.8	22.9	2.9	15.5	-23.0	-7.7	1.6	8.5	3.5	2.4	34.9
Brandon	-0.4	0.6	2.6	20.6	-0.7	-1.4	-19.4	-15.6	16.8	11.2	4.5	1.2	20.2
Wynyard	0.4	-0.3	4.9	23.2	0.7	2.5	-20.6	-2.6	4.4	4.9	2.8	1.2	21.5
Camrose	2.7	-1.5	1.6	6.4	3.1	3.4	1.4	26.8	-4.3	8.8	1.8	3.0	53.3
Yellow grass	0.2	-1.1	3.7	38.0	-3.4	-13.9	-23.8	-3.8	14.1	0.2	3.2	0.6	14.1
Biggar	0.5	-1.0	3.5	17.5	5.0	-3.9	-11.1	-1.6	0.8	1.2	2.1	0.5	13.4
Gleichen	-2.0	0.3	-0.3	-1.8	6.4	-3.0	-0.8	-5.8	-3.0	3.4	0.6	1.2	-4.7
Aneroid	-1.0	-0.7	2.4	17.8	11.0	-10.1	-16.0	-8.7	4.0	-2.4	2.9	0.5	-0.3
Alsask	-0.8	-0.5	1.0	6.8	7.4	-5.2	-8.0	-5.6	-0.5	0.3	1.2	0.6	-3.4
Foremost	-3.4	1.1	-0.2	0.1	9.5	-5.1	-4.7	-10.4	-1.2	1.7	0.8	0.8	-10.8
Winnipeg	-1.0	0.8	-0.5	6.9	2.0	0.5	-11.2	-22.2	16.8	16.5	1.8	0.2	10.5
Dauphin	-0.4	0.4	2.6	15.1	-0.2	3.5	-18.7	-14.4	15.9	14.9	4.4	0.9	24.1
Agassiz	-16.4	25.4	-0.7	-8.2	-24.0	-9.5	-0.5	-2.1	45.1	44.5	40.8	46.2	140.5

Table 9. Simulated 30-year mean planting date, growing season length and stress variables temperature, water, and nitrogen for barley.

Station	**Planting date**		**Growing Season**		**Temperature stress**		**Water stress**		**Nitrogen stress**	
	Historic	$2xCO_2$	Historic	$2xCO_2$	Historic	$2xCO_2$	Historic	$2xCO_2$	Historic	$2xCO_2$
	(day of year)		(days)							
Earlton	127	124	91	87	11	8	0	0	14	19
Normandin	133	128	89	84	11	8	4	7	10	13
Lennoxville	129	116	83	86	7	7	4	5	12	16
Mont Joli	136	130	88	81	10	8	3	7	11	13
Fredericton	127	116	88	87	9	9	0	0	17	21
Kentville	129	116	85	86	8	10	3	3	15	19
Charlottetown	139	119	82	89	9	11	0	0	11	17
Kemptville	126	113	82	85	2	2	15	17	7	10
St Hyacinthe	127	118	79	81	1	1	9	13	6	10
Peterborough	123	108	87	90	7	9	8	10	21	23
Brucefield	124	110	85	86	6	8	7	7	22	25
Harrow	117	94	82	95	7	10	9	12	13	19
Delhi	117	100	87	93	8	10	13	13	15	20
Beaverlodge	128	119	94	85	16	7	3	3	8	15
Melfort	134	126	87	78	12	6	15	16	2	4
Arborg	133	117	85	85	10	9	14	20	2	4
Swan River	134	122	86	82	10	7	15	18	2	4
Brandon	130	109	88	91	8	9	19	33	4	2
Wynyard	129	115	87	84	10	9	13	16	6	6
Camrose	129	114	89	85	12	6	6	10	9	12
Yellow Grass	127	103	91	92	7	9	26	33	8	5
Biggar	127	110	88	86	8	8	20	25	9	8
Gleichen	127	100	94	98	9	9	37	45	4	3
Aneroid	123	98	96	97	8	8	38	42	8	7
Alsask	122	102	93	93	7	5	49	57	1	0
Foremost	123	99	93	95	8	8	34	37	9	10
Winnipeg	130	113	82	85	9	9	11	22	1	2
Dauphin	132	113	87	88	11	10	16	21	1	2
Agassiz	120	90	91	94	8	8	13	14	10	15
Average	**127.6**	**111.7**	**87.5**	**87.9**	**8.6**	**8**	**13.8**	**17.5**	**8.9**	**11.1**

Table 10. Simulated 30-year mean barley yields and standard deviations for 29 stations, using the soils as listed in table 2.

