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# Effects of climate change and $CO_2$ increase on potential agricultural production in Southern Québec, Canada

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ABSTRACT: We assessed the effect of greenhouse gas-induced climate change, as well as the direct fertilization effect of $CO_2$, on crop yields in Québec, Canada. Our methodology coupled the transient diagnostics of 2 Atmosphere–Ocean General Circulation Models (CGCM1 and HadCM3) to the DSSAT 3.5 crop simulation system to simulate current (1961–1990) and future (2040–2069) crop yields for spring wheat, maize, soybean and potato grown in 8 agricultural regions of Québec. For the future (2040–2069), we predict significant yield increases for soybean, lesser increases for wheat, no significant change for maize, and yield decreases for potato. These yields, especially for soybean, are further increased when incorporating the $CO_2$ fertilization effect, but vary according to the crop, climate scenario and agricultural region. Similar trends have been found in comparable agricultural regions in the Northeastern USA and in Southern Finland. These results are useful for designing appropriate crop and farm management adaptation strategies in response to future climate change.

KEY WORDS: Climate change · $CO_2$ increase · Canada · Crop yields



## 1. INTRODUCTION

Agriculture is very sensitive to climatic and, more generally, environmental conditions (Smit 1993, B. Singh et al. 1996, Thomson et al. 2005). Global average surface temperature is expected to increase by 1.4 to 5.8°C over the period 1990 to 2100 (Houghton et al. 2001). This warming is expected to have a significant impact on the precipitation regime and water availability. These changes in precipitation are likely to be accompanied by an increase in its variability (Houghton et al. 2001) and — along with the projected increase in atmospheric $CO_2$ concentration — will directly affect plant growth and development and consequently crop yields (Wong 1979, Monteith 1981, Thomson et al. 2005). A greenhouse gas (GHG)-induced climate change would very likely result in significant changes in crop production, which, considering the importance of agriculture worldwide, could have major socio-economic impacts.

The objective of this study was to assess the effects that rising atmospheric $CO_2$ and climate change may have on agricultural production of wheat, maize, soybean, and potato in the province of Québec, Canada, using the coupled climate scenario–crop model approach. This research differs from the previous studies of a similar nature (Singh & Stewart 1991, B. Singh et al. 1996, 1998, El Maayar et al. 1997) in the choice of the Atmosphere–Ocean General Circulation Models (A–OGCMs) and crop models used.

The present study has evolved from our work in studies for several institutions (Environment Canada, Royal Canadian Geographical Society and Canadian Climate Impacts and Adaptation Network) between 1987 and the present (Singh & Stewart 1991, Bryant et al. 1995, Singh et al. 1996, El Maayar et al. 1997, B. Singh et al. 1998). These studies examined (and continue to examine) climate-related vulnerabilities, impacts, and adaptations in the agricultural sector. In addition, in 2003 we incorporated data from the

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GCMs (general circulation models) CGCM1 and HadCM3, as well as data from the crop model DSSAT 3.5 (Brassard 2003).

## 2. METHODS AND DATA

This study uses the coupled climate scenario–crop model approach in which present and future climate conditions, generated by the selected climate models, following different $CO_2$ and other GHG emission scenarios, are integrated as inputs into the different crop models so as to simulate crop growth, development and production. All model variables, other than weather (e.g. soil, cultivar and management), are held constant between present and future crop yield simulations. Present and future crop yields are then compared to evaluate the impacts of GHG-induced climate change on agriculture. The A–OGCM climate models used in this study are the coupled CGCM1 of the Canadian Centre for Climate Modeling and Analysis (CCCma) and the HadCM3 of the British Hadley Centre. The CGCM1 model is forced by the IS92a emission scenario, whilst the HadCM3 model is forced by both the SRES A2 and B2 emission scenarios (Houghton et al. 2001). The selection of the A–OGCMs was based on their relevance to Canadian conditions and their ability to provide daily climate diagnostics at a relatively fine scale. The crop models used were those of the Decision Support System for Agrotechnology Transfer (DSSAT) version 3.5, namely CERES, CROPGRO and SUBSTOR, suitable for use under Canadian conditions (Mahdian & Gallichand 1997).

This study was conducted in 8 of the 13 agricultural regions of the province of Québec, Canada (Fig. 1). These regions are those of the Régie des Assurances Agricoles du Québec (RAAQ 2001a). The choice of study region was based on the importance of the cultivated acreages and the desire to have as complete a representation as possible of the agricultural landscape of the province of Québec.

Crop yields and changes are evaluated for 4 different crops chosen for their importance to the agricultural sector: spring wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), soybean (*Glycine max* [L.] Merr.) and potato (*Solanum tuberosum* L.). Other factors that determined the choice of these crops included the availability of observed annual regional yield data for validation purposes, and the desire to have a diverse and representative view of the impacts of climate change on crop production potentials in Québec (thus different types of crops were chosen: 2 cereals, one C3

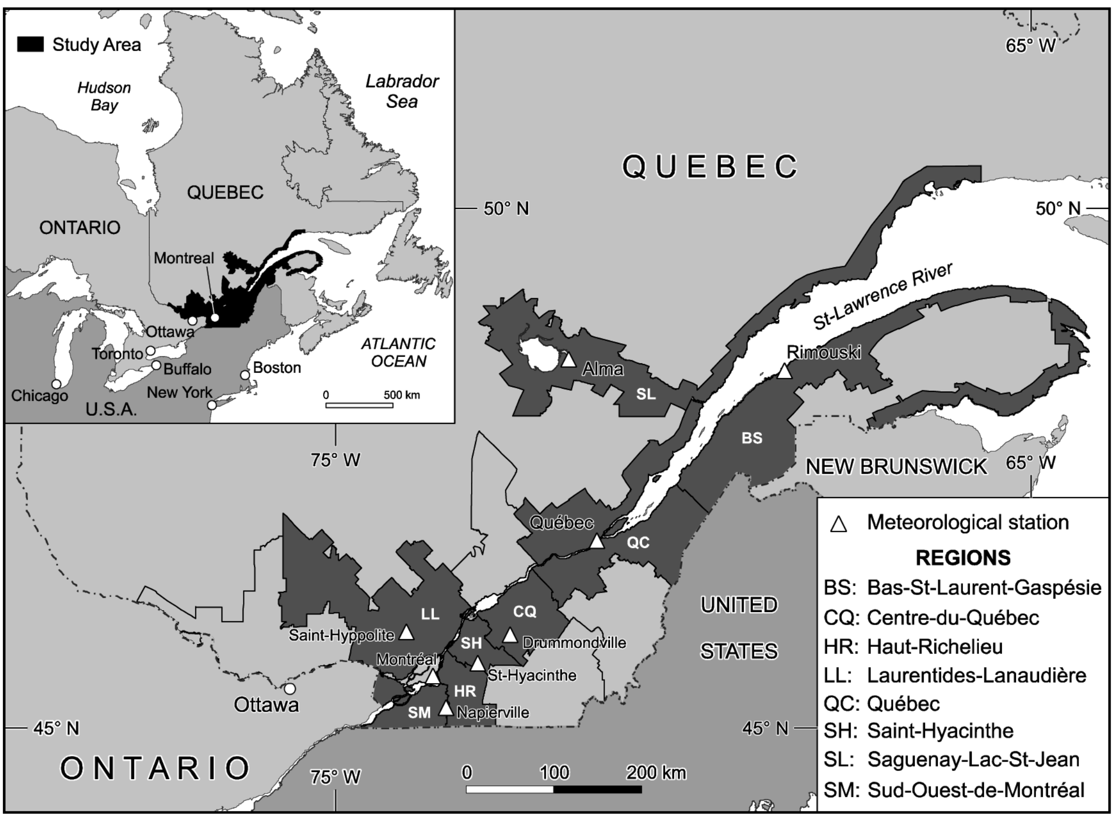


Fig. 1. Agricultural regions and weather stations (Δ) chosen for this study

[wheat] and one C4 [maize]; one grain legume [soybean]; and one root crop [potato]).

