Climate change impacts on Canadian yields of spring wheat, canola and maize for global warming levels of 1.5 °C, 2.0 °C, 2.5 °C and 3.0 °C

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Abstract

Science-based assessments of climate change impacts on cropping systems under different levels of global warming are essential for informing stakeholders which global climate targets and potential adaptation strategies may be effective. A comprehensive evaluation of climate change impacts on Canada’s crop production under different levels of global warming is currently lacking. The DayCent, DNDC and DSSAT models were employed to estimate changes in crop yield and production for three prominent crops including spring wheat, canola and maize in current agricultural regions of Canada. Four warming scenarios with global mean temperature changes of 1.5 °C, 2.0 °C, 2.5 °C and 3.0 °C above the pre-industrial level were investigated. Climate scenarios from 20 Global Climate Models, included in the Coupled Model Intercomparison Project Phase 5 and downscaled with a multivariate quantile mapping bias correction method, were used to drive the crop simulation models. Simulated yield changes demonstrate a potentially positive impact on spring wheat and canola yields at all four temperature levels, particularly when shifting planting date is considered in the simulations. There was less consensus for the currently utilized short-season maize cultivars, as yields were only projected to increase by DNDC compared to a slight decrease by DayCent and a slight increase up to 2.5 °C followed by a decrease at 3.0 °C by DSSAT. These findings indicate that climate at the global warming levels up to 3.0 °C above the pre-industrial level could be beneficial for crop production of small grains in Canada. However, these benefits declined after warming reached 2.5 °C.

1. Introduction

Climate change has already resulted in both negative and positive impacts on global crop yields with the former being more common than the latter (IPCC 2014). For example, between 1981 and 2008, observed warming has negatively impacted maize and wheat yield in many regions, especially in tropical climates, causing global average yields to decline by 3.8% and 5.5%, respectively (Lobell et al 2011). The combined annual losses of these two crops together with barley represent a 40 million tonnes (Mt) per year loss, roughly 2%–3% of the total global production (Lobell and Field 2007). Some studies found positive effects of climate change in high-latitude regions, such as northeast China and the UK (Chen et al 2010, Supit et al 2010); yet even in regions with positive effects, it is unclear if the benefits would continue into the future with continual warming. Since Rosenzweig and Parry (1994) produced the first assessment of climate change impacts on global food supply, numerous studies have shown potential negative impacts, especially of rising temperature, on global crop yields (e.g. Challinor et al 2014, Asseng et al 2015, Liu et al 2016, Zhao et al 2017). It has been reported that for the major crops (wheat, rice and maize) in tropical and temperate regions,
climate change without adaptation would negatively impact production for local temperature increases of 2 °C or more above late-20th-century levels, although certain locations may benefit (IPCC 2014). The potential negative impact of climate change on global crop yields and production raises great concern for future global food security (Wheeler and von Braun 2013).

Canada presently plays a crucial role in global food supply, acting as the world’s fifth largest exporter of agriculture and agri-food products after the EU, the US, Brazil, and China (Agriculture and Agri-Food Canada 2016). Total agricultural land in 2016 was 64.2 million hectares (MH), representing 7% of Canada’s land area with prime farmlands mainly concentrated in the Prairie ecozone and Ontario. Considering Canada’s total land area, many factors can help explain why only a small proportion of the available land area is suitable for farming. Sub-optimal climatic conditions such as low temperature and limited solar radiation in high latitudes, low soil fertility, topography and soil quality all limit the northward expansion of agricultural production. Thus for Canada, longer growing seasons and increased crop heat units under global warming (Qian et al. 2012) will primarily be of benefit for land already in crop production under global warming.

Canada’s annual mean surface air temperature has warmed by 1.8 °C over the period 1950–2016 (Vincent et al. 2018), which is about twice that of the global mean temperature (0.85 °C over the period 1880–2012; IPCC 2014). Its warming rate is projected to continue to be faster than the global rate due to polar amplification (Li et al. 2018). As high temperatures can adversely affect crop yield, it is important to understand how Canada’s crop yields may change under future warming. This is particularly important when evaluating differential impacts of various warming levels in order to compare costs and benefits associated with different warming limits set by the Parties to the United Nations Framework Convention on Climate Change (UNFCCC 2015). Knowledge of these impacts is currently lacking.

