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## Economic impacts of climate change on agricultural crops in Canada by 2051: A global multi-regional CGE model analysis

### Abstract

The agriculture sector plays an important role in Canada's national and provincial economies. Previous studies have projected significant climate change impacts in agricultural crops in Canada, with considerable variation across regions. In this study, we examined the potential economic impact of climate change on agricultural crops across Canadian provinces and territories, the United States, and the rest of the world over the 2006-2051 period using a recursively dynamic, multi-regional CGE model. Two scenarios were defined in the model, including: (1) a baseline scenario where economies grow based on exogenous labor force growth rates and endogenous capital investments; and (2) a climate change scenario where the additional impacts of climate change on agricultural crops were incorporated. Results indicated that the percentage change impacts on agricultural crop production were not always proportional or similar in direction to the resulting impacts on input/output expenditures, trade, GDP or welfare in a region. Price changes, input substitutions, and trade dynamics were the driving forces behind these outcomes. Overall, this analysis can be said to provide the first (and preliminary) estimates of regional economic impacts from climate change in the Canadian agriculture sector. Further analysis is needed to accurately quantify and model the impacts so that they can confidently be used as a baseline when evaluating adaptation options in the sector.

**Keywords:** climate change, agriculture, economic impacts, computable general equilibrium model.

**JEL Classification:** C68, D58, I31, O13, Q54.

### Introduction

The agriculture sector plays an important role in Canada's national and provincial economies. At the national level in 2010, the sector produced over \$50 billion in output and directly or indirectly employed over two million people (Statistics Canada, 2011a; AAFC, 2012). In some of the Atlantic and Prairie provinces, the sector has contributed nearly 10% of provincial output. The sector is the largest in the provinces of Saskatchewan, Ontario, and Alberta where provincial output values have exceeded \$10 billion (\$2006) annually.

While most provincial agricultural sectors have experienced challenges over the past few decades with rising costs, depressed commodity prices, and extreme weather conditions, there are strong indications that agricultural production in many provinces will increase in the future as a result of climate change (Weber and Hauer, 2003). The driving force behind this expected outcome is the projected increase in average annual temperature over the next 50+ years which is expected to lengthen the growing season in Canada, resulting in increased crop yields (Cline, 2007).

A number of recent studies have quantified potential impact of climate change on crop production in Canada. These studies typically employ econometric methods (using crop yield or Ricardian value models) to estimate historical influence of climatic variables on selected crops (yields or value) in localized geographic areas, and then combine the results with general circulation model (GCM) climate predictions to estimate climate-induced impacts (e.g.,

Cabas et al., 2010; Almaraz et al., 2008; Bootsma et al., 2005; Weber and Hauer, 2003). These studies have estimated crop yield increases in the range of 1% to 115%, and crop value increases in the range of 1% to 38%, depending on the type of crop and region of analysis.

Studies that assess the potential economy-wide impacts of climate change on Canadian agriculture are more scant in the literature. A few studies do exist that employ global, multi-regional computable general equilibrium (CGE) models, with Canada defined as one of the regions. For instance, Zhai et al. (2009) used Cline's (2007) estimates of climate change impacts on crop yields in a CGE model and estimated a 0.2% GDP loss and 0.2% welfare gain for Canada by 2080. Ronneberger et al. (2009) on the other hand reported a GDP gain of less than 0.005% for Canada by 2050 as a result of climate-induced changes in agriculture. Furthermore, Reilly et al. (2007) estimated a consumption gain of 0.2% in Canada from climate change impacts on agriculture and forests by 2100. In another study by Bosello et al. (2012), the aggregated region of Canada, Japan and New Zealand as a whole was projected to experience a GDP loss of 0.3% by 2050 from such impacts.

The CGE model studies cited above have either classified Canada as a single region or aggregated Canada with other countries into a single region. However, climate change impacts in the agricultural sector are expected to vary considerably across Canadian provinces and territories (Weber and Hauer, 2003; Reinsborough, 2003). Therefore, the studies undertaken so far fail to appropriately account for regional variation in, and vulnerabilities to, climate change in the Canadian agriculture sector.

The objective of this study was to investigate the regional distribution of economic impacts of climate change on the agriculture sector across Canadian provinces and territories. We conducted our analysis over the 2006-2051 period using a recursively dynamic, multi-regional CGE model. The model included 13 regions, with 11 Canadian provinces and territories, the United States (US), and the rest of world (RW) region. This study was the first to systematically assess the potential economy-wide impacts of climate change in agriculture sector in Canadian regions using such a model.

The remainder of this paper is as follows. In the first section, we describe the structure, calibration, and simulated scenarios of the CGE model. In the second section, we present the results of the economic analysis. The final section provides a discussion of the findings, outlines some of the limitations, and concludes the paper.

## 1. Methods

**1.1. Model specification.** The recursively dynamic CGE model was based on traditional neoclassical economic theory and similar to recent work by Bezabih et al. (2011), Lofgren et al. (2002), and Thurlow (2008). The model was deterministic in nature with assumptions of small-open-economies (price takers) and constant returns to scale technology for each region. The model was formulated as a set of simultaneous linear and non-linear equations, which define: (1) the behavior of economic agents; (2) market conditions; (3) macroeconomic balances; (4) intertemporal components; and (5) steady-state economic growth path. Model equations are presented in the Appendix.