Station	**Baseline scenario (Mg ha^{-1})**		**$2xCO_2$ scenario (Mg ha-1)**	
	Mean	**St. dev.**	**Mean**	**St. dev.**
Earlton	4.39	0.28	4.56 *	0.29
Normandin	4.56	0.43	4.6	0.48
Lennoxville	4.04	0.44	4.08	0.51
Mont Joli	3.79	0.25	3.67	0.56
Fredericton	3.89	0.29	3.98 *	0.28
Kentville	3.6	0.37	3.75 *	0.42
Charlottetown	3.67	0.45	4.00 *	0.5
Kemptville	2.92	0.56	2.91	0.76
St Hyacinthe	2.89	0.41	2.92	0.66
Peterborough	2.82	0.33	2.77	0.44
Brucefield	2.68	0.37	2.6	0.39
Harrow	2.96	0.4	2.94	0.51
Delhi	2.93	0.55	2.93	0.52
Beaverlodge	4.61	0.56	4.86 *	0.63
Melfort	4.17	1.25	4.23	1.52
Arborg	4.16	0.84	3.89	1.46
Swan River	4.21	0.93	4.11	1.28
Brandon	3.96	1.47	3.34 *	1.45
Wynyard	4.16	0.84	4.16	1.16
Camrose	4.47	0.54	4.69	0.79
Yellow Grass	2.96	1.53	2.69	1.56
Biggar	3.08	1.11	3.03	1.24
Gleichen	2.78	1.33	2.57	1.76
Aneroid	2	1.41	1.95	1.59
Alsask	1.84	1.78	1.64	1.54
Foremost	2.1	1.09	2.2	1.44
Winnipeg	4.44	1.06	4.33	1.49
Dauphin	4.46	0.77	4.36	1.41
Agassiz	3.89	0.68	3.81	0.73
Average	**3.53**	**0.77**	**3.5**	**0.94**

* Significantly different at the 0.05 probability level

Table 11. Simulated 30-year mean growing season length and stress variables temperature, water, and nitrogen for spring wheat.

Station	**Growing season length**		**Temperature stress**		**Water stress**		**Nitrogen stress**	
	Historic	2xCO2	Historic	2xCO 2	Historic	2xCO 2	Historic	2xCO 2
	(days)							
Earlton	111	101	6	5	0	0	23	25
Normandin	114	102	7	5	12	18	3	5
Lennoxville	101	98	3	5	7	10	13	15
Mont Joli	111	99	5	4	7	14	14	14
Fredericton	104	101	4	5	0	0	20	24
Charlottetown	105	105	4	6	0	0	20	24
Kemptville	98	97	1	2	29	27	4	6
St Hyacinthe	94	92	1	2	20	21	3	5
Peterborough	105	103	4	6	28	25	2	6
Brucefield	103	101	4	5	23	19	5	8
Melfort	103	93	5	3	36	33	0	0
Arborg	104	98	5	7	31	33	2	3
Swan River	100	93	5	5	29	27	2	3
Brandon	99	97	4	8	34	38	0	1
Wynyard	104	97	5	6	32	31	0	1
Camrose	109	102	5	3	19	24	2	5
Yellow Grass	101	102	5	8	42	43	0	2
Biggar	104	100	4	5	45	43	0	1
Gleichen	110	111	4	4	59	67	0	0
Aneroid	105	106	7	9	37	38	7	7
Alsask	106	104	5	6	43	48	3	2
Foremost	105	107	5	6	37	40	8	9
Winnipeg	97	94	5	8	24	29	0	0
Dauphin	102	98	5	8	31	30	0	0
Agassiz	105	111	3	4	26	27	14	19
Average	**103.9**	**100.4**	**4.4**	**5.3**	**26.1**	**27.4**	**5.8**	**7.4**

Table 12. Simulated 30-year mean spring wheat yields and standard deviations for 29 stations, using the soils as listed in table 2.

Station	**Baseline scenario (Mg ha-1)**		**2xCO2 scenario (Mg ha-1)**	
	Mean	**St. dev.**	**Mean**	**St. dev.**
Earlton	3.2	0.2	3.27 *	0.21
Normandin	4.21	0.72	4.04*	0.87
Lennoxville	3.2	0.55	3.19	0.53
Mont Joli	3.13	0.39	2.87*	0.69
Fredericton	3.13	0.25	3.18 *	0.25
Charlottetown	2.86	0.18	2.96 *	0.37
Kemptville	2.16	0.57	2.23	0.69
St Hyacinthe	2.26	0.45	2.34	0.6
Peterborough	3.23	0.89	3.78	1.05
Brucefield	3.01	0.81	3.18	0.83
Melfort	2.69	1.43	2.86	1.47
Arborg	2.74	0.92	2.43	1.06
Swan River	2.83	0.92	2.72	1.02
Brandon	2.73	1.32	2.28 *	1.21
Wynyard	2.95	1.22	3.05	1.29
Camrose	3.79	1.02	3.79	1.14
Yellow Grass	2.26	1.63	1.87	1.16
Biggar	2.25	1.2	2.31	1.3
Gleichen	1.66	1.19	1.36	1.06
Aneroid	1.95	0.85	1.72	0.85
Alsask	2.15	1.14	1.89	1.11
Foremost	1.91	0.82	1.99	0.89
Winnipeg	3.26	1.03	2.97	1.14
Dauphin	3.09	0.95	3.14	1.24
Agassiz	2.39	0.64	2.35	0.65
Average	**2.76**	**0.85**	**2.69**	**0.91**