Previous studies (Rosenzweig et al. 1993, Wang et al. 2012, Smith et al. 2013, Qian et al. 2016a, 2016b) projected an increase in spring wheat yield (grown mainly on the Canadian Prairies) under future warmer climates in the 2050s due to direct effects of elevated atmospheric CO2 concentration. Maize yields in southern Ontario under rainfed conditions and on the Canadian Prairies under irrigation were projected to increase (Smith et al. 2013, He et al. 2018). In contrast, a recent study projected potential decreases in canola yields due to increased heat/water stress at three locations, in Manitoba, Ontario and Quebec, respectively (Qian et al. 2018). These projections were often only based on one crop model, driven by a limited number of climate scenarios, and thus may not have considered the wide range of uncertainties associated with both climate and crop models. It is also important that we relate the projected crop yield changes to different global warming limits enabling the assessment of opportunities, challenges, and costs associated with these limits.

In this study, we compared climate change impacts on yield for three prominent crops in Canada (spring wheat, canola and maize) at four global mean temperature warming levels (1.5 °C, 2.0 °C, 2.5 °C and 3.0 °C above the pre-industrial level). Yields were simulated by crop models in three modelling systems (DSSAT, DNDC, DayCent; described below as crop models) driven by 20 Global Climate Models (GCMs) simulations used in the Coupled Model Inter-comparison Project Phase 5 (CMIP5, Taylor et al. 2012) (table S1). Although future warming may enable northward expansion of agriculture, this aspect is not considered. This study focuses on crop yield changes for currently cultivated areas across Canada and the projected changes in national production will be useful for developing adaptation policies on the national scale for the Canadian agricultural sector.

2. Materials and methods

2.1. Study areas and major crops

Agricultural production area in Canada is concentrated primarily in the western Prairie Provinces, Ontario and Quebec. Canola and spring wheat are two dominant crops. While maize is a prominent crop, its production region is restricted mostly to southern Ontario and Quebec as well as part of Manitoba due to limitations in heat and/or water. We included maize in our assessment, partly because its production may increase due to increased heat units in a warmer world.

Canada uses an agricultural economic model for the Canadian agricultural sector, namely the Canadian Regional Agricultural Model (CRAM), to conduct its agricultural policy analysis and research (Horner et al. 1992). This modelling system divides Canada into 55 spatial units (CRAM regions) that represent crop production areas (figure 1(a)). Most CRAM regions on the Canadian Prairies and in Ontario overlap with the Census Agricultural Regions that Statistics Canada (Canada’s national statistical agency) uses for reporting crop yield/production and other agricultural activities.

Crop production data for the CRAM regions are most readily available for the most recent 10 year period from 2006 to 2015. Maize has been reported for 27 CRAM regions with a total cultivated area of 1.27 MH and an annual production of 11.70 Mt. The percentage of cultivated area for maize in each CRAM region to the national total area is shown in figure 1(b). Canola has been reported for 34 CRAM regions, with a total cultivated area of 7.25 MH and an average annual production of 13.88 Mt. The percentage of the cultivated area in each CRAM region to the total area is shown in
The cultivated area for spring wheat has been declining, with a 10 year average at 6.47 MH and an average production of 19.21 Mt. Spring wheat is still the most widely reported crop across 48 CRAM regions. Spatial distribution of the cultivated area for spring wheat is shown in figure 1(d). As only spring wheat is targeted in this study, we have used ‘wheat’ hereafter to represent spring wheat. Since yield projections have been used to drive CRAM, crop modelling is conducted based on CRAM regions for each crop in their current cultivated CRAM regions.

2.2. Climate scenarios and timing of global warming levels

Crop models used in this study require a minimum set of climate inputs that includes daily solar radiation (Rad), daily maximum temperature \((T_{\text{max}})\), daily minimum temperature \((T_{\text{min}})\) and daily precipitation \((P)\). Relevant climate data for the historical period 1971–2000 and for four 30 year periods when global temperature is projected to be 1.5 °C, 2.0 °C, 2.5 °C and 3.0 °C above the pre-industrial level were obtained from multiple data sources. Observations of \(T_{\text{max}}\), \(T_{\text{min}}\), and \(P\) for 1971–2000 at a representative station located in the agricultural areas in each CRAM region were obtained from Environment and Climate Change Canada’s National Climate Data and Information Archive (Environment and Climate Change Canada 2017). Values of Rad for the representative stations were extracted from the Princeton Climate Forcing Dataset (Sheffield et al 2006) because solar radiation was not observed at most stations. These data were used for bias correcting and downscaling the GCM simulations. The bias correction is a multivariate form of quantile mapping (Kirchmeier-Young et al 2017, Cannon 2018) that first corrects GCM marginal distributions and multivariate dependence structure between sites and variables to match the 1971–2000 historical observations; and, second, preserves GCM-projected changes in quantiles in future periods. Downscaled GCM data were used to drive the crop models.