In the model, producers were assumed to maximize profits (defined as the difference between revenue earned and the cost of factors and intermediate inputs) subject to constant returns to scale technology with three factors of production: labor, capital and agricultural land services. Production was specified in a two-level nest where at the top level, a composite of value-added and a composite of intermediate inputs are smoothly substitutable in a CES function. At the bottom level, the three primary input factors were assumed to substitute smoothly through a CES composite value-added function under single primary factor nest. Intermediate inputs on the other hand, were determined by fixed-shares through a Leontief function.

Each region had a representative household who received income from supplying inputs of production, and from import tariff revenues transferred to them by their domestic governments. Supplies of input factors were assumed to be fixed within a given time-period. While labor and capital were mobile across sectors, agricultural land services were specific to the agriculture sector. The optimal allocation

between consumption of commodities by households was through maximization of a Stone-Geary Utility function subject to its disposable income constraint.

Total savings were defined as the sum of household savings and foreign savings. Investment demand was determined by total savings factored by a Cobb-Douglas investment preference for each commodity. A Phillips curve was specified in the model to introduce unemployment. This explained the wage-unemployment relationship in the model using factor prices and supplies, and a Laspeyres consumer price index (CPI).

Equilibrium in the factor market required that the demand for inputs equals the supply, with the exception of labor where unemployment (determined through the Phillips curve) created a wedge between the two. Input supplies were exogenously determined in a given period. Equilibrium in the commodities market required that demand for commodities equal supply. Aggregate demand for each commodity comprised household consumption spending (consumption, investment and intermediate) on domestic and imported goods.

With regard to foreign trade, products were differentiated according to their region of origin. On the demand (import) side, the domestic consumers discriminated between the domestically produced and imported goods in the first level of Armington aggregation. In the second level, consumers discriminated between imported goods from different regions (assumption of imperfect substitutes). Therefore, the demand between domestic and imported goods was determined through a CES Armington specification.

On the supply (export) side, the domestic outputs delivered to domestic market were differentiated from products produced for export by the same sector. The export decision of producers was governed by a constant elasticity of transformation (CET) function, which distinguished between exported and domestic goods.

A zero profit condition was applied in the models such that the total value of aggregated imports of a particular good in a given region equaled the total value of imports of that good from all other regions. The world export price (f.o.b.) of a particular good from a particular region was the same as the world import price (c.i.f.) of the same good in the receiving region from the exporting region.

Regional balance of payment was achieved by equating aggregate imports with aggregate exports plus foreign savings at world prices. The global trade balance was assumed to be zero to ensure that the values of bilateral trade flows were cleared.

The model was solved under the ‘square matrix condition’, requiring that the number of endogenous variables equaled the number of equations. To achieve this condition, we exogenously fixed factor supplies and regional and global foreign savings while we allowed the exchange rates to adjust (with the exception that all Canadian provincial economies have their exchange rates tied to one another). The wage rate in each region was exogenously fixed as the numeraire price for each region. Finally, the zero global foreign savings constraint was imposed to ensure that the value of global exports equaled the value of global imports.

**1.2. Model calibration.** The model was calibrated for 23 sectors in each regional economy. The eleven Canadian regions (i.e., Newfoundland and Labrador, NL; Prince Edward Island, PE; Nova Scotia, NS; New Brunswick, NB; Quebec, QC; Ontario, ON; Manitoba, MB; Saskatchewan, SK; Alberta, AB; British Columbia, BC; Territories, TR) were calibrated to their regional economies in 2006 using data from the Statistics Canada input-output (IO) database (Statistics Canada, 2011a). The US economy was calibrated for the same period using annual industry accounts IO data (USDOL, 2011). Both Canada and the US input-output tables use same classification system (North American Industry Classification System-NAICS). Finally, the RW economy was calibrated using data from the Global Trade Analysis Project (first developed by Hertel, 1997) 2004 baseline IO data, and projected to 2006. Specifically, an aggregation utility (GTAPAgg Package) was used to first aggregate the database into three regions (US, Canada and RW) and 23 sectors. We then projected the IO data for the RW to 2006 to match the other regions using historical world economic growth rates between 2004 and 2006 (World Bank, 2011), assuming the same inter-industry technical coefficients between the years.

Interregional trade flow data among the regions was established from the Canadian side (from which data was available). The interprovincial trade data among Canadian regions and their accompanying international trade data were obtained from Statistics Canada (Statistics Canada, 2011b). Then, international trade data from the Canadian regions were further disaggregated into those for the US and RW. This was achieved in two steps. First, trade data between the Canadian regions and the US were obtained from Industry Canada (Industry Canada, 2011) and assigned for the bilateral trade flows between the Canadian regions and the US. Second, the residual value from the international trade portion was assigned to RW. The regional economies were aggregated into 23 sectors at small (S-level) aggregation following the North American Industry Classification System (NAICS, 2002 version), which

was the most detailed and current data that could be obtained from Statistics Canada (2011c) at the time of this study<sup>1</sup>.

The three primary input factors defined in the model were estimated as follows. Capital was estimated as the sum of other operating surplus, indirect taxes on products, subsidies on products, other subsidies on production, and other indirect taxes on production less land services expenditures (described hereafter). Labor was measured by wages, salaries, and supplementary labor income, in addition to ‘mixed income’ (i.e., income of unincorporated businesses). Agricultural land services was more difficult to define since it was not isolated as an input factor in the Canadian and US input-output tables, but rather included in finance, insurance, real estate and rental and leasing sector. Therefore, we used factor share ratios of value-added in the agriculture sector to isolate associated land services expenditures and specified it as factor input for the Canadian regions (Echevarria, 1998). For US and RW, we used the GTAP database where land was specified as factor input.