* Significantly different at the 0.05 probability level

Table 13. Simulated 30-year mean stress variables temperature, water, and nitrogen for canola.

Station	**Temperature stress**		**Water stress**		**Nitrogen stress**	
	Historic	2xCO$_2$	Historic	2xCO$_2$	Historic	2xCO$_2$
Beaverlodge	25	11	13	16	0	0
Melfort	12	6	24	26	0	0
Arborg	11	10	25	29	0	0
Swan River	11	7	25	25	0	0
Brandon	8	10	25	31	0	0
Wynyard	12	9	24	24	0	0
Camrose	17	8	12	18	0	0
Yellow Grass	10	11	27	30	0	0
Biggar	12	9	27	28	0	0
Gleichen	14	13	33	36	0	0
Winnipeg	9	9	21	25	0	0
Dauphin	10	10	30	27	0	0
Average	**12.5**	**9.5**	**24**	**26.3**	**0**	**0**

Table 14. Simulated 30-year mean canola yields and standard deviations for 12 stations, using the soils as listed in table 2.

Station	**Baseline scenario (Mg ha-1)**		**$2xCO_2$ scenario (Mg ha-1)**	
	Mean	**St. dev.**	**Mean**	**St. dev.**
Beaverlodge	2.98	0.69	3.71 *	0.92
Melfort	2.44	0.99	2.61	1.25
Arborg	2.23	0.81	2	1
Swan River	2.32	0.88	2.35	0.98
Brandon	2.37	1.08	1.99 *	1.11
Wynyard	2.49	0.92	2.65	1.12
Camrose	3.21	0.68	3.79 *	1.06
Yellow Grass	2.18	1.06	1.87 *	0.97
Biggar	2.39	0.86	2.53	0.87
Gleichen	2.11	0.9	2.2	1
Winnipeg	2.55	0.84	2.52	1.01
Dauphin	2.21	0.93	2.51 *	1.06
Average	**2.46**	**0.89**	**2.56**	**1.03**

* Significantly different at the 0.05 probability level

Table 15. Simulated 30-year mean planting date, growing season length and stress variables temperature, water, and nitrogen for corn.

Station	**Planting date**		**Growing season length**		**Temperature stress**		**Water stress**		**Nitrogen stress**	
	Historic	2xCO2	Historic	2xCO$_2$	Historic	2xCO$_2$	Historic	2xCO$_2$	Historic	2xCO$_2$
	(day of year)		(days)							
Kemptville	138	129	131	153	12	8	39	64	1	0
St Hyacinthe	136	128	140	159	12	9	34	57	0	2
Peterborough	139	127	125	147	18	14	28	52	3	5
Brucefield	136	129	141	162	19	16	27	46	10	14
Harrow	128	121	161	179	16	15	46	60	7	9
Delhi	134	125	144	166	16	13	45	65	3	6
Average	**135.2**	**126.5**	**140.3**	**161**	**15.5**	**12.5**	**36.5**	**57.3**	**4**	**6**

Table 16. Simulated 30-year mean corn yields and standard deviations for 6 stations, using the soils as listed in table 2.

Station	**Baseline scenario (Mg ha-1)**		**2xCO$_2$ scenario (Mg ha-1)**	
	Mean	**St. dev.**	**Mean**	**St. dev.**
Kemptville	4.82	1.82	4.28 *	1.87
St Hyacinthe	5.14	1.47	4.79 *	1.88
Peterborough	6.12	1.76	5.19 *	2.01
Brucefield	6.32	1.4	5.46 *	2.01
Harrow	5.88	2.25	5.40 *	2.35
Delhi	5.63	1.7	4.90 *	1.81
Average	**5.65**	**1.73**	**5.01**	**1.99**

* Significantly different at the 0.05 probability level

Table 17. Simulated 30-year mean stress variables temperature, water, and nitrogen for soybean.