For our study, the global climate was deemed to have warmed to a specified target level (i.e. 1.5 °C, 2.0 °C, 2.5 °C or 3.0 °C) above the pre-industrial level when a 30 year average of global mean temperature reached that target level for the first time in a GCM simulation. The pre-industrial level of global mean temperature was calculated for the 1850–1900 period in the same GCM. The 15th year of the 30 year window...
Table 1. Major model processes for crop simulation in DSSAT, DNDC and DayCent.

| Model Processes                                    | Crop models | DSSAT | DNDC | DayCent |
|----------------------------------------------------|-------------|-------|------|---------|
| Cumulative heat (thermal time)                     | Yes         |       |      |         |
| Impacted by water and nutrient stress              | Yes         | No    |      |         |
| Harvest triggered by maturity                       | Yes         | Yes   | Yes  |         |
| Cultivar explicit parameterization                 | Yes         | Yes   | Yes  |         |
| Crop growth rate                                   | Yes\(^a\)  | No    |      |         |
| Function of photosynthesis/respiration             | Yes\(^b\)  | Yes   | Yes  |         |
| Function of radiation use efficiency               | Yes\(^b\)  | Yes   | Yes  |         |
| Harvest triggered by maturity                       | Yes         | Yes   | Yes  |         |
| Impacted by water and nutrient stress              | Yes         | Yes   | Yes  |         |
| Temperature response curve                         | Yes         | Yes   | Yes  |         |
| Stage dependent temperature stress                 | No          | Yes   |      |         |
| Stage dependent water stress                        | No          | Yes   |      |         |
| Crop response to atmospheric CO\(_2\)              | Yes         | Yes   | Yes  |         |
| Photosynthetic Carbon assimilation rate             | Yes         | Yes   | Yes  |         |
| Transpiration rate                                 | Yes         | Yes   | Yes  |         |
| Nitrogen use                                       | Yes         | Yes   | Yes  |         |
| Major Model Frameworks                             | Cascade water flow | Yes   | Yes  | Yes\(^c\) |
| Water demand a function of potential evapotranspiration | Yes     | Yes   | Yes  |         |
| Layered nitrogen movement                           | Yes         | Yes   | Yes  |         |
| Heterogeneous soil characterization                 | Yes         | No    |      |         |

\(^a\) The CSM-CROPGRO-Canola model uses the function of photosynthesis.

\(^b\) The CSM-CERES-Maize model and the CSM-CERES-Wheat model use the function of radiation use efficiency.

\(^c\) Unsaturated flow also occurs below field capacity.

was recorded in table S1 as the year the GCM reached the specified level of global warming. Climate scenarios in the corresponding 30 year period were used to represent the climate associated with the global warming level to drive each of the crop models. This approach provides an effective means of linking future climate scenarios for climate change impact studies to the specified levels of global warming. As global warming level was not projected to reach 2.5 °C and 3.0 °C by the end of the 21st century for a few GCMs under the Representative Concentration Pathway (RCP) 4.5, we instead used climate scenarios under RCP8.5 only. On average, the climate was projected to attain global warming levels of 1.5 °C, 2.0 °C, 2.5 °C and 3.0 °C in 2025, 2040, 2052 and 2063, respectively under the RCP8.5 scenario that has a higher emissions level than RCP4.5 (table S1), although there is a large variation in the timing among the 20 GCMs. It is worthwhile to note that our results are associated with global warming levels and thus they could be informative for a wide range of RCP scenarios, although the timing of these global warming levels and the related impacts on crop growth may vary.