### 2.1. Crop models

The DSSAT v3.5 (Tsuji et al. 1998, Hoogenboom et al. 1999) suite of crop models includes a series of submodules that allows the user to input, manipulate and analyze crop, soil and weather data, so as to calibrate and evaluate different crop growth and yield models. Furthermore, the DSSAT 3.5 suite allows for the simulation of crop development and growth under different crop cultivation characteristics, management practices, and environmental conditions (Jones et al. 1998). The crop models included in DSSAT and used in this study are CERES (U. Singh et al. 1991) for wheat and maize, CROPGRO (Boote et al. 1997, 1998) for soybean, and SUBSTOR (Griffin et al. 1993) for potato. These are process oriented models that simulate crop growth and development on a daily time step as a function of climate, soil, cultivar, and crop management; and simulate carbon, water and nitrogen balance in the plant and soil. All models use the same soil water and soil nitrogen modules, presented respectively in Ritchie (1998) and Godwin & Singh (1998). They also require the same input data for soil (notably, extractable water and nitrogen for the different layers of the soil profile) and for daily weather (solar radiation, maximum and minimum temperatures, and precipitation) (Jones et al. 1998). The soil data used in this research was extracted from soil research surveys conducted by Tabi et al. (1990). For each of the 8 agricultural regions, the dominant soil was chosen as representative of the cultivated soils of the region, and its ensuing characteristics chosen as inputs for the crop simulations (Table 1). Detailed information pertaining to cultivars, seeding dates, plant densities, soil parameters and fertilizer inputs are found in Table 2 and Brassard (2003).

The CERES crop model is described in detail by Ritchie et al. (1998). The CROPGRO is described by Boote et al. (1997, 1998). SUBSTOR-potato, originally based on the CERES family of crop models (Jones et al. 1998), is described at length by Griffin et al. (1993) and U. Singh et al. (1998).

### 2.2. Direct $CO_2$ effect on plants

In DSSAT v3.5, the different crop models take into account the direct impact of $CO_2$ on plants, also called the 'fertilization effect'. Atmospheric $CO_2$ concentration affects both water use and biomass production (Tsuji et al. 1998). Following Peart et al. (1989), daily potential transpiration was modified to reflect the influence of $CO_2$ on stomatal conductivity, while daily canopy photosynthesis was modified by a multiplier dependent on $CO_2$ concentration, as described by Curry et al. (1990). The impact of the $CO_2$ fertilization effect is assessed using yield changes obtained with present-day and elevated future annual $CO_2$ concentrations. Crop yield simulations were generated with atmospheric $CO_2$ being fixed at the mid-level (330 ppm in 1975) of the control (1961–1990) period. Future annual atmospheric $CO_2$ concentrations for the years 2040 to 2069 were determined by the emission scenarios used in the A–OGCMs selected for this study (Table 3). This future time slice is chosen to represent the time when effective $CO_2$ would have doubled (Houghton et al. 2001). Further methodological details relating to the multipliers used to adjust for elevated $CO_2$ in the DSSAT crop models are found in Brassard (2003).

Table 1. Dominant soils for the different agricultural regions. Source: RAAQ (2001a)

| Soil type | Soil series | Region | % of region occupied |
|---|---|---|---|
| Sandy loam | St-André | Bas-St-Laurent-Gaspésie | 17.4 |
| | St-Amable | Centre-du-Québec | 19.6 |
| | Tremblay | Saguenay-Lac-St-Jean | 37.9 |
| Clay loam | Ste-Rosalie | Haut-Richelieu | 34.9 |
| | Ste.Rosalie | Laurentides-Lanaudière | 22.9 |
| | Ste-Rosalie | Saint-Hyacinthe | 34.9 |
| | Ste-Rosalie | Sud-Ouest-de-Montréal | 39.4 |
| Clay | Kamouraska | Québec | 9.7 |

Table 2. Data on crop management strategies for Southern Québec. Source: RAAQ (2001a)

| Crop | Planting date (dd/mm) | Planting density ($m^{-2}$) | Row spacing (cm) | Planting depth (cm) | Fertilization (kg N $ha^{-1}$) | Harvest date (dd/mm) |
|---|---|---|---|---|---|---|
| Wheat | 15/05 | 400 | 16 | 3 | 60 | At maturity[a] |
| Maize | 15/05 | 15 | 60 | 7 | 85 | At maturity[a] |
| Soya | 14/05 | 45 | 15 | 4 | 100 | At maturity[a] |
| Potato | 20/05 | 5.1 | 13 | 15 | 200 | 15/09 |

[a]Depending on weather conditions, equipment, manpower, and storage availability (generally September to November)

### 2.3. Weather data and climate scenarios

The baseline climate is represented by observed weather data for the years 1961 to 1990. Simulated A–OGCM data for the years 2040 to 2069 represent the future, higher $CO_2$ climate. The future (2040–2069) climate scenarios for both A–OGCMs are derived by adjusting the observed (1961–1990) data, by incorporating the future changes in the relevant climate variables: solar radiation, maximum and minimum air temperatures and precipitation.

Daily observed precipitation, maximum and minimum temperatures, and solar radiation for the study regions were obtained from Environment Canada (2000). For each region, the data from one of the major weather stations was chosen as representative of the climate of that region, 1 station per region. Also, the weather stations were chosen on the basis of the following criteria: availability of daily data from 1961 to 1990 and location of the station within the agricultural sector and location of the station to a grid point of the downscaled A–OGCM data sets (Fig. 1), as well as proximity.

In instances where data for daily solar radiation were missing, it was computed from the 3 existing variables using the following formula (Hunt et al. 1998):

$$S = a_0 S_0 (T_{max} - T_{min})^{0.5} + a_1 T_{max} + a_2 P + a_3 P^2 + a_4 \qquad (1)$$

where $S$ is the daily solar radiation (MJ m$^{-2}$ d$^{-1}$), $S_0$ the daily solar radiation above the atmosphere (MJ m$^{-2}$ d$^{-1}$), $T_{max}$ and $T_{min}$ the maximum and minimum daily temperatures (°C), $P$ the daily precipitation (mm), and $a_0$, $a_1$, $a_2$, $a_3$ and $a_4$ are empirical coefficients. The empirical coefficients were estimated using solar radiation, maximum and minimum temperatures, and precipitation data from the Montréal (Bréboeuf) weather station, for which daily solar radiation data is available (Environment Canada 2000, S. Trentin pers. comm.).