Station	**Temperature stress**		**Water stress**		**Nitrogen stress**	
	Historic	2xCO2	Historic	2xCO$_2$	Historic	2xCO$_2$

	(days)					
Kemptville	15	11	30	52	0	0
St Hyacinthe	15	12	27	48	0	0
Peterborough	24	18	19	43	0	0
Brucefield	26	24	19	38	0	0
Harrow	15	12	30	45	0	0
Delhi	16	12	29	45	0	0
Average	**18.5**	**14.8**	**25.7**	**45.2**	**0**	**0**

Table 18. Simulated 30-year mean soybean yields and standard deviations for 6 stations, using the primary soils as listed in table 2.

Station	**Baseline scenario (Mg ha-1)**		**2xCO_2 scenario (Mg ha-1)**	
	Mean	**St. dev.**	**Mean**	**St. dev.**
Kemptville	1.64	0.56	1.76 *	0.76
St Hyacinthe	1.8	0.47	1.92 *	0.83
Peterborough	2.15	0.52	2.36 *	0.69
Brucefield	2.31	0.47	2.69 *	0.87
Harrow	2.09	0.76	2.38 *	1.01
Delhi	1.92	0.56	2.20 *	0.79
Average	**1.99**	**0.56**	**2.23**	**0.83**

* Significantly different at the 0.05 probability level

Table 19. Simulated 30-year mean planting date, growing season length and stress variables temperature, water, and nitrogen for potatoes and winter wheat.

Station	**Planting date**		**Growing season length**		**Temperature stress**		**Water stress**		**Nitrogen stress**	
	Historic	2xCO2	Historic	2xCO$_2$	Historic	2xCO$_2$	Historic	2xCO$_2$	Historic	2xCO$_2$
	(day of year)		(days)							
Potatoes										
Normandin	133	128	131	143	21	18	4	13	0	2
Fredericton	127	116	125	140	12	14	7	20	2	6
Kentville	129	116	121	137	11	12	14	27	2	6
Charlottetown	139	119	120	139	13	15	0	0	1	6
Agassiz	120	90	121	136	9	9	31	32	13	20
Average	**129.5**	**113.6**	**123.5**	**139.2**	**13.3**	**13.9**	**11.2**	**18.4**	**3.4**	**7.9**
Winter wheat										
Kentville	265	274	319	293	109	88	8	4	16	23
Harrow	268	274	295	276	95	75	19	17	3	10
Delhi	262	268	309	286	102	81	24	18	3	16
Average	**264.8**	**272.1**	**307.8**	**284.9**	**102**	**81.3**	**17.1**	**13.4**	**7.1**	**16.4**

Table 20. Simulated 30-year mean potato and winter wheat yields and standard deviations.

Station	**Baseline scenario (Mg ha-1)**		**$2xCO_2$ scenario (Mg ha-1)**	
	Mean	**St. dev.**	**Mean**	**St. dev.**
Potatoes				
Normandin	7.45	0.66	9.71*	0.97
Fredericton	7.92	0.75	8.89 *	0.97
Kentville	6.72	0.96	7.45 *	1.36
Charlottetown	6.76	0.66	8.33 *	0.69
Agassiz	4.83	1.04	4.9	1.04
Average	**6.74**	**0.81**	**7.86**	**1.01**
Winter Wheat				
Kentville	3.56	0.48	4.20 *	0.47
Harrow	3.52	0.73	4.22 *	0.92
Delhi	3.55	0.8	4.17 *	0.92
Average	**3.54**	**0.67**	**4.19**	**0.77**

* Significantly different at the 0.05 probability level

Table 21. Crop heat units for corn and soybeans and growing degree days for cotton and peanuts calculated for the 1965-1995 baseline and the 2xCO2 climate scenario.