In terms of parameter specifications, elasticities of substitution in the composite value-added function, and income elasticities of demand for commodities were obtained from Dimaranan et al. (2006). Armington, CET elasticities and import tariffs were derived from GTAP database following sectoral aggregation. For simplicity and due to lack of region and sector specific (in some cases) data, we assumed the same elasticities existed for all regions.

Unemployment rate data for the Canadian regions were obtained from provincial labor force survey estimates (Statistics Canada, 2011e). We estimated mean annual rates across all age groups from the seasonally adjusted monthly rates (both sexes). Unemployment rate data for the territories were missing; therefore we assumed it was similar to the adjacent province, Alberta. For the US, we use the annual average unemployment rate, civilian labor force 16 years and over (USDOL, 2011). Due to lack of unemployment rate data for the RW, we assumed a worldwide average rate from International Labor Organization (ILO, 2011) applied.

<sup>1</sup> The NAICS 2002 version has 25 sectors. However, we disaggregated manufacturing [31-33] into three sectors: wood products manufacturing [321], pulp and paper manufacturing [322] and ‘other manufacturing’ [31-33 except 321 and 322]. We also aggregated five other service sectors into one sector: Other services (except public administration) [81]; Operating, office, cafeteria, and laboratory supplies [not NAICS defined]; Travel and entertainment, advertising and promotion [not NAICS defined]; Transportation margins [not NAICS defined]; and Non-profit institutions serving households [8131] (numbers in parenthesis represent NAICS 2002 codes). For further details on the sectors, see Statistics Canada Table 381-0013 (Statistics Canada, 2011d).

The CGE model was formulated as static and solved recursively (sequentially) over a 45-year (2006-2051) time period. For every period, capital stock in each region was updated via a capital accumulation equation which was based on an endogenous growth rate as determined by return on capital rate and total savings. Total labor supply grew at a constant rate based on population growth rate forecasts. For the Canadian regions, we estimated average annual growth rates (percent) between 2010 and 2036 (the furthest point under the category) from the medium growth (M2) projection scenario (2006 to 2008 trends), both sexes, all ages category (Statistics Canada, 2011f), as the most representative of future population trends. For the US, we used the annual projections from 1999 to 2100 from US Census Bureau (USCB, 2011) and annualized the growth rates. For the RW, we used the projected average annual world population growth rates from 2000 to 2050 (United Nations, 2004). Finally, land services supply in the agriculture sector was exogenously fixed over time to allow for climate change shocks in the agriculture sector.

**1.3. Model solutions and simulations.** The model was solved using the General Algebraic Modeling System (GAMS) software with a nonlinear programming (NLP) algorithm along with CONOPT3 solver (GAMS, 2012; Rosenthal, 2012). After solving the model for the initial period equilibrium to replicate the 2006 benchmark IO data, we simulated two economic scenarios, including: (1) a baseline (BL) scenario; and (2) a climate change (CC) scenario. For the BL scenario, we simulated a dynamic growth path of the economy (i.e., without climate change impacts on agriculture sector) where economies grow based on exogenous labor force growth rates and endogenous capital investments. For the CC scenario, we added to the BL scenario the additional impacts of climate change on agricultural crops. Here, we changed agricultural land services supply according to crop yield change estimates<sup>1</sup>.

The regional changes in agricultural land services supply considered in the CC scenario were based on estimates from Cline (2007) for US and RW regions and Weber and Hauer (2003) for Canadian regions. Specifically, Cline (2007) synthesized several studies using Ricardian and production function (crop) models, and combined these with leading general circulation models climate projections to establish “preferred” estimates of climate change impacts on agricultural productivity for more than 100 counties over the 2003-2080 period. In Weber and Hauer

(2003), a Ricardian model was used to estimate the impacts of climate change on Canadian agriculture across ten provinces over the 1995-2051 period.

Since the analysis by Cline (2007) and Weber and Hauer (2003) employed different methods and projected climate change impacts over different time periods, a number of adjustments were required to effectively use these estimates in our analysis. First, we converted Weber and Hauer’s (2003) projected impacts of climate change on agriculture productivity (measured as change in land value per hectare) over a 56-year period (1995-2051) into annualized percentage change impacts over a 45-year period (2006-2051) to match our time-frame of analysis. Second, we took Cline’s (2007) ‘preferred’ impact estimate for Canada as a whole, the US, and the world as a whole<sup>2</sup> (measured as a change in agricultural output potential, with carbon fertilization, over a 77-year period; 2003-2080) and proportioned these impacts (i.e., the Ricardian model, crop model and ‘preferred’ estimates) over a 45-year period (2006-2051). Third, we adjusted the 45-year provincial Ricardian impact estimates of Weber and Hauer (2003) using Cline’s (2007) procedure for Canada as a whole to estimate what we call Cline’s equivalent ‘preferred’ provincial impact estimates. Because Weber and Hauer (ibid.) did not include the territories region of Canada in their analysis, we assumed this region had the same climate change impact as the province with the greatest impact because of its furthest north (higher latitude) geographic location (Mendelsohn and Reinsborough, 2007). Table 1 provides the estimated 2006-51 impacts on agricultural land services. These values were annualized and used in the climate change scenario.