The impact of climate change on agricultural production was assessed using the observed baseline (1961–1990) data and the adjusted A–OGCM-simulated future (2040–2069) climate scenarios. The required daily weather variables—solar radiation, maximum and minimum temperatures, and precipitation—were derived using observed data for the baseline period and from the CGCM1 and HadCM3 diagnostics for the future period. The CGCM1 model is described in Flato et al. (2000). A description of the HadCM3 is given in Gordon et al. (2000) and Pope et al. (2000). These 2 models were chosen for this research based on the availability of daily weather data, as required by the DSSAT models, and for the general quality and reliability of the simulated current climate compared to observed data (Brassard 2003). However, it must be cautioned that, based on comparisons with observed data over the last 2 decades, the HadCM3 A2 scenario appears to overestimate the net greenhouse forcing of the climate system and this may influence our results for the 2040–2069 time period.

The spatial resolution of both A–OGCMs used was too low (CGCM1: 3.8 × 3.8°; HadCM3: 2.5 × 3.75°) to adequately represent the regional variability of the pertinent climate parameters amongst the different agricultural regions for the future climate (Fig. 1). In order to circumvent this scaling problem, we used the gradient plus inverse distance squared (GIDS) method (Nalder & Wein 1998, Price et al. 2000) to downscale the A–OGCM's simulated climate data sets to 1° latitude by 1° longitude grids. For each agricultural region, the closest point of the downscaled grid is selected, and the weather data at these points are retained as the new regionalized data sets for the future (2040–2069) simulated climate for each agricultural region.

Table 3. Average changes in the climate variables between baseline (1961–1990) and future (2040–2069) climates as predicted by the 3 climate scenarios for agricultural regions of Southern Québec. Present atmospheric $CO_2$ concentration set at mid-level of 1961–1990 period (1975: 330 ppm)

| Climate scenario | $T_{max}$ (Δ°C) | $T_{min}$ (Δ°C) | Precipitation (Δ%) | Future $CO_2$ (ppm) |
|---|---|---|---|---|
| CGCM1 | 2.1 | 3.2 | 0.6 | 468–565 |
| HadCM3 A2 | 2.6 | 2.7 | 7.7 | 488–618 |
| HadCM3 B2 | 2.4 | 2.3 | 2.7 | 456–522 |

### 2.4. Crop yield validations

The DSSAT suite of crop models have been extensively used and validated in several locations worldwide (Peart et al. 1989, Adams et al. 1990, Touré et al. 1995, Travasso et al. 1996, Dhakhwa et al. 1997, Mahdian & Gallichand 1997, Mavromatis & Jones 1998, Mati 2000, Southworth et al. 2000, Smith & Lazo 2001). In order to verify the applicability of the CERES, CROPGRO and SUBSTOR crop models to the selected agricultural regions, and to ensure the reliability of their results, validation of the simulated crop yields were conducted. This was done by comparing—for the different crops and agricultural regions—yields that were simulated using observed weather data with actual yields. As shown in Table 4, observed yield data, obtained from the Régie des Assurances Agricoles du Québec (RAAQ 1997, 2001b), is not available for every year of the 1961–1990 period (depending on crop and region).

Validation is hence done by comparing the averages of the simulated and observed yields for the given period of available observed data. The results, presented in Table 5, are expressed as the percentage difference between average simulated and observed yields, and the statistical significance of this difference is tested by comparing the averages using the Wilcoxon-Mann-Whitney test. A non-parametric test was chosen because of the small sample size and the unknown distribution of — and difference in — the standard deviation (or variance) between the 2 average yield sets. Table 5 provides further validation tests, namely the root mean square error (RMSE) and the modelling efficiency test (EF), a dimensionless statistic similar to the regression $R^2$ (Mayer & Butler 1993).

According to Ritchie at al. (1998), a difference between observed and simulated yields of up to ±15% is judged acceptable. As seen in Table 5, for most crops and regions, the validation results are within this range. For wheat, only the Québec region shows a statistically significant ($p = 0.1$) difference between observed and simulated yields. On the other hand, for maize, only 2 regions, namely Québec and Laurentides-Lanaudière show statistically significant ($p = 0.1$) differences. With the exception of the regions of Québec and Saint-Hyacinthe, there are no significant differences between the simulated and observed yields of soybean. The smaller size of the validation samples used for soybean ($n = 4$) might explain the high differences between observed and simulated yields in these regions. Finally, the results for potato show a significant ($p = 0.1$) difference between the simulated and observed yields for only one region, namely the Centre-du-Québec region. Furthermore, both the RMSE and EF statistics reaffirm the poor relationship between observed and simulated yields for the control period (1961–1990) for wheat in the Québec region, for maize in the Laurentides-Lanaudière and Québec regions, for soybean in the Québec and Saint-Hyacinthe regions, and for potato in the Centre-du-Québec region (Fig. 1, Table 5).

Brassard (2003) performed a verification of yields from observed data compared to those simulated with the three A–OGCM scenarios data for the baseline climate (1961–1990). This was done by computing the percentage difference between the 30 yr average yields simulated with the CGCM1 and HadCM3 A2 and B2 baseline climates to that simulated with observed weather parameters. The results indicated that the yields simulated with weather data from the A–OGCMs, especially the 2 HadCM3 scenarios, are very close in magnitude to yields simulated with baseline observed data (Brassard 2003).

Table 4. Years of available data for observed yields for selected crops and agricultural regions for the control (1961–1990) period. na: no data available

| Region | Wheat | Maize | Soybean | Potato |
|---|---|---|---|---|
| Bas-St-Laurent-Gaspésie | 1985–1990 | na | na | 1978–1990 |
| Centre-du-Québec | 1985–1990 | 1978–1990 | 1987–1990 | 1978–1990 |
| Haut-Richelieu | 1985–1990 | 1978–1990 | 1987–1990 | 1978–1990 |
| Laurentides-Lanaudière | 1985–1990 | 1978–1990 | 1987–1990 | 1978–1990 |
| Québec | 1985–1990 | 1984–1990 | 1988–1990 | 1978–1990 |
| Saint-Hyacinthe | 1985–1990 | 1978–1990 | 1987–1990 | 1985–1990 |
| Saguenay-Lac-St-Jean | 1985–1990 | na | na | 1978–1990 |
| Sud-Oeust-de-Montréal | 1985–1990 | 1978–1990 | 1987–1990 | 1978–1990 |

