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Simulated Canola Yield Responses to Climate Change and Adaptation in Canada

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ABSTRACT

A projected future warmer climate implies significant impacts on canola (*Brassica napus* L.) production in Canada. We aimed to use a modeling approach to simulate climate change impacts on canola yield in Canada and to evaluate potential adaptation measures. The CSM-CROPGRO-Canola model was used to simulate the responses of canola to the projected climate change at Brandon on the Prairies, and West Nipissing and Normandin in eastern Canada. Future climate scenarios for the near (2041–2070) and distant (2071–2100) future under two representative concentration pathways (RCP4.5 and RCP8.5) were developed based on climate change simulations by a regional climate model CanRCM4. Seeding dates were estimated from air temperature, precipitation, and soil moisture to account for the potential of earlier seeding as an adaptation measure. Compared to the baseline climate, simulated seed yield reduction was 42, 21, and 24% in the near future and of 37, 27, and 23% in the distant future, under RCP4.5, respectively for Brandon, West Nipissing, and Normandin. A larger reduction was simulated under RCP8.5, especially in the distant future at Brandon and West Nipissing. The simulated seed yield reduction was associated with increases in heat and water stresses under rainfed conditions with current N fertilizer application rates. Coping with heat and water stresses is a big challenge for canola production in Canada under the projected climate change, especially on the Canadian Prairies.

Core Ideas

- Responses of canola to climate change in Canada were simulated using a crop model.
- An overall negative impact of climate change on canola yield was simulated.
- Yield reductions are due to the increased heat stress and/or water stress.
- The effects of earlier seeding could be very limited as an adaptation measure.
- Developing canola cultivars tolerant to heat and water stresses is an urgent need.

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Rapeseed (*Brassica* spp., including canola) is the second largest oilseed crop across the globe (Yadava et al., 2012). The global harvested area of rapeseed has doubled during the past three decades and canola predominates in the production of rapeseed (Fischer et al., 2014). Canada is the first country in the world to produce large quantities of rapeseed with low erucic acid in the oil and low glucosinolates in the meal. The varieties of rapeseed producing the "double low" seeds were developed in the 1970s and are known as canola. Canada accounts for 22% of the global cultivated area of canola/rapeseed, and exports 90% of its production (FAOSTAT, 2015). Canola cultivation area in Canada, more than 95% on the Canadian Prairies, has been expanded from 2.5 million ha in the late 1980s to 8.5 million ha in recent years. Seed yield has increased from below 1500 kg ha^{-1} to around 2000 kg ha^{-1} in the same time period (Statistics Canada, 2017). A study released in 2013 shows that Canadian-grown canola contributes CAN$19.3 billion to the Canadian economy each year (Canola Council of Canada, 2016).

The Canadian Prairies constitute the northern branch of the Great Plains of North America and produce the majority of Canada's annual grain and oilseed crop. The annual mean temperature varies from –2.0 to 4.0°C and annual precipitation ranges from 300 to 500 mm in the agricultural areas. Water stress is a limiting factor for crop production on the Canadian Prairies, especially in southern Alberta and Saskatchewan. In contrast, the Boreal Shield (Canada's largest ecozone) has annual precipitation of roughly 1000 mm and an annual mean temperature ranging from 1.0 to 4.0°C in the eastern portion in Ontario and Quebec. The Boreal Shield ecozone currently supports a very limited area of annual crops due to poor soils and cold temperatures, but the climate in the southern part may become suitable for expanded agricultural production on the better soils in the projected warmer future. An increase of 3.0 to 3.5°C in annual mean temperature was projected in these regions for the near future while precipitation changes were relatively uncertain (Qian et al., 2013). Even larger increases in temperature were

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Abbreviations: DSI, drought stress index; DSSAT, Decision Support System for Agrotechnology Transfer; HI, harvest index; NUE, nitrogen use efficiency; RCP, Representative Concentration Pathway; RMSE, root-mean squared error; Y_P, potential yield; Y_{WL}, water-limited yield; WUE, water use efficiency.

projected for the distant future. The projected climate change also indicates an increase in extreme weather conditions such as high temperatures during the growing season (Qian et al., 2010).