Differences in economic outcomes between the BL and CC scenarios were interpreted as the economy-wide impacts of climate change on agricultural crops. Specific economic variables assessed in the models under each scenario included: input (labor and capital) expenditures, trade (imports, exports, and terms of trade), output (by sector, and total), prices (input, output, import, export, consumer price index), exchange rates, unemployment, income, investment, consumption, GDP, welfare (compensating variation<sup>3</sup>), and others. In this paper, we focused on presenting results associated with input expenditures, trade, output (agriculture sector and total), prices (import, export, consumer price index),

<sup>1</sup> Land services supply in agriculture sector was assumed to be measured in “productivity” units, where there existed a direct and monotonic relationship between the percentage changes in crop yield and land services supply (Darwin et al., 1995).

<sup>2</sup> We used climate change impacts for “World” (i.e., the entire world) from Cline (2007, Table 5.9, p. 77) here to represent “Rest of the World” (i.e., the entire world minus Canada and US) in our case.

<sup>3</sup> Compensating variation is the amount of income that must be taken away from an individual given a set of new prices so that the utility of the individual is the same as it was before price change. Compensating variation represents a more accurate estimate of welfare than consumer surplus because the former accounts for income effects while the latter does not.

exchange rates, GDP and welfare (compensating variation as a percentage of GDP) impacts. We presented cumulative (2006-2051) economic impacts of

climate change in present-value (2006) terms, discounted at 4% rate<sup>1</sup>. All values were in Canadian billion dollar terms.

Table 1. Climate change impacts on crop yields and agricultural land service expenditures across Canadian regions, the United States, and the rest of the world (% change over the 2006-2051 period)

Region	Impact on crops			Impact on agricultural land services <sup>d</sup>
	Ricardian models <sup>a</sup>	Crop models <sup>b</sup>	Preferred <sup>c</sup>	
Newfoundland and Labrador	16	-	9	6
Prince Edward Island	15	-	8	7
Nova Scotia	23	-	13	12
New Brunswick	53	-	29	16
Quebec	49	-	28	24
Ontario	45	-	25	21
Manitoba	134	-	75	73
Saskatchewan	152	-	85	67
Alberta	112	-	63	61
British Columbia	22	-	12	10
Territories	152	-	85	0
United States	12	-2	5	2
Rest of the world	2	-4	-2	-1

Notes: <sup>a</sup>Values for United States and rest of the world regions were derived from Cline (2007). Values for Canadian regions were derived from Cline (2007) and Weber and Hauer (2003). <sup>b</sup>Values for United States and rest of the world regions were derived from Cline (2007). Consistent values for Canadian regions were not available. <sup>c</sup>Values for United States and rest of the world regions were derived from Cline (2007). Values for Canadian regions were estimated using the relationship between 'Ricardian' and 'Preferred' values for Canada as a whole, as calculated by Cline (2007). <sup>d</sup>Values are the 'preferred' estimates (column 4) adjusted for respective share of crops in each regional agriculture sector (based on the percentage of 'grains and other crops' output in the 'agriculture' sector output as defined under NAICS, 2002).

## 2. Results

Cumulative, present value economic impacts of climate-induced changes in agricultural land services across Canadian provinces, the US, and RW over the 2006-51 period are presented in Tables 2, 3 and 4. The following details the findings.

**2.1. Inputs.** Many Canadian provinces experienced reductions in their labor and/or capital input expen-

ditures (Table 2). This was largely due to factor substitution following increases in their agricultural land services. Labor substitution tended to be relatively greater than capital substitution due to imperfect labor markets. Similar factor substitution results emerged in the US. In the RW, on the other hand, the climate-induced reduction in agricultural land services had little to no effect on labor and capital input expenditures.

Table 2. Trade, input, and output impacts of climate change on agricultural crops in Canadian Provinces, US, and rest of world regions (cumulative % change, 2006-2051, 4% discounted)

Region	Input		Trade			Output	
	Labor	Capital	Import	Export	TOT <sup>a</sup>	AgriSector <sup>b</sup>	Total
Newfoundland	-0.03	0.00	1.19	7.54	-4.97	-39.45	-11.27
Prince Edward Island	-1.37	-0.10	2.54	9.09	-2.00	24.03	2.12
Nova Scotia	0.64	0.00	-2.29	3.79	-6.84	0.85	4.50
New Brunswick	-0.24	0.00	2.21	10.34	-5.34	49.60	0.60
Quebec	0.57	0.12	-0.63	5.77	-6.89	1.77	-0.71
Ontario	-0.43	0.30	10.52	19.60	-4.21	16.69	4.66
Manitoba	-0.05	-0.02	-1.94	5.06	-5.83	19.02	-1.44
Saskatchewan	-0.32	-0.02	-5.78	1.37	-5.92	8.46	-5.19
Alberta	-0.05	-0.38	-1.24	5.66	-4.90	9.43	-3.91
British Columbia	3.00	-0.54	-0.88	7.96	-5.65	-1.85	0.70
Territories	-0.02	-0.02	-11.03	-8.22	-9.37	-4.60	-5.51
United States	-1.16	-0.21	7.55	-0.10	10.90	5.59	0.84
Rest of the World	0.00	-0.02	9.76	-2.87	16.64	-3.71	-4.42

Note: <sup>a</sup>TOT = terms of trade. <sup>b</sup>AgriSector = agricultural sector.

<sup>1</sup> This rate approximated the mean yield on long-term Government of Canada bonds over the 2005-2012 period (Bank of Canada, 2012).

**2.2. Trade.** A majority of Canadian provinces realized reductions in their imports (Table 2). This was largely due to consumers and producers responding to increases in their agricultural land services by reducing their demand for relatively more expensive imports and relying more on domestic production to meet their composite demand. In the US and RW, imports increased as import prices fell (Table 3) and consumers and producers substituted domestic for foreign goods and services.