Table 5. Relative difference (RD; %), root mean square error (RMSE) and modelling efficiency (EF) between observed yields and yields simulated with observed climate data; RD = [(Observed−Simulated) / Observed] × 100, average over 30 yr; na: no data available; *p = 0.1

| | RD (%) | RMSE | EF |
|---|---|---|---|
| **Wheat** | | | |
| Bas-St-Laurent-Gaspésie | −0.9 | 0.02 | 0.99 |
| Centre-du-Québec | −17.8 | 0.43 | 0.56 |
| Haut-Richelieu | −0.4 | 0.01 | 0.99 |
| Laurentides-Lanaudière | 15.8 | 0.42 | 0.43 |
| Québec | 58.4* | 1.43 | −3.74 |
| Saint-Hyacinthe | 1.0 | 0.53 | 0.98 |
| Saguenay-Lac St-Jean | 2.4 | 0.05 | 0.99 |
| Sud-Oeust-de-Montréal | 14.3 | 0.45 | 0.42 |
| **Maize** | | | |
| Bas-St-Laurent-Gaspésie | na | na | na |
| Centre-du-Québec | −7.7 | 0.49 | 0.89 |
| Haut-Richelieu | −1.8 | 0.11 | 0.99 |
| Laurentides-Lanaudière | 32.9* | 2.43 | −3.17 |
| Québec | 82.2* | 5.28 | −11 |
| Saint-Hyacinthe | −3.5 | 0.27 | 0.96 |
| Saguenay-Lac St-Jean | na | na | na |
| Sud-Oeust-de-Montréal | 0 | 0 | 1 |
| **Soybean** | | | |
| Bas-St-Laurent-Gaspésie | na | na | na |
| Centre-du-Québec | 6.4 | 0.15 | 0.85 |
| Haut-Richelieu | −1.5 | 0.04 | 0.98 |
| Laurentides-Lanaudière | 1.5 | 0.04 | 0.98 |
| Québec | 72.3* | 1.34 | −4.44 |
| Saint-Hyacinthe | −34.4* | 0.99 | −6.45 |
| Saguenay-Lac St-Jean | na | na | na |
| Sud-Oeust-de-Montréal | 2.6 | 0.07 | 0.95 |
| **Potato** | | | |
| Bas-St-Laurent-Gaspésie | −5.6 | 1.21 | 0.53 |
| Centre-du-Québec | −27.0* | 6.38 | −1.5 |
| Haut-Richelieu | 0.2 | 0.04 | 0.99 |
| Laurentides-Lanaudière | 9.9 | 2.22 | 0.6 |
| Québec | −8.5 | 1.65 | 0.75 |
| Saint-Hyacinthe | 1.8 | 0.42 | 0.99 |
| Saguenay-Lac St-Jean | 3.3 | 0.46 | 0.96 |
| Sud-Oeust-de-Montréal | −1 | 0.18 | 0.99 |

However, it must be cautioned that the focus of this study resides in the assessment of the impacts of $CO_2$-induced climate change and ambient $CO_2$ on average yields and their variability, for the selected crops and regions, with the emphasis on the relative yield changes between current (1961–1990) and future (2040–2069) periods. This would lessen the importance of the absolute values of the yield validation results between observed and simulated yields that are at times somewhat divergent (Table 5).

## 3. RESULTS

This section presents the effects of a $CO_2$-induced climate change on wheat, maize, soybean and potato production, expressed as the relative changes in yields between baseline (1961–1990) and future (2040–2069) climate. Results are presented as percentage changes in average yields ($Yield_{avg}$), and calculated as follows:

$$\% \Delta Yield_{avg} = [(Yield_{avg(2040-2069)} - Yield_{avg(1961-1990)}) / Yield_{avg(1961-1990)}] \times 100 \quad (2)$$

Yields simulated with the A–OGCMs future (2040–2069) climate are compared to those simulated with the current (1961–1990) climate. Differences between baseline and future yields are assessed using Student's *t*-tests.

### 3.1. Crop yield changes

Relative changes in the average yields of wheat, maize, soybean and potato predicted between present (1961–1990) and future (2040–2069) climates are shown for each of the 8 agricultural regions in Table 6.

Nearly all future climate scenarios, except the HadCM3 A2 scenario for the Haut-Richelieu region, predict an increase in wheat yields in all agricultural regions; with most of these increases being statistically significant at both the p = 0.01 and p = 0.05 levels (Table 6). The CGCM1 scenario predicts its highest yield increases in the Bas-St-Laurent-Gaspésie (88.6%) and Québec (42.4%) agricultural regions. For the HadCM3 A2 scenario, the largest yield increases are found in the Saint-Hyacinthe (15.2%) and Sud-Ouest-de-Montréal (10.5%) regions. For the HadCM3 B2 scenario, the largest yield increases are found in the Québec (14.6%) and Saguenay-Lac-St-Jean (13.7%) regions. On the other hand, the lowest yield increases for the CGCM1 scenario are found in the Centre-du-Québec (4.8%) and Haut-Richelieu (4.4%) regions. Similarly, for the HadCM3 A2 scenario the lowest yield increases are in the Bas-St-Laurent-Gaspésie (6.2%), Saguenay-Lac-St-Jean (4.8%) and Haut-Richelieu (–30.0%) regions; while for the HadCM3 B2 scenario, the lowest yield increases are to be found in the Bas-St-Laurent-Gaspésie (5.5%) and Centre-du-Québec (5.0%) regions. In light of the widely varying yield predictions for wheat, it is very likely that the large decrease in yields predicted by the HadCM3 A2 scenario in the Haut-Richelieu (–30%) region and the unduly high yield increase predicted by the CGCM1 scenario for the Bas-St-Laurent-Gaspésie (88.6%) region may be due to aberrations attributable to

Table 6. Relative change (%) in yields between baseline and future climate, as predicted by the 3 climate scenarios for the 4 crops studied; *p = 0.01; **p = 0.05

| | CGCM1 | HadCM3 A2 | HadCM3 B2 |
|---|---|---|---|
| **Wheat** | | | |
| Bas-St-Laurent-Gaspésie | 88.6* | 6.2 | 5.5 |
| Centre-du-Québec | 4.8 | 9.1* | 5.0 |
| Haut-Richelieu | 4.4 | –30.0* | 12.1* |
| Laurentides-Lanaudière | 20.7* | 8.4* | 10.6* |
| Québec | 42.4* | 10.4 | 14.6** |
| Saint-Hyacinthe | 5.5** | 15.2* | 11.4* |
| Saguenay-Lac St-Jean | 18.5** | 4.8 | 13.7** |
| Sud-Oeust-de-Montréal | 7.4** | 10.5* | 12.3* |
| Mean | 24.0 | 4.3 | 10.7 |
| **Maize** | | | |
| Bas-St-Laurent-Gaspésie | 67.5* | 212.1* | 221.5* |
| Centre-du-Québec | 1.7 | 7.6 | 6.3 |
| Haut-Richelieu | –1.7 | 13.2** | 9.9 |
| Laurentides-Lanaudière | 5.2 | –1.9 | –0.8 |
| Québec | 3.9 | –10.1** | –5.7 |
| Saint-Hyacinthe | –6.9** | 11.3 | 4.3 |
| Saguenay-Lac St-Jean | 7.5 | –10.1 | 0.8 |
| Sud-Oeust-de-Montréal | –1.7 | 19.1* | 14.0 |
| Mean | 9.4 | 30.2 | 31.3 |
| **Soybean** | | | |
| Bas-St-Laurent-Gaspésie | 42.4* | 580.9* | 515.8* |
| Centre-du-Québec | 26.8* | 111.1* | 80.2* |
| Haut-Richelieu | 26.0* | 106.2* | 77.9* |
| Laurentides-Lanaudière | 34.0* | 79.0* | 73.2* |
| Québec | 97.9* | 35.9** | 41.5* |
| Saint-Hyacinthe | 29.2* | 97.5* | 64.2* |
| Saguenay-Lac St-Jean | 35.2* | 68.0* | 59.3* |
| Sud-Oeust-de-Montréal | 25.7* | 95.8* | 74.6* |
| Mean | 39.7 | 146.8 | 123.3 |
| **Potato** | | | |
| Bas-St-Laurent-Gaspésie | 32.1* | 5.2 | 5.3 |
| Centre-du-Québec | –8.3 | 1.6 | –2.3 |
| Haut-Richelieu | –34.3* | –4.4 | –4.9 |
| Laurentides-Lanaudière | 12.9 | –14.7 | –8.4 |
| Québec | –28.7* | –27.5* | –23.7* |
| Saint-Hyacinthe | –11.5 | –2.1 | –13.4 |
| Saguenay-Lac St-Jean | 9.4 | –26.0* | –16.0* |
| Sud-Oeust-de-Montréal | –40.3* | –11.1 | –6.9 |
| Mean | –8.6 | –9.9 | –8.8 |