2.3. Dynamic crop models

Three crop modelling systems were used namely the Decision Support System for Agrotechnology Transfer (DSSAT v4.6) (Jones et al 2003, Hoogenboom et al 2015), DeNitrification DeComposition (DNDC) (Li 2000, Smith et al 2013), and the Daily CENTURY Model (DayCent) (Parton et al 1998, Del Grosso et al 2001). These three models were selected because of the different model structures employed (table 1). Furthermore, as discussed below, these models are widely used and evaluated both globally and for Canada. Important processes such as the influences of crop diseases and pests, as well as direct damages due to extreme weather such as floods, hail and tornadoes, are not yet simulated in these models, as these processes are difficult to represent in crop models. These limitations in crop models should be accounted for when interpreting yield projections.

DSSAT includes several crop growth models in the crop system model (CSM) including the CSM-CERES-Maize model, the CSM-CERES-Wheat model and the CSM-CROPGRO-Canola model. These crop growth models were calibrated and evaluated with Canadian cultivars and current growing conditions (Jing et al 2016a, 2016b, 2017). DNDC is a well-known process-based model used to simulate carbon and nitrogen biochemistry for agricultural systems over a wide range of agricultural management, soil and climatic conditions. It is able to estimate the growth of a wide variety of crops (Zhang and Niu 2016) and has been evaluated for simulating crop yield in Canada under both current (Abalos et al 2016, Grant et al 2016, Ehrhardt et al 2018, He et al 2018) and future climate (Smith et al 2013, He et al 2018). DayCent is the daily time-step version of the CENTURY biogeochemical model (Parton et al 1994). The DayCent model is capable of simulating crop yields in Canada with comparable levels of performance as other crop models.
(Smith et al. 2012, Sansoulet et al. 2014, Grant et al. 2016, Dutta et al. 2017). DNDC and DayCent also performed similarly for simulating soil processes (Grant et al. 2016, Dutta et al. 2017, Guest et al. 2017) even though DNDC does not simulate a heterogeneous soil profile. Similar levels of performance can, in part, be attributed to the fact that many of these models employ a layered cascade water et al. 2016, Dutta et al. 2017) for simulating soil processes formed similarly for simulating soil processes. Interestingly, both DNDC and DayCent only explicitly simulate net primary production of crops (plant respiration is calculated from this output), while DSSAT simulates photosynthesis and respiration to determine C assimilation. Although DNDC likely employs the simplest approach for simulating crop biomass (empirical crop-specific growth curves, limited by nutrient and water stresses), the version employed for this study incorporates significant developments for capturing climate change impacts. These include representation of crop temperature stress based on cultivars grown in Canada (Weikai and Hunt 1999), temperature stress during anthesis, and the impacts of CO2 on crop water use and N use efficiency based on free-air concentration enrichment studies (Smith et al. 2013, Leakey et al. 2009).

2.4. Crop simulation
Climate and soil data, crop parameters and crop management data are required as input to the crop simulation models. We used the minimum set of required climate variables—daily Rad, Tmax, Tmin and P—in all simulations as other variables are less reliable and not readily available. The models were run across three soil textures (sandy loam, loam and clay loam) for each CRAM region. Crop parameters in the crop growth models in DSSAT are more comprehensively described for each cultivar than for DNDC and DayCent. Although multiple cultivars are often used in practice, wheat cultivar AC Barrie, maize cultivar P9411 HR, and canola cultivar InVigor 5440 calibrated in Canada by Jing et al. (2016a, 2016b, 2017) were used to simulate continuous wheat, maize and canola in the CRAM regions where the crop is currently cultivated, as shown in figure 1. Crop cultivars in DNDC and DayCent are more generically described, but when it was feasible, each model used crop parameters consistent with the cultivars used in DSSAT. Therefore, the estimated yield changes only characterize current cultivar production and do not reflect the potential gains that would be observed when adopting new crop cultivars for a warmer climate. Direct effects of the atmospheric CO2 concentration on crop growth and yield were simulated by using the historical and projected values of the atmospheric CO2 concentration based on Meinshausen et al. (2011). Moreover, all simulations were also conducted using the current level of atmospheric CO2 concentration (~380 ppm), so as to allow for the investigation of the effects of CO2 on the crop yield changes, as such information can be useful for improving crop models.