The increase in agricultural land services also resulted in an increase in most provinces' exports (Table 2). On the other hand, exports in the US and RW declined, largely as a result of an appreciation in each countries' exchange rate (Table 3). The resulting impact on the terms of trade was negative for Canadian provinces and positive for US and RW regions (Table 2), implying that Canadian region exports became cheaper while their imports became more expensive, in relative terms to those of the US and RW regions.

Table 3. Price and exchange rate impacts of climate change on agricultural crops in Canadian Provinces, US, and rest of world regions (cumulative % change, 2006-2051, 4% discounted)

Region	CPI <sup>a</sup>	Import price	Export price	Exchange rate
Newfoundland	0.04	1.82	-2.66	-
Prince Edward Island	1.40	0.64	-0.74	-
Nova Scotia	-0.78	3.20	-0.70	-
New Brunswick	0.13	2.64	-3.19	-
Quebec	-0.41	3.98	-1.96	-
Ontario	-0.07	5.80	1.29	-
Manitoba	0.43	4.55	1.18	-
Saskatchewan	0.43	3.64	-1.44	-
Alberta	0.66	2.05	-2.25	-
British Columbia	-6.53	6.24	1.73	-
Territories	0.01	3.16	-3.62	-
United States	3.29	-13.09	3.03	8.41
Rest of the World	0.70	-14.61	3.89	10.22

Notes: <sup>a</sup> Consumer price index.

**2.3. Output.** Most Canadian provinces realized increases in their agriculture sector output (Table 2), which were largely similar in direction to the change in their agricultural land services. Exceptions included NL, TR, and BC. The two regions of NL and TR in particular experienced negative agriculture sector output impacts despite their small increases in agricultural land services largely due to a loss in their competitive position in comparison to other regions. The US and RW regions exhibited an increase and decrease in their agriculture sector output, respectively, which align with the climate-induced changes in

their agricultural land services. Total output followed a similar pattern for most regions.

**2.4. GDP.** All regions experienced increases in their GDP (Table 4). In Canadian provinces and the US region, these increases were consistent (though not proportional) with the respective increases in their agricultural land services. The RW, on the other hand exhibited a GDP gain despite having an agricultural land services decline. This GDP gain arises from its enhanced global competitiveness following climate change shocks across the regions. Specifically, RW recorded a 16.64% gain in its terms of trade (Table 2), the highest of all regions.

Some provinces such as BC recorded among the highest GDP impacts of all provinces (Table 4) despite their relatively low agricultural land services impacts (Table 1), and vice-versa for other provinces such as SK. Such disproportional impacts were largely attributed to the magnitudes and direction of change of GDP components and their associated price adjustments. Particularly critical here were the changes in export prices which influenced the competitiveness in international trade. For instance, BC had the largest provincial increase in export prices at 1.73% (Table 3), which increased exports by 7.96%, and resulted in a significant contribution to its 6.34% GDP increase. SK, on the other hand had a relatively small reduction in its export price at 1.44%, leading to a small change in its exports at 1.37%, thereby contributing little to its 0.54% GDP increase.

**2.5. Welfare.** A majority of Canadian provinces exhibited welfare losses (Table 4). Only four regions (i.e., NS, QC, AB and BC) realized welfare gains. The highest welfare gain of 5.59% in BC was largely a result of a 6.54% decrease in their consumer price index in the region (Table 3), the greatest among all the regions. On the other hand, PE had the greatest welfare loss at 1.11%, largely arising from a consumer price index gain of 1.41%, which was second highest after that of US at 3.30%.

Table 4. GDP and welfare impacts of climate change on agricultural crops in Canadian Provinces, US, and rest of world regions (cumulative % change, 2006-2051, 4% discounted)

Region	GDP	Welfare <sup>a</sup>
Newfoundland	2.47	-0.13
Prince Edward Island	0.81	-1.11
Nova Scotia	1.40	1.17
New Brunswick	1.51	-0.35
Quebec	0.46	0.19
Ontario	1.01	-0.57
Manitoba	1.33	-0.05
Saskatchewan	0.54	-0.45

Table 4 (cont.). GDP and welfare impacts of climate change on agricultural crops in Canadian Provinces, US, and rest of world regions (cumulative % change, 2006-2051, 4% discounted)

Region	GDP	Welfare <sup>a</sup>
Alberta	2.51	1.85
British Columbia	6.34	5.59
Territories	0.37	-0.08
United States	0.59	-0.99
Rest of the World	0.26	-0.31

Notes: <sup>a</sup>Welfare = compensating variation as a percentage of regional GDP.

### 3. Discussion and conclusions

This study has provided a number of important findings. For instance, we found that a region's estimated economic impacts were not always proportional, or similar in direction, to the climate-induced changes in the region's agricultural land services. Other studies such as Zhai et al. (2009) and Iglesias et al. (2012) have found similar results. From our analysis, we determined that foreign trade markets can have an important influence on the economic variables.

Generally, many economic impacts (including those for inputs, trade, GDP and welfare) were smaller in percentage change terms than the respective change in agricultural land services. This was largely due to the relatively low contribution of agricultural sector to regional economies. Iglesias et al. (2012) found similar results.

Another finding that was consistent with other literature was that GDP and welfare impacts within a region did not necessarily follow a similar direction of change. Often, we found cases where there were GDP gains and welfare losses. Zhai et al. (2009) found similar patterns. This meant that even though the economy may have expanded through gains from trade, household welfare ultimately depended on the net effect of changes in input and consumer prices.