methodological or model errors. Only in 3 agricultural regions: Saint-Hyacinthe, Sud-Ouest-de-Montréal and Laurentides-Lanaudière, do all 3 climate scenarios predict statistically significant increases in the average yields of wheat. In the north-eastern regions: Bas-St-Laurent-Gaspésie, Québec and Saguenay-Lac-St-Jean; and in Laurentides-Lanaudière, the CGCM1 scenario predicts higher yield increases than both the HadCM3 (A2 and B2) scenarios. However, in the more central and southern regions: Saint-Hyacinthe, Sud-Ouest-de-Montréal, Haut-Richelieu and Centre-du-Québec, the CGCM1 scenario generally predicts lower yield increases. Taking the mean over all regions, wheat yield increases are highest for the CGCM1 (24 %) scenario and lowest for the HadCM3 A2 (4.3 %) scenario. However, the CGCM1 results are skewed by the unduly high values for the Bas-St-Laurent-Gaspésie region (Table 6).

The maize results appear to indicate that, with the exception of the Bas-St-Laurent-Gaspésie region, $CO_2$-induced climate change will have little or no impact on maize crop yields (Table 6). Most of the differences between current (1961–1990) and future (2040–2069) yields are not statistically significant ($p = 0.05$) and the yield changes, except for the Bas-St-Laurent-Gaspésie region, are between the ±15 % intervals. For the Bas-St-Laurent-Gaspésie region, the 3 future climate scenarios predict an important and significant increase in maize yields, which seems unexpectedly high, because the current (1961–1990) climate does not allow for widespread cultivation of maize in this region. Overall, the HadCM3 A2 scenario is predicting significant changes in maize yield: increases in the Sud-Ouest-de-Montréal (19.1 %) and Haut-Richelieu (13.2 %) regions, and a decrease in the Québec (–10.1 %) region. Similarly, the HadCM3 B2 scenario is also predicting yield increases, although not significant, in both the Sud-Ouest-de-Montréal (14.0 %) and Haut-Richelieu (9.9 %) regions. The only significant yield changes for maize predicted by the CGCM1 scenario is an average yield decrease of –6.9 % in the Saint-Hyacinthe region. When considering the overall mean across all regions, maize yield increases are modest for the CGCM1 (9.4 %) scenario and reasonably high for HadCM3 A2 (30.2 %) and HadCM3 B2 (31.3 %) scenarios. But again, these mean values are influenced by the unduly high yield changes predicted for the Bas-St-Laurent-Gaspésie region (Table 6).

Soybean is the only crop for which all 3 climate scenarios consistently point to a statistically significant increase in yields in the future in all agricultural regions (Table 6). The predicted increase in soybean yields ranges from 25.7 % (CGCM1 scenario in the Sud-Ouest-de-Montréal region) to 111.1 % (HadCM3 A2 scenario in the Centre-du-Québec region). The soybean yield increases of 580.9 % and 515.8 % obtained for the HadCM3 A2 and B2 scenarios in the Bas-St-Laurent-Gaspésie region are considered much too high and may, as with maize, result from the fact that the current climate (1961–1990) does not lend itself to widespread cultivation of soybean in this northerly region. For both the HadCM3 (A2 and B2) scenarios, the highest yield increases can be found in the Centre-du-Québec (HadCM3 A2: 111.1 %, HadCM3 B2: 80.2 %) and the Haut-Richelieu (HadCM3 A2: 106.2 %, HadCM3 B2: 77.9 %) regions, while the lowest yield increases are found in the Québec (HadCM3 A2: 35.9 %, HadCM3 B2: 41.5 %) and Saguenay-Lac-St-Jean (HadCM3 A2: 68.0 %, HadCM3 B2: 59.3 %) regions. On the other hand, the CGCM1 scenario predicts the highest yield increases for the regions of Québec (97.9 %) and Bas-St-Laurent-Gaspésie (42.4 %), and the lowest yield increases for the regions of Sud-Ouest-de-Montréal (25.7 %) and Haut-Richelieu (26.0 %). As was the case with wheat, yield changes of soybean are higher for the CGCM1 scenario in the more northerly agricultural regions (Bas-St-Laurent-Gaspésie, Québec and Saguenay-Lac-St-Jean) and also in the higher elevation Laurentides-Lanaudière region, and lower in the more southerly and central regions (Saint-Hyacinthe, Sud-Ouest-de-Montréal, Haut-Richelieu and Centre-du-Québec). Considering the overall mean across all regions, soybean yield increases are high for the CGCM1 (39.7 %) scenario and very high for the HadCM3 A2 (146.8 %) and HadCM3 B2 (123.3 %) scenarios. But again, these mean values are influenced by the unduly high yield changes predicted for the Bas-St-Laurent-Gaspésie region, especially in the case of the HadCM3 (A2 and B2) scenarios (Table 6).

The predicted yield results for potato show a general tendency toward diminishing future yields, but only in the Québec region do the 3 climate scenarios agree on significant decreases (CGCM1: –28.7 %; HadCM3 A2: –27.5 %; HadCM3 B2: 23.7 %; Table 6). The CGCM1 scenario also predicts significant potato yield decreases in the Sud-Ouest-de-Montréal (–40.3 %) and Haut-Richelieu (–34.3 %) regions, while both the HadCM3 (A2 and B2) scenarios project yield reductions in Saguenay-Lac-St-Jean (HadCM3 A2: –26.0 %; HadCM3 B2: –16.0 %). Aside from these yield changes, the only other significant change in potato yields observed is an increase of 32.1 % predicted by the CGCM1 scenario for the Bas-St-Laurent-Gaspésie region. Although small and statistically non-significant, an increase in potato yields is also projected for the Bas-St-Laurent-Gaspésie region according to both the HadCM3 (A2 and B2) scenarios. Taking the mean of potato yield changes across all regions, all 3 climate scenarios project an overall decrease in yields ranging from –8.6 % (CGCM1 scenario) to –9.9 % (HadCM3 A2 scenario).

Generally, higher yields for all crops and according to all future climate scenarios are projected for the more northerly regions and higher elevations. This may be attributed to the fact that these regions are not very well suited to growing these crops under the current climate, so that climate warming would create more optimal temperatures for the cultivation of these crops. On the other hand, the more southerly regions would suffer yield decreases on account of acceleration of maturation and increased moisture stress (B. Singh et al. 1998). In general, it would also appear that the inter-annual variability of yields for all crops and agricultural regions under the CGCM1 and the 2 HadCM3 (A2 and B2) climate scenarios will increase in the future. This general increase in the inter-annual variability of yields in the future will be higher in the more northerly and higher elevation regions and lower in the more southerly lower elevation regions (Brassard 2003).