Studies based on crop experiments show that the development of *Brassica* species responds significantly to the environment, especially to temperature (Morrison et al., 1989; Nanda et al., 1996), as heat stress during flowering can result in a reduction in seed yield (Morrison and Stewart, 2002). Therefore, the projected warmer future climate is suspected to be unfavorable to cool-season crops such as canola. As a counteraction, earlier seeding and higher N fertilizer application rates are often considered as potential adaptation measures to avoid heat stress at key growth stages and to meet an increased N demand under a warmer climate. So far no comprehensive assessment has been conducted on the potential impacts of climate change and the effects of potential adaptation measures on canola growth and yield in Canada, although such studies are necessary for developing climate change adaptation strategies for canola production.

Open-top chambers (OTC) and free-air carbon dioxide enrichment (FACE) are two types of common environmental control chambers used to mimic field conditions to study the impacts of climate change on crop growth (Long et al., 2006; Messerli et al., 2015; Norby et al., 1997). Numerous climate chambers would be required to mimic climate scenarios involving multiple climatic factors for a long-term experiment, which could add extra costs for building, operating and managing these chambers. On the other hand, crop growth models simulate crop development and growth by integrating many interactive processes among climate, crop, soil and management practices. Once a model has been properly parameterized and evaluated, it can be used, together with field experiments, for extrapolation of experimental results over a wide range of management practices and weather conditions (Bouman et al., 1996; Tsuji et al., 1998). Therefore, crop growth models are the most common tools for assessing climate change impacts on crop production (Asseng et al., 2013; White et al., 2011).

The CSM-CROPGRO-Canola model, included in the Decision Support System for Agrotechnology Transfer (DSSAT v4.6, Hoogenboom et al., 2015; Deligios et al., 2013), has been successfully adapted for simulating canola growth and yield in Canada (Jing et al., 2016). Our objectives for this study were (i) to simulate canola growth and yield under distinct climate conditions across three locations across Canada, (ii) to simulate the responses of canola growth and yield under a set of future climate scenarios developed with a regional climate model, and (iii) to evaluate the potentials of climate change adaptation measures for canola production in Canada. It should be kept in mind that uncertainty in simulating the response of crops to climate change is large due to differences in the structures and parameters among crop models, in addition to uncertainties in climate change projections (Asseng et al., 2013). Multi-model ensembles are often recommended to account for such uncertainties (Bassu et al., 2014; Martre et al., 2015). This study represents the first attempt to use a dynamic crop model to assess the climate change impacts on canola growth and yield in Canada.

MATERIALS AND METHODS

Study Locations

Three locations: Brandon (49°52′ N, 99°59′ W) in Manitoba on the Canadian Prairies; West Nipissing (46°22′ N, 80°5′ W) in Ontario; and Normandin (48°51′ N, 72°32′ W) in Quebec in eastern Canada, were used in this study (Fig. 1). These