When comparing our Canadian provincial economic impact estimates to those of other studies conducted at a national level, we find significant differences. For instance, we estimated provincial present value GDP impact gains that ranged between 0.37% and 2.47% over the 2006-51 period, depending on the region. Weighting these percentages by the value of GDP in each province and aggregating them results in a 1.7% GDP increase for Canada as a whole. However, Zhai et al. (2009) estimated a GDP loss of 0.2% for Canada as a whole. Ronneberger et al. (2009), on the other hand, found less than 0.005% GDP gain for Canada. Furthermore, for the US region, we estimated GDP impact gain of 0.59%, which was larger in magnitude compared to Zhai et al. (2009) who estimated a GDP loss for US at 0.1%. Additionally, for RW, we estimated a GDP gain of 0.26%.

This was higher than the range estimated by Iglesias et al. (2012) at -0.1% to 0.15% for various world regions. Similar differences emerged for welfare. The differences in our findings with these others can be attributed to a number of factors including differences in model specifications, crop impacts considered, projection time frame considered, and others.

A number of limitations in this study are worth noting. For instance, we generated estimates of regional climate change impacts on agricultural land services from different sources (i.e., Cline, 2007; Weber and Hauer, 2003), using an *ad-hock* technique. This data represent, at best, only ball-park estimates. Additionally, we did not use disaggregated data, or model, the regional variation in agricultural land service impacts from climate change across the US or the rest of world region, which is expected to be significant (IPCC, 2007). Future work needs to be directed toward refining this data and model so that more precise economic impact estimates can be determined.

Finally, further research is needed into estimating the simultaneous impacts of climate change in agriculture and other sectors such as forestry, tourism, energy, etc. As noted by IPCC (2007), climate change will affect multiple sectors simultaneously, and this will cause significant interaction effects between sectors. The interaction effects will change the structure and growth of economies over time. Therefore, a focus on estimating economic impacts of climate change in any one sector neglects these interaction effects, and may therefore lead to imprecise estimates. Studies such as Bigano et al. (2008) and Eboli et al. (2010) confirm this conjecture. Investigating the extent of such interaction effects is the intent of the authors in future research.

Despite the above limitations, this study provided the first estimates of provincial, economy-wide impacts of climate change on agricultural crops across Canada. The results from this study can be used as baseline information for policy makers when planning and designing provincial climate change adaptation strategies in agricultural sectors across Canada.

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## Appendix

Table A1. CGE model variables

Variable <sup>a</sup>	Description
Production block:	
$FAD_{of}$	Factor input demand
$FAS_{of}$	Factor supply
$VAD_{oi}$	Value-added input demand
$IDE_{oi}$	Composite intermediate input
$PVA_{oi}$	Value-added tax inclusive input price
$PID_{oi}$	Intermediate input price
$PF_{of}$	Factor price
$PD_{of}$	Domestic output producer price (before production tax)
$PDD_{oi}$	Consumer price of domestic output sold to domestic markets
$X_{oi}$	Domestic sales of composite commodities
$XD_{oi}$	Domestic production (output)
$XDD_{oi}$	Domestic output delivered to home markets
Household block:	
$INC_o$	Household total gross income
$SAH_o$	Household savings
$CBUD_o$	Household disposable income (budget) after tax and savings
$SBUD_o$	Household discretionary (supernumerary) budget
$CON_{oi}$	Household consumption demand of commodities
$SAT_o$	Household total savings
$INV_{oi}$	Investment demand for commodities
$TRMT_o$	Total import tariff revenues
$UNEMP_o$	Unemployment level (Phillips curve)
$CPI_o$	Consumer price index
Other prices block:	
$PP_{oi}$	Domestic tax inclusive producer output price
$PC_{oi}$	Domestic tax inclusive consumer price
$PX_{oi}$	Composite commodities demand price
$IMP_{oi}$	Composite imports
Foreign trade block:	
$EXP_{oi}$	Composite exports
$MO_{od}$	Imports by d from o
$EO_{od}$	Exports by o to d

Table A1 (cont.). CGE model variables

Variable <sup>a</sup>	Description
Foreign trade block:	
$PM_{di}$	Domestic composite imports price
$PE_{oi}$	Domestic composite exports price
$PWEO_{iod}$	World export price f.o.b. inclusive of export tax or subsidy
$PWMO_{iod}$	World import price c.i.f. inclusive of transportation costs
$SAF_o$	Regional foreign savings
$GFS$	Global foreign savings
$EXR_o$	Exchange rate
Other:	
$OBJ$	Dummy objective variable

Note: <sup>a</sup> Subscripts  $i$  and  $j$  are sets that denote sectors ( $i, j = 1, 2, \dots, 23$ ); Subscripts  $o$  and  $d$  are sets that denote regions ( $o, d = 1, 2, \dots, 13$ ); Subscript  $f$  is a set that denotes input factors ( $f = 1, 2, 3$ ).