Station	**CHU's**		**GDD, cotton**		**GDD, peanuts**	
	Baseline scenario	**2xCO$_2$ scenario**	**Baseline scenario**	**2xCO2 scenario**	**Baseline scenario**	**2xCO2 scenario**
Earlton	1887 ±170	2445 ±130	719 ±105	933 ±111	372 ±85	567 ±96
Normandin	1663 ±157	2189 ±144	610 ±88	861 ±92	296 ±68	475 ±77
Lennoxville	2483 ±121	3065 ±131	966 ±67	1276 ±83	541 ±61	782 ±69
Mont Joli	1735 ±181	2350 ±145	609 ±96	875 ±96	296 ±71	478 ±80
Fredericton	2460 ±146	3077 ±150	922 ±81	1217 ±83	495 ±66	717 ±70
Kentville	2675 ±124	3261 ±180	976 ±78	1258 ±94	527 ±68	737 ±77
Charlottetown	2321 ±149	2905 ±156	802 ±75	1076 ±81	410 ±57	610 ±64
Kemptville	2699 ±131	3315 ±141	1082 ±88	1420 ±105	634 ±77	898 ±89
St Hyacinthe	2955 ±149	3551 ±159	1170 ±90	1509 ±104	704 ±77	973 ±84
Peterborough	2491 ±134	3111 ±152	984 ±97	1336 ±117	547 ±85	814 ±102
Brucefield	2796 ±191	3416 ±196	1084 ±113	1447 ±135	620 ±96	907 ±113
Harrow	3562 ±189	4208 ±245	1453 ±108	1870 ±135	921 ±91	1268 ±111
Delhi	3017 ±143	3647 ±186	1215 ±93	1600 ±110	729 ±79	1037 ±92
Beaverlodge	1382 ±195	2175 ±157	477 ±93	791 ±93	180 ±57	363 ±74
Melfort	1851 ±210	2540 ±196	700 ±125	1034 ±132	351 ±90	599 ±111
Arborg	1922 ±203	2704 ±196	732 ±122	1172 ±142	385 ±95	720 ±126
Swan River	1977 ±211	2659 ±194	769 ±124	1145 ±137	402 ±96	698 ±117
Brandon	2105 ±197	2912 ±192	871 ±134	1352 ±151	480 ±110	857 ±135
Wynyard	1923 ±220	2688 ±197	743 ±120	1143 ±123	384 ±89	688 ±107
Camrose	1756 ±140	2673 ±143	623 ±81	1029 ±90	274 ±58	534 ±71
Yellow Grass	2055 ±216	2849 ±196	887 ±128	1369 ±140	489 ±103	865 ±123
Biggar	1960 ±152	2728 ±166	771 ±100	1161 ±103	397 ±78	684 ±90
Gleichen	1691 ±145	2484 ±151	685 ±94	1068 ±108	324 ±68	579 ±85
Aneroid	1981 ±179	2725 ±167	879 ±122	1335 ±135	478 ±97	823 ±117
Alsask	1933 ±140	2729 ±155	807 ±104	1225 ±119	420 ±83	720 ±100
Foremost	2060 ±156	2889 ±148	868 ±104	1301 ±113	460 ±84	768 ±98
Winnipeg	2307 ±226	3151 ±222	932 ±143	1449 ±172	534 ±119	942 ±154
Dauphin	1986 ±201	2732 ±174	789 ±126	1227 ±135	423 ±97	766 ±122
Agassiz	2984 ±220	3947 ±282	1015 ±98	1435 ±127	492 ±71	783 ±94