Earlier planting for wheat and canola is often considered as an adaptation measure to avoid heat stress at critical phenological stages, such as flowering and grain/seed filling in a warmer future climate. Our previous studies (Qian et al. 2016b, 2018) included simulations with fixed planting dates for canola and wheat. We discovered that the projected yield increase would often be smaller when a fixed planting date instead of a varying planting date was used in simulations (Qian et al. 2016b). The projected yield reductions were estimated to be larger when a fixed planting date was used in comparison to a varying planting date (Qian et al. 2018). Thus, the use of fixed planting dates might result in higher impacts of climate change on crop yields. Therefore, for this study, planting dates in the simulations were estimated using the methodologies described in Bootsma and De Jong (1988) for wheat and canola and methods in Bootsma and Brown (1995) for maize based on daily Tmax, Tmin and P at the location. In addition to planting date, nitrogen (N) fertilizer application and irrigation are also important agronomic management practices. Additional fertilizer might be required to meet crop N demand for warmer climates. To isolate the climate impacts, we simulated the potential yield (Yp) for seeds/grains and the water-limited yield (Yw) of the crops grown without N stress. The simulated Yp of a crop is associated with its cultivar and local climate without water stress, thus soil water status influenced by soil texture does not play a role in these simulations. In contrast, soil texture did have impacts on crop growth and yield in the simulations of Yw. Simulated yields across the three soil textures were averaged for each CRAM by using the weighted areal fractions of the three types in the CRAM region. Crop production in Canada is about 99% rainfed, and spring crops such as wheat and canola are seldom irrigated. Therefore, water stress is an important factor to evaluate, and we adopted a drought stress index (DSI) of Semenov and Shewry (2011) to investigate the impact of water stress on crop yield. DSI is defined as a percentage of the yield loss due to water stress, thus DSI = (Yp − Yw)/Yp × 100. Medians of DSI (DSImed) were calculated from the annual yields simulated for the baseline climate and the 30 year periods for future climate scenarios under the four global warming levels.

2.5. Changes in crop yield/production
Percent changes relative to baseline 2006–2015 yields were used to present the projected yield changes for individual CRAM regions. Crop production for each CRAM region was estimated by multiplying the yield with the average acreage of the crop for 2006–2015 in the region, and the Canadian production was derived by summing up the production from each CRAM region that included the respective crop (figure 1).
Note that changes in percent yield are calculated relative to the baseline yield, meaning a large percent change may occur even when the net change in kg ha$^{-1}$ is small. The Analysis of Variance (ANOVA) was applied to assess the relative contribution of crop models and GCMs to the overall uncertainty in the projected crop yield changes. Correlation analysis was used to investigate the relationships between the simulated crop yields and climate conditions in the growing season.

3. Results

Projected changes in growing season mean temperature ($T_h$), diurnal temperature range (DTR), and precipitation ($P$) under the global warming levels of 1.5 $^\circ$C, 2.0 $^\circ$C, 2.5 $^\circ$C and 3.0 $^\circ$C, relative to the baseline climate of 2006–2015 for maize, canola and wheat are shown in figure S1 and described in the supplementary material is available online at stacks.iop.org/ERL/14/074005/mmedia.

Projected changes (%) in the simulated crop production under water-limited (rainfed) conditions for canola, wheat and maize in Canada under global warming levels of 1.5 $^\circ$C, 2.0 $^\circ$C, 2.5 $^\circ$C, and 3.0 $^\circ$C relative to the baseline climate of 2006–2015, are shown in figure 2 for DayCent, DNDC and DSSAT. Simulated crop productions or yields, under conditions without water and N stress are presented as $Y_p$, to be compared against $Y_w$, water-limited productions/yields simulated under conditions with limited water and no N stress. The boxplots in figure 2 show the ranges of projected yield ($Y_w$) changes across the 20 GCMs simulated by the three crop models. All three crop models projected, in general, an increase in canola and wheat yields ($Y_w$) with the increase being larger and more variable at a higher global warming level. This result was attributed to the increased uncertainty in the climate projections from the 20 GCMs at higher global warming levels. Maize yields ($Y_w$) are projected to increase by DNDC but to decrease by DayCent at higher global warming levels. A very small increase in maize yields is simulated by DSSAT and the magnitude of the increases decreases with the global warming levels. The range of the projected yield ($Y_w$) changes across the 20 GCMs is often much larger with DSSAT than for DayCent and DNDC. This may imply that projected crop yield ($Y_w$) changes with DSSAT are more sensitive to the climate input.