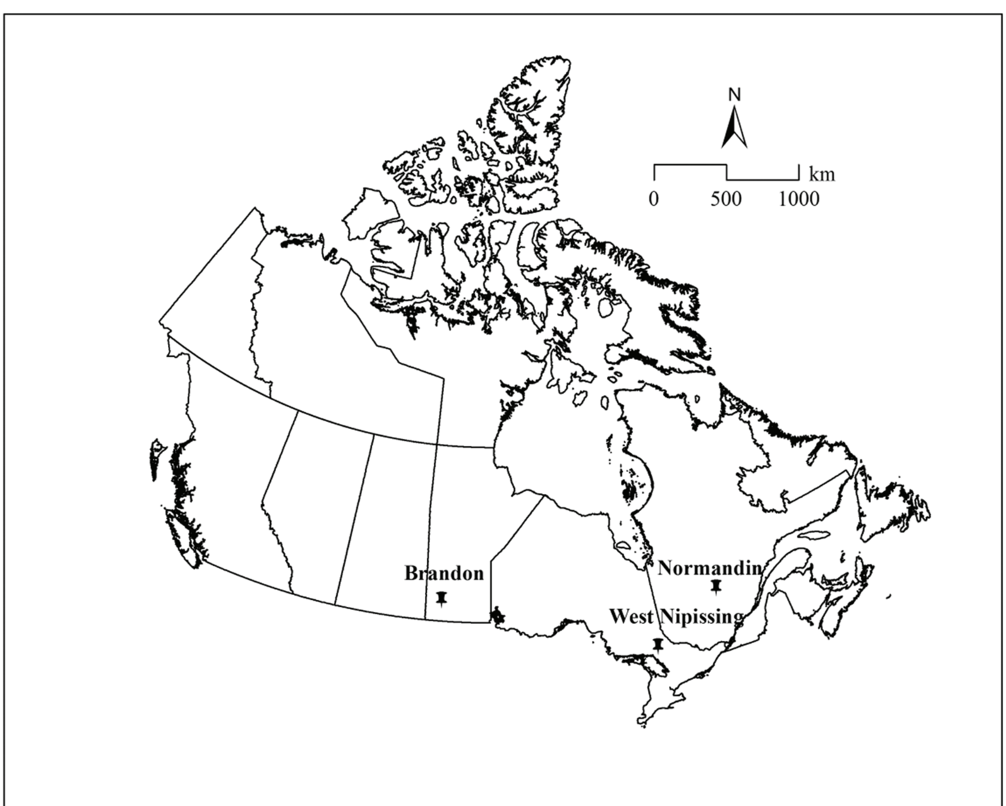

Fig. 1. Study locations across Canada.

three locations represent the current canola growing regions in Canada and the potential for Northward expansion into northern Ontario and Quebec. Soil properties and the growing season (May–August) climate characteristics are shown in Tables 1 and 2. These locations were also selected on the basis of the availability of field experiment data for model calibration and evaluation. In fact, diversity of soil and weather conditions of the field experiments is good for model calibration and evaluation (He et al., 2017).

Field Experiments

Field experiments were conducted at Brandon in 2010 and 2012, at West Nipissing in 2012, 2013, and 2014; and at Normandin in 2010, 2011, and 2012. Two hybrid canola cultivars were grown in these experiments: InVigor 5440 was used at Brandon and West Nipissing, and InVigor 5030LL (5030LL hereafter) at Normandin. At West Nipissing, canola was sown at a rate of 5.6 kg seeds ha^{-1} at a depth of 0.6 to 1.2 cm and a row spacing of 0.2 m. Fertilizer N rates ranging from 0 to 200 kg ha^{-1} were applied at seeding. The plant density was 53 plants m^{-2} in 2012, 50 plants m^{-2} in 2013, and 62 plants m^{-2} in 2014. Seed yields were manually measured at maturity in 2012 and 2013, and no yield was measured in 2014 due to waterlogging during canola ripening. Details of this experiment can be found in Jing et al. (2016). At Brandon and Normandin, N fertilizer at a rate of 90 kg ha^{-1} was applied at seeding each year. Canola was sown in 10-m^2 size plots at a seeding rate of 5.6 kg ha^{-1} at Brandon and in 15.8-m^2 size plots at a seeding rate of 6.0 kg ha^{-1} at Normandin. At maturity, seed yield was determined using a plot combine in an area located in the middle of each plot. Details of the experiments at Brandon and Normandin can be found in Bélanger et al. (2015). Data collected in the field experiments were used to calibrate crop genetic parameters in the CSM-GROPGRO-Canola model and to evaluate model simulations.