Table A2. CGE model parameters

Parameters <sup>a</sup>	Description
Elasticities of substitution:	
$\sigma V_{oi}$	Substitution in the composite value-added function
$\sigma P_{oi}$	Substitution between the composite value-added input and the composite intermediate input
$\sigma A_{oi}$	Armington substitution between imports and domestic commodities
$\sigma T_{oi}$	CET substitution between domestic and export markets
$\sigma M_{oi}$	Substitution of imports of different origins
$\sigma Y_{oi}$	Income elasticities of demand for commodities
Share parameters:	
$\gamma V_{oif}$	Share parameter in composite value-added input function
$\gamma P_{oi}$	Share parameter in total cost (production) function
$\gamma A_{oi}$	CES share parameter in level one of the Armington aggregation function
$\gamma T_{oi}$	CET share parameter in transformation function
$\gamma M_{oid}$	Share parameters in the second level of Armington aggregation function
Efficiency (shift) parameters:	
$\phi V_{oi}$	Shift parameter in the composite value-added input function
$\phi P_{oi}$	Shift parameter in total cost (production) function
$\phi A_{oi}$	Shift parameter in the first level of Armington function
$\phi T_{oi}$	Shift parameter in transformation function
$\phi M_{oi}$	Shift parameter in the second level of Armington aggregation function
Other parameters:	
$IO_{oij}$	Technical coefficients of intermediate inputs
$\eta_o$	Phillips curve parameter
$\alpha_{oi}$	Cobb-Douglas share parameter (preference) for investment goods
$\psi_{oi}$	Budget shares in nested-LES household utility function
$\mu H_{oi}$	Household subsistence consumption level
$\lambda_{oi}$	Marginal propensity to save
$tm_{iod}$	Import tariff rate (at the sector and region-to-region level)
$te_{oid}$	Export tax /subsidy rate (at the sector and region-to-region level)
Dynamic growth path:	
$GRW_o$	Initial steady-state labor growth rate
$RRR_o$	Real rate of return on capital
$TIME_t$	Time period into the future from base year 2006
$GRW_{ot}$	Growth rate factor for capital

Notes: <sup>a</sup>Subscripts  $i$ , and  $j$  are sets that denote sectors ( $i, j = 1, 2, \dots, 23$ ); Subscripts  $o$ ,  $d$  are sets that denote regions ( $o, d = 1, 2, \dots, 13$ ); Subscript  $f$  is a set that denotes input factors ( $f = 1, 2, 3$ ); Subscript  $t$  is a set that denotes time period in years from base year 2006 ( $t = 1, 2, 3, \dots, 45$ ).

Table A3. CGE model equations

Equations <sup>a</sup>	Description
Production block:	
$FAD_{of} = \left( \frac{1}{\varnothing V_{oi}} \right)^{(1-\sigma_{V_{oi}})} \left( \gamma V_{of} \frac{PVA_{oi}}{PF_{of}} \right)^{\sigma_{V_{oi}}} VAD_{oi}$ <p>where <math>\sum_{f=1}^3 \gamma V_{of} = 1</math></p> <p><math>f</math> = denotes labor, capital, and agricultural land services.</p>	Factor demand by firm
$VAD_{\alpha} = \left( \frac{1}{\varnothing P_{\alpha}} \right)^{(1-\sigma_{P_{\alpha}})} \left( 1 - \gamma P_{\alpha} \left( \frac{PD_{\alpha}}{PVA_{\alpha}} \right) \right)^{\sigma_{P_{\alpha}}} XD_{\alpha}$	Value-added demand
$IDE_{\alpha} = \left( \frac{1}{\varnothing P_{\alpha}} \right)^{(1-\sigma_{P_{\alpha}})} \left( \gamma P_{\alpha} \frac{PVA_{\alpha}}{PID_{\alpha}} \right)^{\sigma_{P_{\alpha}}} XD_{\alpha}$	Composite intermediate input
$PP_{\alpha} XD_{\alpha} = PVA_{\alpha} VAD_{\alpha} + PID_{\alpha} IDE_{\alpha}$	Zero profit condition for the firm
Household block:	
$INC_o = \sum_{f=1}^3 (PF_{of} FAS_{of}) + TRMT_o$	Household total gross income
$SAH_o = \lambda INC_o$	Household savings
$CBUD_o = INC_o - SAH_o$	Household disposable income (budget) after tax and savings
$CBUD_o = CBUD_o - \sum_{i=1}^{23} PC_{oi} + \mu H_{oi}$	Household discretionary (supernumerary) budget
$PC_{oi} CON_{oi} = PC_{oi} \mu H_{oi} + \psi_{oi} CBUD_o - \sum_{j=1}^{23} PC_{oj} + \mu H_{oj}$	Household consumption demand of commodities
$SAT_o = SAH_o + SAF_o$	Household total savings
$PC_{oi} INV_{oi} = \alpha I_{oi} SAT_o$	Investment demand for commodities
$TRMT_o = \sum_{i=1}^{23} \sum_{d=1}^{13} tmo_{iod} (MO_{iod} P WMO_{ido}) EXR_o$	Total import tariff revenues
$\left( \frac{PF_{of} / CPI_o}{PF_{of}^0 / CPI_o^0} \right) = \eta_o \left( \frac{UNEMP_o / FAS_{of}}{UNEMP_o^0 / FAS_{of}^0} - 1 \right)$ <p>where <math>f</math> denotes labor.</p>	Unemployment level (Phillips curve)
$CPI_o = \frac{\sum_{i=1}^{23} PC_{oi} CON_{oi}^0}{\sum_{i=1}^{23} PC_{oi}^0 CON_{oi}^0}$	Consumer price index
Market clearing block:	
$\sum_{i=1}^{23} FAD_{of} = FAS_{of} - UNEMP_o$ <p>where <math>f</math> denotes labor.</p>	Market clearing for labor