### 3.2. The $CO_2$ fertilization effect

In general, there is a relative increase in future (2040–2069) compared to current (1961–1990) yields when incorporating the $CO_2$ fertilization effect, except for maize and potato yields for certain regions and climate scenarios (Table 7). On account of the inadequacy of the Bas-St-Laurent-Gaspésie data, because its coastal location creates problems with the land–sea mask, this region is not included in this analysis. The $CO_2$ fertilization effect is particularly important in soybean yields, where it is responsible for yield increases ranging from 34.4 to 97.7%, depending on scenario and region. In fact, for soybean, the relative yield increase attributable to the $CO_2$ fertilization effect is more important than that caused by the change in climate. The contribution of the $CO_2$ fertilization effect is highest in the Québec (97.7%) region for the CGCM1 scenario, in the Saint-Hyacinthe (76.4%) and Centre-du-Québec (76.3%) regions for the HadCM3 A2 scenario, and in the Centre-du-Québec (56.7%) and Québec (56.2%) regions for the HadCM3 B2 scenario. It is lowest in the Laurentides-Lanaudière (34.4%) and Saint-Hyacinthe (34.7%) regions for the CGCM1 scenario, in the Laurentides-Lanaudière (52.1%) and Saguenay-Lac-St-Jean (57.0%) regions for the HadCM3 A2 scenario, and in the Laurentides-Lanaudière (44.5%) and Saguenay-Lac-St-Jean (48.4%) regions for the HadCM3 B2 scenario (Table 7). It would appear then that there is a greater regional variability in the importance of the $CO_2$ fertilization effect with the HadCM3 A2 scenario, compared to the other 2 future climate scenarios.

For most of the climate scenarios and agricultural regions, future (2040–2069) wheat yields would generally seem to decrease without the $CO_2$ fertilization effect (Table 7). In general, wheat yield increases due to the direct $CO_2$ effect range from 6.8% for the CGCM1 scenario in the Saguenay-Lac-St-Jean region to 47.3% for the HadCM3 A2 scenario in the Québec region. For wheat yields then, the $CO_2$ fertilization effect is most important in the Québec (28.4%) region for the CGCM1 scenario, in the Québec (47.3%) and Saint-Hyacinthe (17.1%) regions for the HadCM3 A2 scenario, and in the Québec (32.9%) and Sud-de-Montréal (15.0%) regions for the HadCM2 B2 scenario (Table 7). For both wheat and soybean, the HadCM3 A2 scenario usually predicts a greater $CO_2$ fertilization effect, because of higher $CO_2$ levels, followed in order by the HadCM3 B2 and the CGCM1 scenarios (Table 7).

For maize, the CGCM1 scenario predicts slightly greater yields due to the $CO_2$ fertilization effect for all regions except the Centre-du-Québec (–0.5%) and Québec (–3.2%) regions; the yield increases ranging from 0.3% (Laurentides-Lanaudière) to 5.5% (Haut-Richelieu) (Table 7). Similarly, both the HadCM3 (A2 and B2) scenarios project increasing yields on account of the $CO_2$ fertilization effect in all regions except Saguenay-Lac-St-Jean (HadCM3 A2: –2.3%, HadCM3 B2: –2.9%). The HadCM3 A2 and B2 scenario yield increases on account of the $CO_2$ fertilization effect range from 4.6% (HadCM3 B2: Laurentides-Lanaudière) to 18.5% (HadCM3 A2: Saint-Hyacinthe) (Table 7).

The results of yield changes attributable to the $CO_2$ fertilization effect for potato are less significant, even contributing negatively to future yields in some cases. The CGCM1 scenario predicts yield losses for all regions except the Centre-du-Québec region, though of small magnitude, ranging from –0.9% in the Sud-de-Montréal to –9.6% in the Québec (Table 7) regions. On the other hand, both the HadCM3 (A2 and B2) scenarios project—as expected—increasing yields on account of the $CO_2$ fertilization effect, in all regions except Saint-Hyacinthe and Saguenay-Lac-St-Jean, where yield losses are very minimal. The HadCM3 A2 and B2 yield increases on account of the $CO_2$ fertilization effect range from 2.6% (HadCM3 B2: Haut-Richelieu) to 16.3% (HadCM3 A2: Saint-Hyacinthe) (Table 7).

However, these yield projections are with respect to the baseline period 1961–1990. Using updated trends in observed yields, at the regional (Province of Québec) level for wheat (1987–2004), soybean (1987–2001), potato (1986–2001) and maize (1987–2004), we examined whether recent changes in climate and ambient $CO_2$ concentrations are influencing crop yields. At the regional scale, there are indications of trends of increasing yields, especially for potato and maize and to a lesser extent for soybean and wheat (Fig. 2). But,

Table 7. Relative change (%) of future yields with and without the $CO_2$ fertilization effect for the 3 climate scenarios and the 4 crops studied