The CSM-CROPGRO-Canola Model

The CSM-CROPGRO-Canola model in DSSAT v4.6 was adapted from CSM-CROPGRO for simulating winter rapeseed without N and water stresses under a Mediterranean environment (Deligios et al., 2013). It was further adapted for simulating spring canola in eastern Canada with N and water stresses (Jing et al., 2016). The CSM-CROPGRO-Canola model requires soil data; daily weather data, cultivar parameters; and management data such as seeding dates, irrigation, and fertilization to simulate crop growth and yield on a daily step. Three levels of genetic coefficients are required for the CSM-CROPGRO-Canola model. They are categorized as species, ecotype, and cultivar. Using the same methodology of model calibration and evaluation for cultivar InVigor 5440 at West Nipissing as detailed in Jing et al. (2016), we calibrated the cultivar coefficients for 5030LL based on field experiment data for 2010 at Normandin. The experimental data at Brandon and the remaining independent data at Normandin for 2011 and 2012 were used for model evaluation. Cultivar parameters for 5030LL are shown in Table 3, sharing the same

Table 1. Soil properties (top 30 cm) at three locations.

Location	Soil series	Soil texture	Clay	Silt	Available water capacity	Organic matter	Bulk density
			%		cm^3 cm^{-3}	kg kg^{-1}	g cm^{-3}
Brandon	Newdale	sandy clay loam	26	26	0.30	0.050	1.2
West Nipissing	Azilda	silty loam	14	67	0.23	0.021	1.3
Normandin	Alma	silty loam	19	52	0.21	0.046	1.1

Table 2. Baseline (1971–2000) climate conditions during the growing season (1 May–31August) at three locations along with the projected conditions based on the CanRCM4 climate model under scenarios RCP4.5 and RCP8.5 for the near (2041–2070) and distant (2071–2100) future.

Location	Scenario		Precipitation	Mean air temperature	Growing degree days†	Number of days with high temperature†
			mm	°C	°C-d, T_b = 0°C	T_{max} ≥ 29.5°C
Brandon	Baseline	1971–2000	272.1	15.7	1941	14.2
	RCP4.5	2041–2070	278.6	18.8	2314	39.6
		2071–2100	275.9	19.8	2433	48.7
	RCP8.5	2041–2070	288.9	19.7	2423	46.7
		2071–2100	257.9	22.6	2777	73.7
	Baseline	1971–2000	382.5	15.8	1928	3.0
West Nipissing	RCP4.5	2041–2070	401.9	18.4	2263	13.4
		2071–2100	394.9	19.1	2349	20.1
	RCP8.5	2041–2070	366.3	19.5	2397	22.9
		2071–2100	389.9	21.9	2687	47.7
Normandin	Baseline	1971–2000	358.5	14.1	1737	5.7
	RCP4.5	2041–2070	396.0	17.0	2089	17.3
		2071–2100	484.7	17.4	2144	20.6
	RCP8.5	2041–2070	413.8	17.8	2193	23.6
		2071–2100	470.6	20.2	2484	49.9

† T_b is base temperature for accumulating growing degree days and T_{max} is daily maximum air temperature.

Table 3. Cultivar parameters in the CSM-CROPGRO-Canola model: definition and calibrated values for cultivars InVigor 5440 and 5030 LL.

Parameter	Definition	InVigor 5440	5030 LL
PP-SEN	Slope of the relative response of development vs. photoperiod (1/hour)	–0.011	–0.006
EM-FL	Time between emergence and flower appearance (PD†)	28.5	30.5
FL-SH	Time between first flower and beginning pod (PD)	13	10
FL-SD	Time between first flower and beginning seed (PD)	19	18
SD-PM	Time between beginning seed and physiological maturity (PD)	26.5	23
FL-LF	Time between beginning seed and end of leaf expansion (PD)	3	3
LFMAX	Maximum leaf photosynthetic rate, mg CO_2 m^{-2} s^{-1}	1.28	1.28
SLAVR	Specific leaf area of cultivar under standard growth conditions, cm^2 g^{-1}	330	312
SIZLF	Maximum size of full leaf, cm^2	100	100
SFDUR	Seed filling duration for pod cohort under standard conditions (PD)	20	20
PODDUR	Duration of pod addition under standard conditions (PD)	10	10

† PD, Photothermal day.

parameters for species and ecotype as InVigor 5440. In fact, these two cultivars are similar although InVigor 5440 has a slightly higher yield potential than 5030LL.