Table A3 (cont.). CGE model equations

Equations <sup>a</sup>	Description
$\sum_{i=1}^{23} FAD_{oif} = FAS_{of}$ <p>where <math>f</math> denotes capital.</p>	Market clearing for capital
$FAD_{oif} = FAS_{of}$ <p>where <math>f</math> denotes land and <math>i</math> denotes agricultural sector.</p>	Market clearing for land
$X_{oi} = CON_{oi} + INV_{oi} + \sum_{j=1}^{23} IO_{oj} XD_{oj}$	Market clearing for commodities
Foreign trade block:	
(a) Import side:	
$XDD_{oi} = \left( \frac{1}{\varnothing A_{oi}} \right)^{(1-\sigma A_{oi})} \gamma A_{oi} \left( \frac{PX_{oi}}{PDD_{oi}} \right)^{\sigma A_{oi}} X_{oi}$	Domestic demand for domestically produced goods (demand side)
$IMP_{oi} = \left( \frac{1}{\varnothing A_{oi}} \right)^{(1-\sigma A_{oi})} \left( (1-\gamma A_{oi}) \frac{PX_{oi}}{PM_{oi}} \right)^{\sigma A_{oi}} X_{oi}$	Domestic demand for composite imported goods
$PX_{oi} X_{oi} = PDD_{oi} XDD_{oi} + PM_{oi} IMP_{oi}$	Armington CES zero profit condition (cost minimization)
$MO_{oid} = \left( \frac{1}{\varnothing A_{oid}} \right)^{(1-\sigma M_{oid})} \left( \gamma M_{oid} \frac{PM_{od}}{1 + tmo_{oid} EXR_d PWMO_{oid}} \right)^{\sigma M_{oid}} IMP_{od}$ <p>where <math>\sum_{o=1}^{23} \gamma M_{oid} = 1</math></p>	CES aggregation function of imports by origin and destination
$PM_{di} IMP_{di} = \sum_{o=1}^{23} \left( (1 + tmo_{oid}) EXR_d PWMO_{oid} MO_{oid} \right)$	Zero profit condition of aggregated imports by origin and destination
$PWMO_{iod} = PWEO_{iod}$	World import price c.i.f. inclusive of transportation costs
(b) Export side:	
$XDD_{oi} = \left( \frac{1}{\varnothing T_{oi}} \right)^{(1-\sigma T_{oi})} \left( \gamma T_{oi} \frac{PP_{oi}}{PDD_{oi}} \right)^{\sigma T_{oi}} XD_{oi}$	Domestic supply of domestic output (supply side)
$EXP_{oi} = \left( \frac{1}{\varnothing T_{oi}} \right)^{(1-\sigma T_{oi})} \left( (1-\gamma T_{oi}) \left( \frac{PP_{oi}}{PE_{oi}} \right) \right)^{\sigma T_{oi}} XD_{oi}$	Export demand for domestic output
$PP_{oi} XD_{oi} = PE_{oi} EXP_{oi} + PDD_{oi} XDD_{oi}$	CET zero profit condition (profit maximization)
$EXP_{oi} = \frac{1}{PE_{oi}} \sum_{d=1}^{13} \left( \left( \frac{EXR_o}{1 + teo_{isd}} \right) PWEO_{isd} MO_{isd} \right)$	Regional aggregated exports
$PWEO_{isd} = (1 + teo_{isd}) \left( \frac{1}{EXR_o} \right) PE_{oi}$	World export price f.o.b. inclusive of export tax or subsidy

Table A3 (cont.). CGE model equations

Equations <sup>a</sup>	Description
$\sum_{i=1}^{23} \sum_{o=1}^{13} (P_{WMO_{iod}} MO_{iod}) = \sum_{i=1}^{23} \sum_{o=1}^{13} (P_{WEO_{ido}} MO_{ido}) + SAF_d$	Regional balance of payments (foreign savings)
$\sum_{o=1}^{13} SAF_o = 0$	Global foreign savings
Artificial objective function:	
$OBJ = 1$	Dummy objective variable
Macroeconomic cosurity:	
$\overline{FAS}_{of} = FAS_{of}^0$	Exogenously fix factor endowments
$\overline{SAF}_{of} = SAF_{of}^0$	Exogenously fix foreign savings
$\overline{PF}_{of} = PF_{of}^0$ where $f$ denotes labor.	Fixed domestic numeraire in each region
$\overline{EXR}_o = EXR_o^0$ for Canadian region(s) only	Fixed international numeraire for all regions
Dynamic growth path:	
$RRR_o = PF_{of}^0 FAS_{of}^0 \left( \frac{GRW_o}{SAT_o^0} \right)$ where subscript $f$ denotes capital factor	Real rate of return on capital
$GRW_{o\sigma} = \frac{SAT_o RRR_o}{PF_{of} FAS_{of}}$ where subscript $f$ denotes capital factor	Growth rate factor for capital
$\overline{FAS}_{of} = (1 + GRW_{o\sigma}) FAS_{of}$ where subscript $f$ denotes capital	Capital growth
$\overline{FAS}_{of} = (1 + GRW_o) FAS_{of}$ where subscript $f$ denotes labor	Labor growth
$\overline{FAS}_{of} = FAS_{of}^0$ where subscript $f$ denotes agricultural land services	Agricultural land services growth

Notes: <sup>a</sup>Superscript 0 denotes initial equilibrium level; Subscripts  $o$  and  $d$  are sets that denote regions of origin and destinations ( $o, d = 1, 2, \dots, 13$ ), respectively; Subscripts  $i$  and  $j$  are sets and aliases that denote sectors of the economy ( $i, j = 1, 2, \dots, 23$ ) for each region; Subscript  $f$  is a set that denotes input factors ( $f = 1, 2, 3$ ); and subscript  $t$  is a set that denotes time period in years from base year 2006 ( $t = 1, 2, \dots, 45$ ).