| | Wheat | | | Maize | | | Soybean | | | Potato | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | With $CO_2$ | Without $CO_2$ | Fertilizer effect | With $CO_2$ | Without $CO_2$ | Fertilizer effect | With $CO_2$ | Without $CO_2$ | Fertilizer effect | With $CO_2$ | Without $CO_2$ | Fertilizer effect |
| **CGCM1** | | | | | | | | | | | | |
| Centre-du-Québec | 4.8 | –3.0 | 7.8 | 1.7 | 2.3 | –0.5 | 26.8 | –8.7 | 35.5 | –8.3 | –10.3 | 2.0 |
| Haut-Richelieu | 4.4 | –3.9 | 8.3 | –1.7 | –7.2 | 5.5 | 26.0 | –10.5 | 36.5 | –34.3 | –32.4 | –1.9 |
| Laurentide-Lanaudière | 20.7 | 12.5 | 8.2 | 5.2 | 4.9 | 0.3 | 34.0 | –0.3 | 34.4 | 12.9 | 20.9 | –8.0 |
| Québec | 42.4 | 14.0 | 28.4 | 3.9 | 7.0 | –3.2 | 97.9 | 0.2 | 97.7 | –28.7 | –19.2 | –9.6 |
| Saint-Hyacinthe | 5.5 | –0.3 | 5.8 | –6.9 | –10.2 | 3.3 | 29.2 | –5.5 | 34.7 | –11.5 | –9.9 | –1.6 |
| Saguenay-Lac-St-Jean | 18.5 | 11.7 | 6.8 | 7.5 | 4.8 | 2.7 | 35.2 | –0.7 | 35.9 | 9.4 | 11.4 | –2.1 |
| Sud-Ouest-de-Montréal | 7.4 | –1.4 | 8.8 | –1.7 | –5.6 | 3.9 | 25.7 | –9.9 | 35.7 | –40.3 | –39.4 | –0.9 |
| Mean | 14.8 | 4.2 | 1.6 | 1.1 | –0.6 | 1.7 | 39.2 | –5.1 | 44.3 | –14.4 | –11.3 | –3.1 |
| **HadCM3 A2** | | | | | | | | | | | | |
| Centre-du-Québec | 9.2 | –3.1 | 12.3 | 7.6 | –8.4 | 15.9 | 111.1 | 34.9 | 76.3 | 1.6 | –9.9 | 11.5 |
| Haut-Richelieu | –30.0 | –43.4 | 13.3 | 13.2 | –0.3 | 13.5 | 106.2 | 35.6 | 70.7 | –4.4 | –9.5 | 5.1 |
| Laurentide-Lanaudière | 8.4 | –7.3 | 15.7 | –1.9 | –7.6 | 5.7 | 79.0 | 26.9 | 52.1 | –14.7 | –22.1 | 7.4 |
| Québec | 10.4 | –37.0 | 47.3 | –10.1 | –20.5 | 10.4 | 35.9 | –25.9 | 61.8 | –27.5 | –27.3 | –0.2 |
| Saint-Hyacinthe | 15.2 | –1.9 | 17.1 | 11.3 | –7.2 | 18.5 | 97.5 | 21.0 | 76.4 | –2.1 | –18.4 | 16.3 |
| Saguenay-Lac-St-Jean | 4.8 | –7.3 | 12.1 | –10.1 | –7.8 | –2.3 | 68.0 | 11.1 | 57.0 | –26.0 | –25.9 | –0.1 |
| Sud-Ouest-de-Montréal | 10.6 | –4.5 | 15.1 | 19.1 | 4.4 | 14.8 | 95.8 | 27.6 | 68.1 | –11.1 | –16.9 | 5.8 |
| Mean | 4.1 | –14.9 | 19.0 | 4.1 | –6.8 | 10.9 | 84.8 | 18.7 | 66.1 | –12.0 | –18.6 | 6.5 |
| **HadCM3 B2** | | | | | | | | | | | | |
| Centre-du-Québec | 5.0 | –3.4 | 8.4 | 6.3 | –9.8 | 16.1 | 80.2 | 23.5 | 56.7 | –2.3 | –12.3 | 10.0 |
| Haut-Richelieu | 12.2 | 0.9 | 11.3 | 9.9 | –4.5 | 14.4 | 77.9 | 24.6 | 53.3 | –4.9 | –7.5 | 2.6 |
| Laurentide-Lanaudière | 10.7 | –1.4 | 12.1 | –0.8 | –5.3 | 4.6 | 73.2 | 28.7 | 44.5 | –8.4 | –15.1 | 6.7 |
| Québec | 14.6 | –18.3 | 32.9 | –5.7 | –14.3 | 8.6 | 41.5 | –14.8 | 56.2 | –23.7 | –23.6 | –0.1 |
| Saint-Hyacinthe | 11.5 | –0.6 | 12.1 | 4.3 | –14.0 | 18.3 | 64.2 | 10.8 | 53.4 | –13.4 | –28.2 | 14.8 |
| Saguenay-Lac-St-Jean | 13.7 | 2.9 | 10.8 | 0.8 | 3.7 | –2.9 | 59.3 | 10.9 | 48.4 | –16.0 | –15.8 | –0.2 |
| Sud-Ouest-de-Montréal | 12.4 | –2.6 | 15.0 | 14.0 | –1.0 | 15.1 | 74.6 | 22.0 | 52.7 | –6.9 | –11.1 | 4.2 |
| Mean | 11.4 | –3.2 | 14.6 | 4.1 | –6.5 | 10.6 | 67.3 | 15.1 | 52.2 | –10.8 | –16.2 | 5.4 |
| Overall mean | 10.1 | –4.6 | 14.7 | 3.1 | –4.6 | 7.7 | 63.8 | 9.6 | 54.2 | –12.4 | –15.3 | 2.9 |

these trends in maize and potato yields are more a reflection of changing market and management conditions (RAAQ 2001b). As cautioned by B. Singh et al. (1998), it is difficult to assess whether these trends in crop yields are due to climate and $CO_2$ changes or to improvements in agricultural management practices.

Overall, then, taking the mean of all scenarios across all agricultural regions, it would appear that for wheat, yields would supposedly decrease (–4.6%) without the $CO_2$ fertilization effect. But when the $CO_2$ fertilization effect (14.7%) is included, yields will increase (10.1%). For maize, yields are again projected to decrease (–4.6%) without the $CO_2$ fertilization effect, but as expected will increase (3.1%) when the $CO_2$ fertilization effect (7.7%) is added. In the case of soybean, yields are projected to increase marginally (9.6%) without the $CO_2$ fertilization effect, but to increase substantially (63.8%) when the $CO_2$ fertilization effect (54.2%) is added. However, in the case of potato, yields are expected to decrease significantly (–15.3%) without the $CO_2$ fertilization effect. But when the $CO_2$ fertilization effect (2.9%) is added yield losses are reduced (–12.4%) when the $CO_2$ fertilization effect (54.2%) is included (Table 7).

## 4. DISCUSSION

This study shows that most crop yields will likely be different in the future under the effects of increased atmospheric $CO_2$ and the resulting climatic changes, as expressed by the 3 future climate scenarios. For the future climate (2040–2069), and not including the $CO_2$ fertilization effect, soybean yields are projected to be significantly higher in all of the agricultural regions of Québec; wheat yields are also projected to increase, particularly in the western-central regions of Québec; maize yields are projected to increase slightly or stay relatively unchanged; potato yields, however, are projected to decrease, especially according to the CGCM1 scenario. The fact that all 3 climate scenarios project decreasing potato yields in the future for the Québec region, the only region dominated by clay soils (Table 1), may be partly responsible for this condition. Overall, there is a clear A–OGCM model-linked pattern emerging from these results. For all crops, the more positive changes (highest increase or smallest decrease) are found in the more northerly agricultural regions when using the CGCM1 scenario, and in the south–central regions according to both the HadCM3 scenarios. On the other hand, it seems that the more southerly and central agricultural regions (Sud-Ouest-de-Montréal, Haut-Richelieu, Saint-Hyacinthe, Centre-du-Québec) would be most favored by the changing climate in terms of a lower inter-annual variability of yields for the crops considered. This diverging tendency demonstrates the importance of using more than one A–OGCM for impact analysis and adaptation purposes, because they usually predict different spatial patterns of future climate, which in turn gives different simulated yields (Hoogenboom 2000).