Root-mean squared error (RMSE) and the normalized root-mean squared error (nRMSE), along with model simulation efficiency (EF) and index of agreement (d) used in Jing et al. (2016), were applied to evaluate the performance of the model.

Climate Data and Future Scenarios

Weather data for Brandon and Normandin included daily maximum and minimum temperatures and total precipitation recoded on a site near the experimental fields for the experimental years, as well as 30-yr baseline data of 1971 to 2000. The weather data for West Nipissing were obtained from the nearby weather station (North Bay) of Environment Canada (Environment Canada, 2016). Daily solar radiation was estimated using the methodology proposed by Allen et al. (1998) based on solar radiation at the top of the atmosphere and observed daily temperature range. The daily weather data for the experimental years were used as input for the CSM-CROPGRO-Canola model for the calibration of crop genetic parameters and for evaluation of the model against the measured crop data in the experiments.

Climate scenarios for the three locations for near future (2041–2070) and distant future (2071–2100) were developed using the equidistant cumulative distribution function (CDF) matching method, a bias correction method described in Qian et al. (2016) based on climate change simulations by a Canadian Regional Climate Model (CanRCM4) (Scinocca et al., 2016) on a 0.22° horizontal grid resolution (approximately 25 km). The 30-yr baseline climate data were used for CDF matching in the bias correction of the CanRCM4 data. The bias-corrected CanRCM4 data for Brandon showed annual cycles of daily maximum and minimum temperatures and solar radiation much closer to the observed ones for the baseline period (1971–2000) than the raw CanRCM4 data (Fig. 2). The climate change simulations were conducted by the Canadian Centre for Climate Modeling and Analysis (CCCma) under two forcing scenarios of Representative Concentration Pathways (RCPs), RCP4.5 and RCP8.5 (van Vuuren et al., 2011). RCP4.5 and RCP8.5 represent medium-low and high emission scenarios with a radiative forcing of 4.5 and 8.5 w m^{-2} at the end of the 21st century, respectively. The parent global model used to drive CanRCM4 is the current version of the CCCma's Global Earth System Model CanESM2 (Canadian Earth System Model) (Arora et al., 2011). Daily outputs from CanRCM4 were obtained from the CCCma's website (http://www.cccma.ec.gc.ca/data/data.shtml) for the historical baseline period 1971 to 2000 and for the future period 2041 to 2100 under the forcing scenarios RCP4.5 and RCP8.5. The atmospheric CO_2 concentrations were projected to be 498 and 571 ppm averaged over 2041 to 2070, and 532 and 801 ppm averaged over 2071 to 2100 under RCP4.5 and RCP8.5, respectively. These levels of the atmospheric CO_2 concentration were used in crop simulations to account for the direct effects of the CO_2 levels on crop growth.

Crop Growth Simulations

The evaluated CSM-CROPGRO-Canola model was used to simulate canola development, growth, and yield in response to the projected climate change under the four future climate scenarios: both the near future and the distant future under RCP4.5 and RCP8.5. Simulations were also conducted for the baseline climate of 1971 to 2000. Two cultivars InVigor 5440 and 5030LL were used in these simulations for verifying the sensitivity of canola genetics to the climate change scenarios. Because the simulated seed yield responses of the two cultivars to future climates were very similar, only the results for InVigor 5440 are shown and discussed hereafter.

Soil properties in Table 1 at each location were used in the simulations. This implies that some simulation results are only relevant to the soils used in the simulations and crop response to climate with other types of soils can be different. However, soil properties may not have any effects in simulations without water and N stress, that is, the simulations for potential yield discussed later. To take into account the year-to-year variations of seeding date, seeding dates in the simulations were estimated using the criteria developed by Bootsma and De Jong (1988), based on daily air temperatures, precipitation, and estimated soil moisture on a loam soil with an available water-holding capacity (AWC) of 150 mm by the Versatile Soil Moisture Budget model (VSMB) (Baier et al., 1979; Akinremi et al., 1996). Planting was assumed to start when 10 d had occurred after 15 April meeting the following criteria: $0.75T_{max} + 0.25T_{min} > 7°C$; daily precipitation <2 mm; snow on ground <10 mm; $SW_1 < 0.90\ AWC_1$ and $SW_2 < 0.95\ AWC_2$. T_{max} and T_{min} are daily maximum and minimum temperature. SW_1 and SW_2 are available soil water in zones 1 and 2 in the VSMB model. AWC_1 and AWC_2 refer to AWC in zones 1 and 2. 15 April was changed to 15 March for future scenarios to account for potential earlier planting resulting from climate warming. The latest planting date was set to 15 June in the estimation. Therefore, potentially earlier planting dates were automatically taken into consideration in the simulations for the projected warmer climate. A fixed planting date, 15 May, was also used in all simulations to assess the potential of using earlier seeding as an adaptation measure to a future warmer climate.