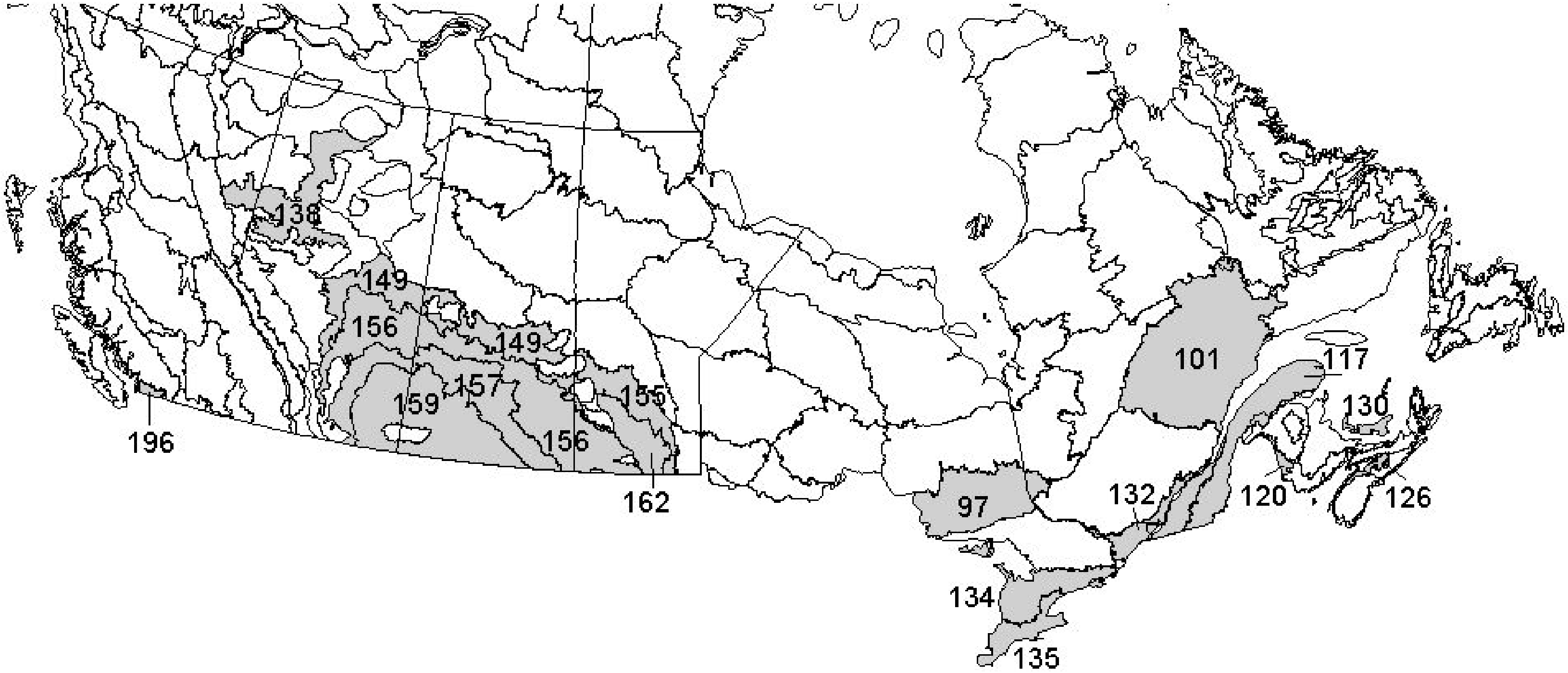

Figure 1. Location of ecoregions used in the study. Ecoregion numbers and names are linked in Table 1.

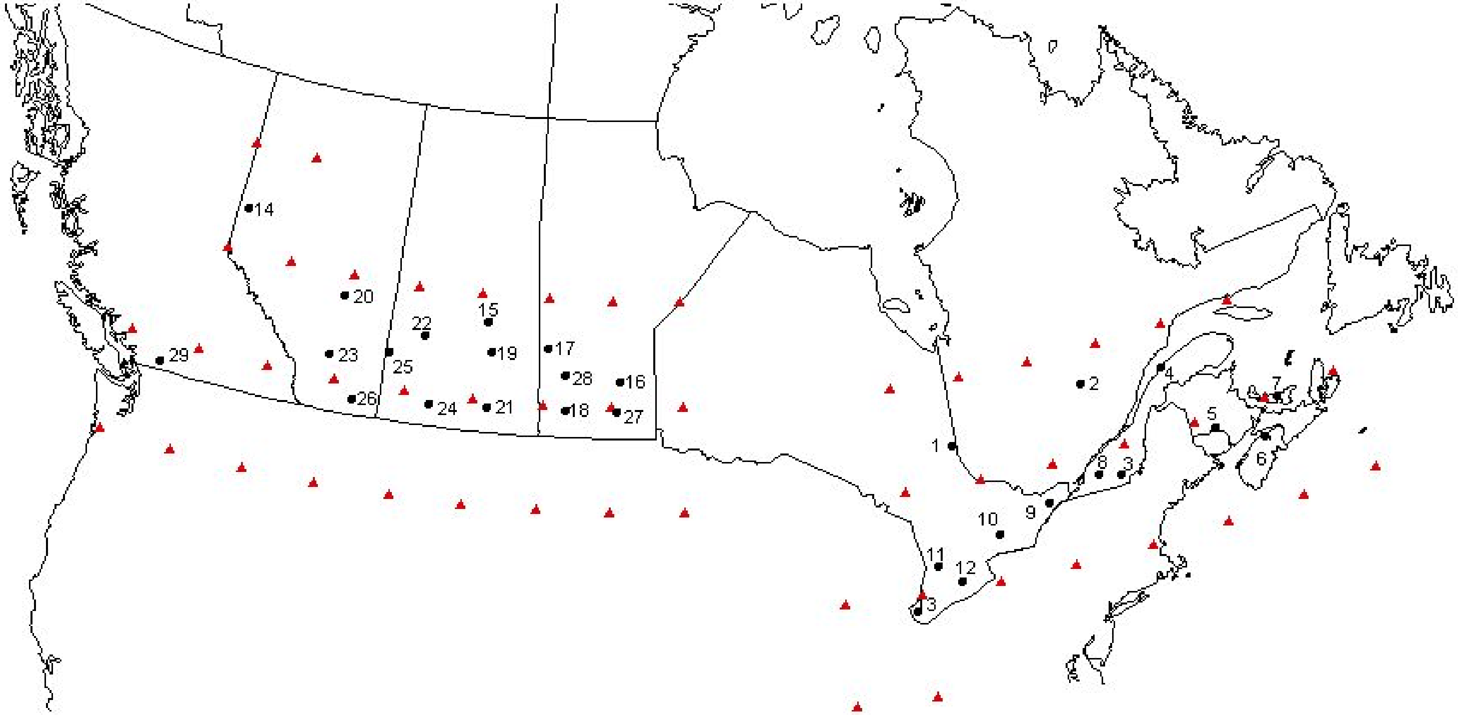

Figure 2. Location of climate stations and GCM gridpoints in study area. Climate station numbers and names are linked in Table 1.