Table 2 shows ensemble means of projected crop yield ($Y_w$) changes from the 20 GCMs for canola, wheat and maize, alongside changes simulated without the direct effects of elevated atmospheric CO2 concentration. Under the increasing global warming levels, projected yield changes were more comparable among the three crop models for wheat than for other two crops. Furthermore, the impacts of elevated atmospheric CO2 concentration on wheat and canola yields are comparable among the three crop models. Maize yields were projected to markedly increase as global warming levels increased using DNDC. A very slight increase in maize yields were simulated by DSSAT at the global warming levels up to 2.5 $^\circ$C and then a reduction occurred at 3 $^\circ$C. A slight decrease in yields was projected by DayCent across all levels. Negative impacts on maize yields increased as global warming levels increased for both DayCent and DSSAT. Benefits of elevated CO2 from improved water use efficiency on maize growth are reflected by all three models.
Ensemble means of the projected changes in crop potential yield ($Y_p$) from the 20 GCMs for canola, wheat and maize, are shown in table S2. When compared with the projected changes in $Y_w$ in table 2, higher increases in $Y_w$ than $Y_p$ were projected for canola by DayCent and DNDC but much lower increases by DSSAT. The three crop models demonstrated good agreement for future projections of reduced water stress at the global warming levels of 2.0 °C, 2.5 °C and 3.0 °C for wheat. DayCent and DSSAT simulated higher water stress in the future, which resulted in decreases or smaller increases in $Y_w$ than $Y_p$ for maize. In contrast, the projected increases in $Y_w$ by DNDC are higher than $Y_p$, but water stress was still higher. The increased $Y_w$ resulted from more favourable temperatures for maize production in the future in DNDC, whereas $Y_p$ response to temperature was limited by maximum growth. Projected changes in $\text{DSI}_{\text{med}}$ which represent projected changes in the impacts of water stress on crop yields, are shown in figure 3. The very large uncertainty in projected changes for DSI by DSSAT partly explains the model’s larger uncertainty in projected yield changes relative to the other two models.

4. Discussion

Canadian temperature has warmed at a faster rate than the global mean and this trend is projected to continue. Precipitation is also projected to increase, though not consistently, by about 5% at global warming levels of 2.0 °C and 2.5 °C but less at 3.0 °C for the growing season in regions with canola and wheat. In contrast, no increase or a slight decrease in precipitation occurs for regions with maize (figure S1). Rising temperature, changes in growing season precipitation, potentially shortened crop life cycle, combined with improved water use efficiency under the elevated atmospheric CO2 concentration can all have impacts on crop production in Canada, especially on the Canadian Prairies where water stress is the critical limiting factor. Therefore, differences in the crop models, climate scenarios and regional distributions, may result in uncertainties in the projected crop yield changes.

The projected yield changes for wheat with DSSAT are larger than the other two models and remain positive even when the direct effects of CO2 were not simulated. This could be related to the temperature thresholds in the CSM-CERES-Wheat model, which did not include the impacts of heat stress during anthesis and other related phenological periods. The impact of heat stress on growth during the critical flowering period for wheat is included in DNDC (Smith et al. 2013). Most modelling studies assessing climate change impacts on crop yields do not well simulate heat stress (White et al. 2011), and the simulation of the impacts of heat stress in models can be improved (Eyshi Rezaei et al. 2015). We ascertain that much of the projected increase in crop yields for wheat and canola is a consequence of the direct effects of elevated atmospheric CO2 concentration. This is a reasonable conclusion as the doubling of CO2 concentration has been reported to increase yields in C3 crops by about 30% (Hatfield et al. 2011), although this number is subject to high uncertainty as this yield increase may also require additional N inputs to meet nitrogen demands over time. In C4 crops (such as maize) there is effectively no CO2 response to C assimilation in comparison to C3 crops (such as wheat and canola) (Leakey et al. 2006). Rather significant increases in maize yields were simulated by DNDC. This is due to DNDC’s adoption of the temperature response functions from the six maize cultivars developed from field experiment studies in Ontario (Weikai and Hunt 1999, Smith et al. 2013) whereby the optimum temperature for maize growth is about 30 °C, and biomass and yields are negatively impacted below this temperature. In order to understand the relationships between crop yields and water/temperature stress in the crop models, correlations between simulated water-limited annual yield ($Y_w$) and growing season
mean temperature ($T$), precipitation totals ($P$), Drought Severity Index (DSI), and the simulated potential yields ($Y_p$) for the three crop models and each crop were calculated by pooling all the variables from the 20 GCMs (table S3) and the impacts are described in Supplementary material.