Long-term crop simulations were performed in a sequence mode with continuous canola for simplicity. Simulation results for the first year were discarded in all analyses; thus results are not sensitive to initial conditions, such as soil water content, ammonia, and nitrates used to start the simulations. Nitrogen fertilizer at the rate of 100 kg N ha^{-1} was applied at seeding in the simulations for the baseline climate and under future climate scenarios. An increased N rate of 150 kg ha^{-1} was also used in the simulations under future climate scenarios to meet the potentially higher demand for N of canola growing in a warmer climate. Potential yield (Y_P) was simulated by turning off both water and N stresses in the simulations. In addition, water-limited yield (Y_{WL}) was also simulated by turning off

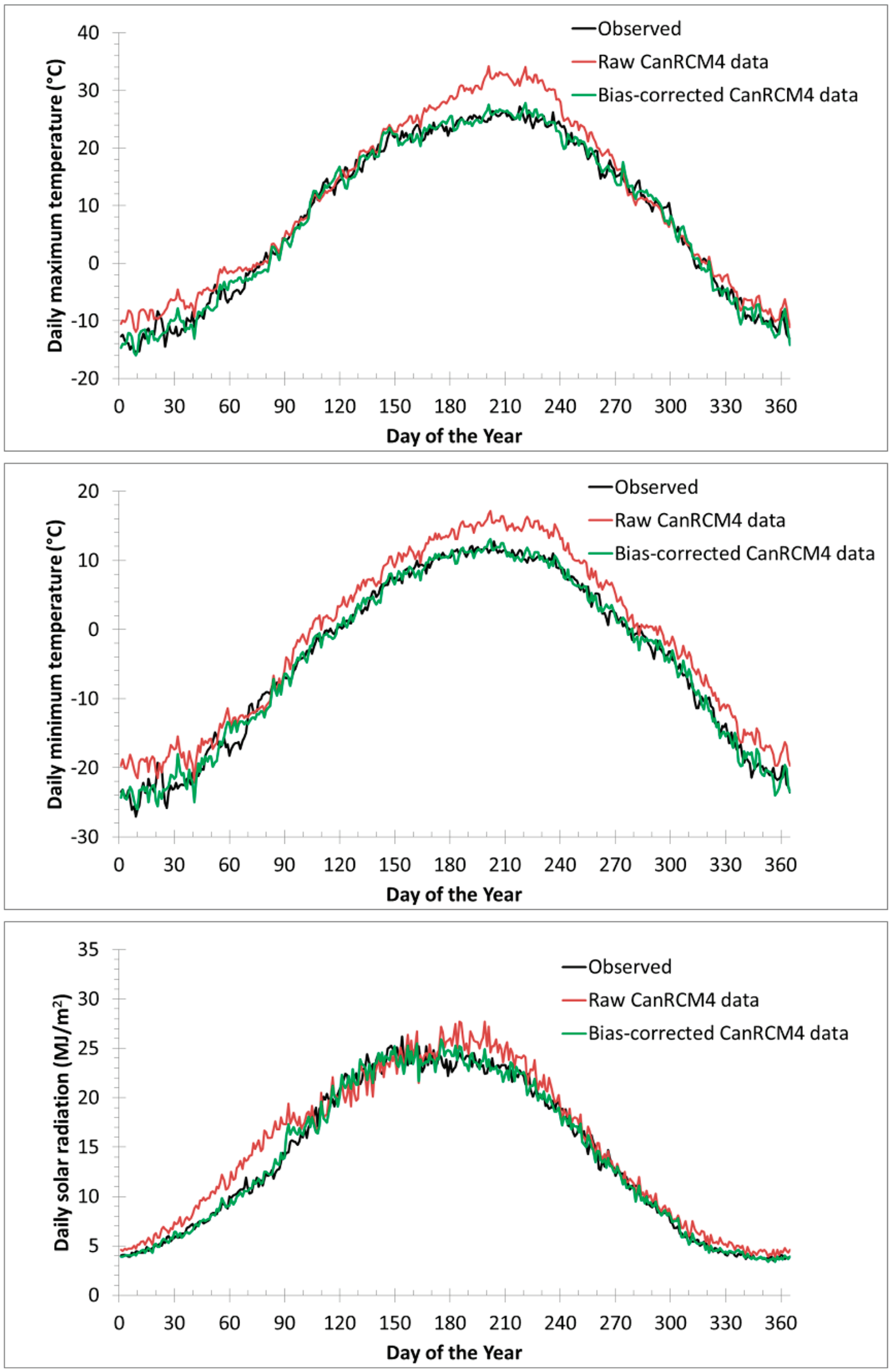

Fig. 2. Annual cycles of daily maximum and minimum temperatures and solar radiation at Brandon for the baseline period (1971–2000) estimated from historical observed data, raw and bias-corrected CanRCM4 data.

only the N stress in the simulations. Both the potential and the water-limited yields were used to provide for a better understanding of climate change impacts on canola growth and yield by excluding the N stress, that is, using unlimited N as N fertilizer application is one of the strategies in crop management.

Indicators of Climate Change Impacts

The simulated changes in crop development and yields, in terms of 30-yr means for the four climate scenarios, that is, 2041 to 2070 and 2071 to 2100 under RCP4.5 and RCP8.5, were analyzed against the baseline climate of 1971 to 2000. Changes in seeding date and the length of growing period from seeding to physiological maturity, as well as a number of crop indices, were employed to understand how canola growth and yield responded to climate change in the simulations. These crop indices include harvest index (HI), water use efficiency (WUE) defined as the seed yield (kg ha^{-1}) produced per millimeter of transpiration during the growing period and nitrogen use efficiency (NUE) defined as the seed yield (kg ha^{-1}) produced per kilogram of crop N uptake in the simulations.