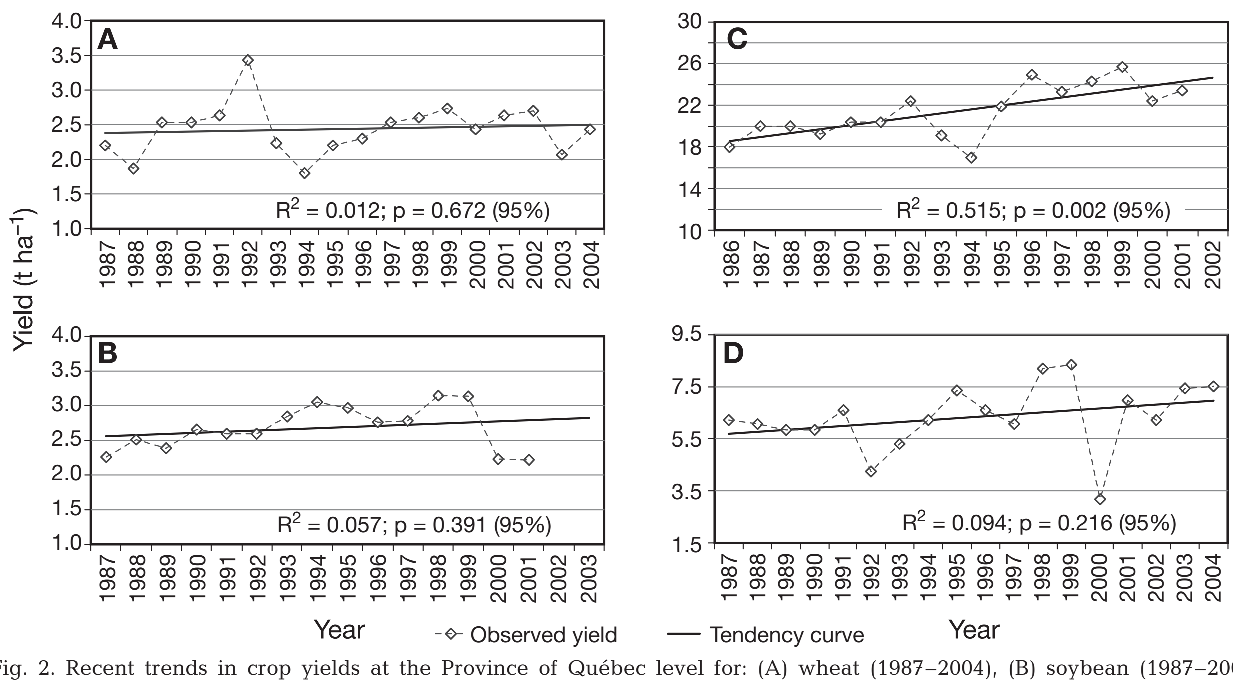


Fig. 2. Recent trends in crop yields at the Province of Québec level for: (A) wheat (1987–2004), (B) soybean (1987–2001), (C) potato (1986–2001) and (D) maize (1987–2004). Source: RAAQ (2001b)

When integrating the $CO_2$ fertilization effect, future crop yields generally increase slightly for maize and potato, appreciably for wheat and significantly for soybean. However, the CGCM1 scenario projects slightly decreased yields of potato in all regions, except Centre-du-Québec, even when integrating the $CO_2$ fertilization effect. These results are similar to those of Holden et al. (2003). The yields results of this study relating to $CO_2$ enrichment are consistent with other studies (Cure & Acock 1986; Idso & Idso 1994, Thomson et al. 2005). They show the greater importance of the direct $CO_2$ fertilization effect for C3 species such as wheat and soybean, where it is responsible for most of the anticipated increase in future yields. The direct $CO_2$ effect has less of an impact on a C4 crop yields, such as maize, because these crops are already near their maximum photosynthesis rate at current $CO_2$ levels (Kimball et al. 1993).

The changes in yields obtained in this study differ somewhat from those of previous studies conducted in Québec on the impacts of climate changes on agriculture (Singh & Stewart 1991, B. Singh et al. 1996, 1998, El Maayar et al. 1997). The research of Singh & Stewart (1991) obtained similar results for soybean, but predicted increases in maize and potato yields, and a decrease in wheat yields. The results of B. Singh et al. (1996, 1998) predicting increases in maize and potato and decreases in wheat and soybean yields, are also somewhat different from those of this study. The study of El Maayar et al. (1997), the only previous research that has considered the $CO_2$ fertilization effect in the Québec region, provided similar results only for wheat and soybean, and only in some agricultural regions. These previous studies adopted a similar methodological approach, except that they used a different crop model, the Food and Agricultural Organization (FAO 1978) model, and earlier versions of different A–OGCMs: the Goddard Institute for Space Studies (GISS; Singh & Stewart 1991) and the CCCma (B. Singh et al. 1996, 1998, El Maayar et al. 1997) climate scenarios. In the El Maayar et al. (1997) study, yield decreases, found in wheat and soybean in about half of the agricultural regions, are attributable to acceleration of maturation and increased moisture stress. With lesser warming, as in this study, both of these factors would have a lesser impact on yields, since crop development would be slower and evapo-transpiration lower. Also, the impact of moisture stress is further reduced by the change in stomatal conductivity in response to the higher $CO_2$ concentration that is included in the DSSAT crop models used in this study. As a result, future soybean and wheat yields are higher in this study, while the future yields of maize, which, being a C4 species and greatly favored by elevated temperature and much less sensitive to water availability, are lower (Loomis & Connor 1992). Also, there is a difference with respect to the number and boundaries of the study regions, which would lead to differences in the soil characteristics, and consequently yields, used in the crop modeling. Finally, unlike this study, which uses the transient A–OGCM diagnostics, the previous studies used the equilibrium output scenarios ($1 \times CO_2$ and $2 \times CO_2$), that involved temporal downscaling of monthly to daily data and which could have influenced the results.

Other studies conducted with CERES, CROPGRO and SUBSTOR in near or comparable regions have found results similar to that of the present research. For instance, using the GISS A–OGCM, Adams et al. (1990) found that New England (USA) wheat and soybean yields would increase in a doubled-$CO_2$ world, while maize yield might show small decreases. Southworth et al. (2000) obtained decreasing or unchanging future maize yields, particularly for short- or medium-season hybrids, for some parts of the Midwestern Great Lakes region (USA) with climate scenarios based on the HadCM2 A–OGCM. Also, a study conducted in southern Finland, which presents a climate somewhat similar to that of Québec, showed increasing wheat yields for future climate scenarios also based on the HadCM2 model (Saarikko 2000). Finally, the study on future potato yields by Holden et al. (2003) for Ireland obtained results similar to those of this study.

The low spatial resolution of the A–OGCM makes it difficult to accurately predict the impacts of climate change at the regional level (Hoogenboom 2000). Even downscaling techniques, like the GIDS method used here, though they give adequate results, can still be an additional source of error (Nalder & Wein 1998, Price et al. 2000). Also, there is the problem of uncertainty in the simulation of some important climate processes in A–OGCMs: most importantly, both the amount and spatial distribution of precipitation events are highly uncertain which, when considering the importance of water for plant growth and yield, would have a great impact on the accuracy of simulated yields (Mearns et al. 1995, B. Singh et al. 1998).

Crop models, such as those used in this study, do not account for all the important environmental and management factors affecting plant development and growth. The impacts of tillage, intercropping, and excess soil water are not accounted for, and the quality of the simulations may be inadequate under severe environmental stress conditions (Jones et al. 1998). The same is true for pests, competitors, and diseases, which are not modeled in DSSAT crop models (except for pests in CROPGRO, not used in this study; Jones et al. 1998). Manning & Tiedemann (1995) showed that the future climate will probably be favorable to pathological agents (bacteria and fungus), which would be detrimental to future yields.

Furthermore, the coupled A–OGCM climate scenario–crop model approach assumes that the only changing factor affecting future yields is climate, and that other environmental conditions and farm management strategies remain unchanged. But one must bear in mind that the predictions made in this manner may be an inaccurate reflection of how crop yields may really change, since most of the factors that are held constant will vary following $CO_2$-induced climate change. Farmers generally tend to have a proactive approach to agriculture: they change their practices in response to environmental and economic conditions (Bryant et al. 1995). As climate changes, they adapt, either by modifying their irrigation practices, by changing the cultivars grown, by planting at earlier or later dates, to name a few possibilities. Nonetheless, a sensitivity assessment of future yields, as in this study, not considering these changes in agricultural practices, is necessary in order to determine the nature and direction of future adaptation.

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