Some studies have indicated that crop models may be responsible for a greater proportion of uncertainty in yield projections as compared to the variations across downscaled GCMs (Asseng et al 2013). Great efforts have been taken by the global research community to compare and improve crop models (Rosenzweig et al 2013, Ehrhardt et al 2018). In the global scale crop model ensemble assessments, models are often employed across contrasting environments without detailed calibration and evaluation. For this study, we purposely selected crop simulation models that employ different frameworks and processes. Furthermore, these models were calibrated and evaluated based on experimental data at several locations across Canada. Results from ANOVA are shown in table S4 for the projected changes in $Y_p$ by three crop models under climate scenarios from the 20 GCMs at four global warming levels. The projected changes in canola and wheat yields are not significantly different among the three crop models at the global warming levels 1.5°C and 2.0°C; thus the uncertainty is likely more associated with the GCMs. The differences among the crop models for wheat become significant at the global warming levels of 2.5°C and 3.0°C, although the contribution from the GCMs is still larger than the crop models at 2.5°C. Not surprisingly, the projected changes in maize yields are significantly different among the crop models as well as the GCMs but the relative contribution to the uncertainty from the crop models is larger than the GCMs at all four global warming levels.

In addition to the uncertainty at the national level, regional differences can be large in projected yield changes across the cultivated areas of Canada. As canola is currently the dominant crop, we have chosen to show the ensemble mean of projected changes in canola yields ($Y_w$) over the 20 GCMs and three crop models in each of the 34 CRAM regions (figure 4). Negative impacts in Ontario are projected to be more pronounced at the global warming levels of 2.0°C and above than for 1.5°C; however, canola is mostly grown on the Canadian Prairies where positive impacts are projected to increase at higher warming levels. Ensemble means of the projected wheat and maize yield changes are shown in figures S2 and S3. Simulated wheat production may have benefited more from the impact of elevated atmospheric CO2 concentration on crop water use accompanied by increased precipitation (figure S2). Negative impacts on maize yields are projected for southern Ontario while positive effects could be expected in Manitoba and northern regions in Ontario and Quebec. However, it should be noted that while the projected changes are applicable to current agricultural regions in figure 1, in fact, only a small portion of a CRAM region is cultivated even though the projections are mapped across the whole CRAM region.

As stated previously, these projections are based on current crop cultivars. Proactive adaptation measures including the introduction of new cultivars, which can take advantage of an extended growing season and increased crop heat units, would result in larger increases in crop yields (Smith et al 2013). Current maize production in Canada is only viable with the use of short season cultivars and is presently concentrated...
in southern Ontario. The maize cultivar employed in the simulations with the CSM-CERES-Maize model in DSSAT only required 900 degree-days (base temperature $10^\circ C$) from planting to maturity while a medium-season cultivar needs 1300–1500 degree-days. Warming temperatures are projected to negatively impact maize yield in southern Ontario when the global warming level moved above $2.0^\circ C$ in contrast to the continued positive influences experienced in cooler Manitoba. Thus the use of longer season maize cultivars might be a beneficial adaptation strategy. In warmer areas of the world, maize yields are likely to be reduced under global warming unless maize breeding can offset these losses (Challinor et al 2016). Statistical analysis based on historical county-level yields in the United States shows that maize yields increase with temperature up to $29^\circ C$ but temperatures above this threshold are very harmful (Schlenker and Roberts 2009). Similarly, canola and wheat could also achieve potentially higher yield increases through the adjustment of cultivars. However, Moore and Lobell (2014) find that adaptation potential of European agriculture in response to climate change can be high for maize but limited for wheat and barley.