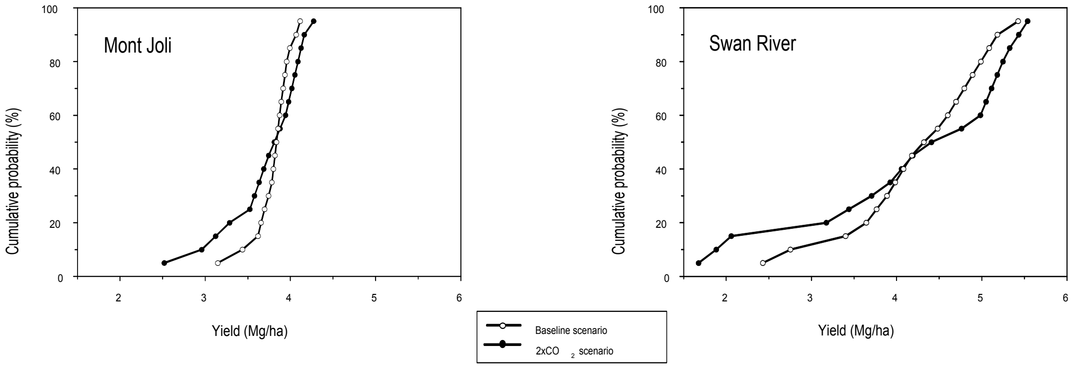

Figure 3. Temporal variability of simulated barley yields using the 1965 - 1995 baseline and the $2xCO_2$ climate scenario at Mont Joli and Swan River.

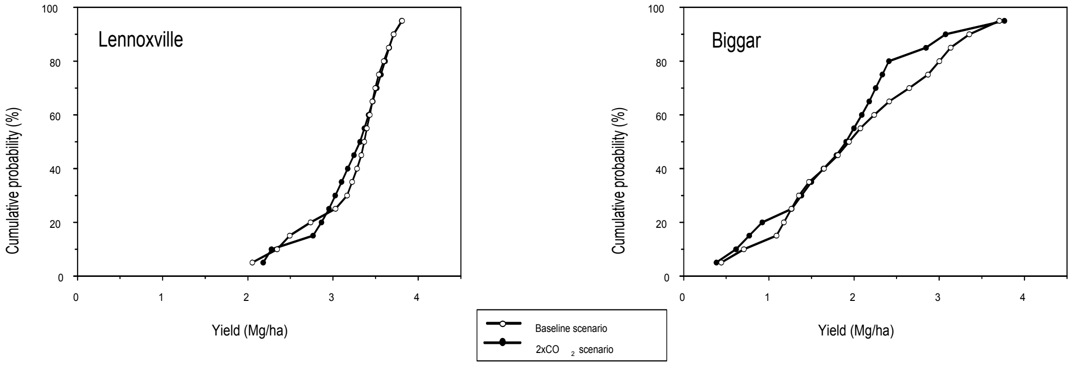

Figure 4. Temporal variability of simulated spring wheat yields using the 1965 - 1995 baseline and the $2xCO_2$ climate scenario at Lennoxville and Biggar.

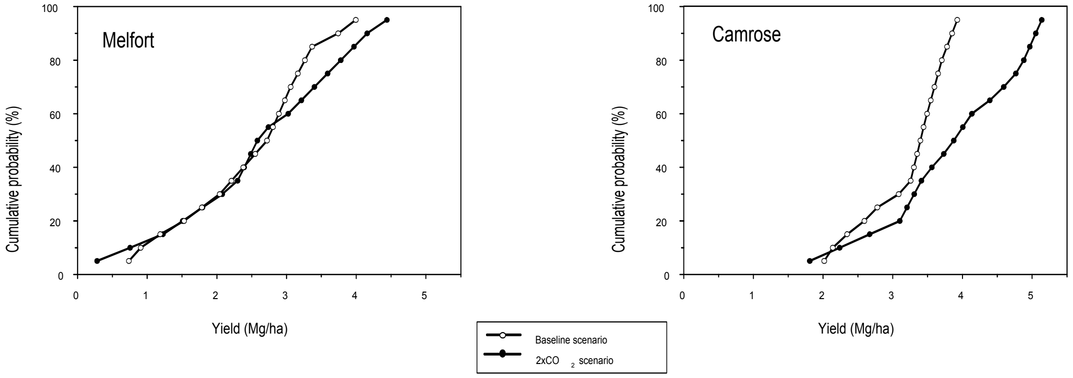

Figure 5. Temporal variability of simulated canola yields using the 1965 - 1995 baseline and the $2xCO_2$ climate scenario at Melfort and Camrose.

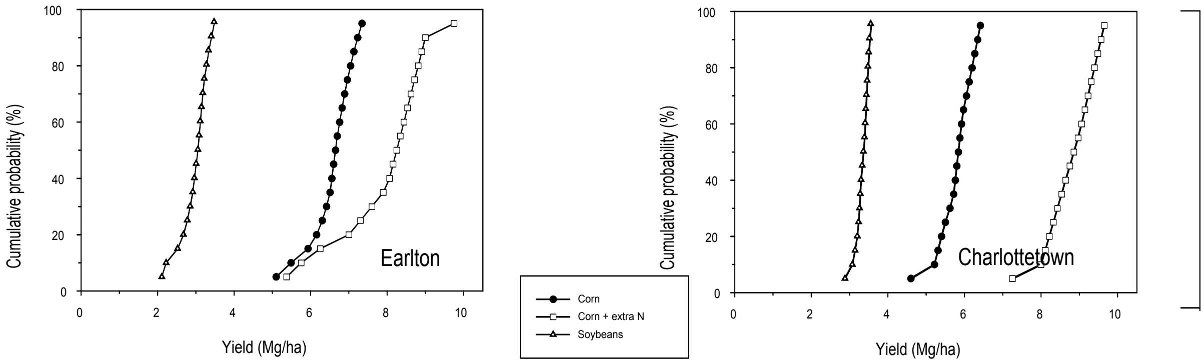

Figure 8. Cumulative probability functions of simulated corn and soybean yields using the 2xCO$_2$ climate scenario at Earlton and Charlottetown.

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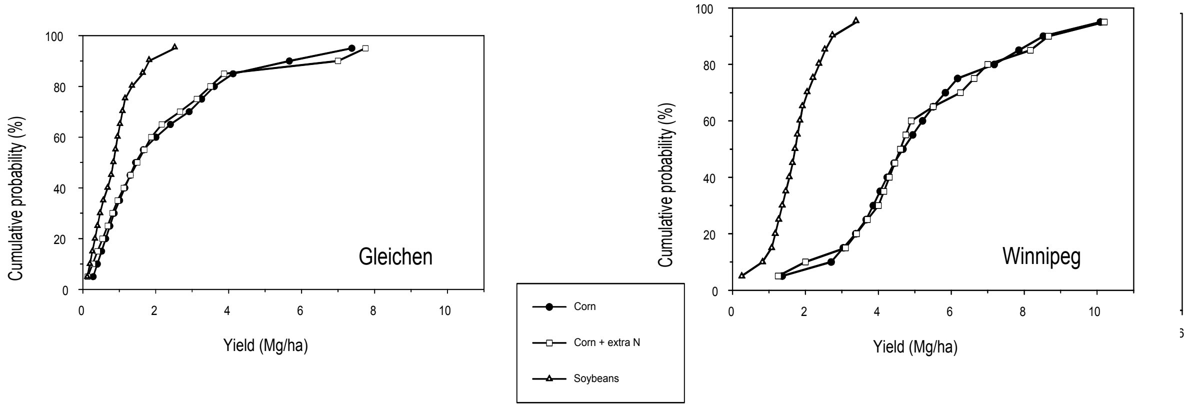

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Figure 9. Cumulative probability functions of simulated corn and soybean yields using the 2xCO$_2$ climate scenario at Gleichen and Winnipeg.

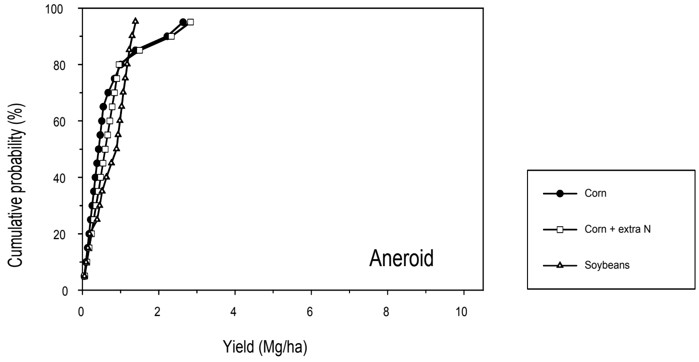

Figure 10. Cumulative probability functions of simulated corn and soybean yields using the 2xCO$_2$ climate scenario at Aneroid.