For this study, changes in crop yields were analysed only for agricultural regions where the crops are currently grown. There could be potential to grow warm season crops such as maize and soybean in more northern regions with increased temperatures in the future. Some producers have already changed the extent of their production for certain crops due to changes in historical climate and to development of more cold resistant cultivars. For example, soybean production has expanded from 1.51 MH in 2010 to 2.95 MH in 2017 (Statistics Canada 2017). Maize for grain expanded from 0.3 MH in 1965 to 1.45 MH in 2017. In addition to the potential expansion of warm season crops, spring crops such as canola and wheat may expand to some of the more northern regions that currently lack sufficient heat units providing that suitable land is available. Therefore, with the potential for changes in crop type and cropland expansion in a warmer world, Canada might have the potential for increased production of canola, wheat and maize in the future.

To our knowledge, this study is the first comprehensive assessment of climate change impacts on crop production for major crops in Canada using multiple process-based crop models with climate scenarios from a large ensemble of climate models targeting the global warming levels of 1.5, 2.0, 2.5 and $3.0^\circ C$ above the preindustrial levels. Therefore, there are no

Figure 4. Projected changes (in percentage relative to the baseline climate of 2006–2015) of canola yield in CRAM regions under the global warming levels of (a) $1.5^\circ C$, (b) $2.0^\circ C$, (c) $2.5^\circ C$, and (d) $3.0^\circ C$, as ensemble mean over the three crop simulation models DayCent, DNDC and DSSAT and the 20 GCMs.

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published ensemble studies for Canada available for comparison, although the projected changes are mostly in the same direction as those found in studies based on simulations with one crop model and a limited number of climate scenarios (e.g. Wang et al 2012, Smith et al 2013, Qian et al 2016a, 2016b, 2018, He et al 2018). Our results are consistent with previous modelling studies showing crop yield increases due to elevated atmospheric CO₂ concentrations by enhancing photosynthesis and water use efficiency (e.g. Elliot et al 2014, Durand et al 2018). Worldwide, historical crop yield trends have more commonly shown reductions rather than increases due to climate change even though the atmospheric CO₂ concentration has been increasing (Porter et al 2014). Global and regional studies mostly indicated yield reductions for wheat and maize, especially in low latitudes (Bassu et al 2014, Porter et al 2014, Rosenzweig et al 2014, Asseng et al 2015, Zhao et al 2017), and many results found that limiting warming to 1.5 °C would result in less severe negative impacts on wheat and maize yields than at 2.0 °C (Schleussner et al 2016, Huang et al 2017, Iizumi et al 2017). Interestingly, a recent study (Ruane et al 2018) found that yields for the C₃ crops including wheat improve in nearly all regions around the world for a 2.0 °C warmer world as CO₂ effects would offset the negative impacts of increasing temperature. They also identified that water-stressed regions, such as the Canadian Prairies, show the largest gains, likely due to the improved water use efficiency with the elevated CO₂. This recent study agrees well with our projections for wheat, and likely canola as a C₃ crop, in Canada. Unlike the C₃ crops, they projected continuing decreases in maize yields from the +1.5 °C world to the +2.0 °C world. Our results, similar to other modelling results, suggest it is critical to include the CO₂ effects on crop production in climate change impact studies, while such effects might not be well captured in statistical yield modelling. It should be noted that, like most other modelling studies, our modelling study does not characterize yield losses as a result of extreme climate events. This may be significant as the incidence of extreme climate events in the 2.0 °C world is deemed to be clearly higher than the +1.5 °C world (King and Karoly 2017).

5. Conclusions

Based on crop model simulations driven with climate scenarios simulated by 20 CMIP5 GCMs, we provided projections of future changes in yield for three prominent crops namely canola, spring wheat, and maize under 1.5 °C, 2.0 °C, 2.5 °C and 3.0 °C global warming levels. Canola and wheat yields were projected to increase with global warming, while maize yield was simulated to increase or slightly decrease depending on the characteristics of the currently grown cultivar and differences among the crop models. It appears that future warming accompanied by increased CO₂ concentration will remain beneficial to crop yields at the global warming level of 2.0 °C for Canada.

We found significant spread in the projected changes of yield across the 20 GCMs. This implies the necessity of using multiple climate scenarios in climate change impact studies, especially because uncertainties in climate projections are still difficult to reduce. The projections for spring wheat and canola by the three crop models were more consistent than for maize. Additional efforts are needed to further compare and improve biophysical processes in crop models such as critical temperature thresholds for crop development and growth as well as water stress. It was also found that uncertainty in projected yields increased with higher warming levels, which may be associated with the increased uncertainty in climate projections, but this might also be a result of the uncertainty in crop models.

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