Heat stress, defined as the number of days with the daily maximum air temperature exceeding 29.5°C during three growth stages (vegetative, flowering, and seed development), was analyzed as a future warmer climate could result in greater heat stress. In addition, a heat stress index defined as accumulation of degrees of daily maximum air temperature exceeding the above threshold during the growth stages was also used. The temperature threshold of 29.5°C and the definition of the heat stress index were adopted from the experimental study in Morrison and Stewart (2002). The entire life cycle from seeding to physiological maturity is divided into vegetative and reproductive (flowering + seed development) stages by the date of first flower, the anthesis date in the simulation. The flowering stage is a 30-d period after first flower following the guideline of the Canola Council of Canada (2017). A drought stress index (DSI) was adopted from Semenov and Shewry (2011) to investigate the impact of water stress on canola yield. The DSI is defined as a percentage of the yield loss due to water stress, thus DSI = $(Y_P\text{-}Y_{WL})/Y_P \times 100$. Median and the 90th percentile of DSI (DSI_{med} and DSI_{90}) were calculated from the annual canola yield simulated for the baseline climate and four future scenarios.

RESULTS

Model Evaluation

The CSM-CROPGRO-Canola model was first evaluated with cultivars InVigor 5440 and 5030LL at experimental sites (Brandon and Normandin) prior to simulating the impact of climate change. As seed yield was targeted in the projection, we only showed the evaluation results on seed yield, and biomass at Brandon and Normandin in 2012 (Fig. 3). A detailed evaluation for other crop attributes such as leaf area index, biomass, and N concentration from the experiment at West Nipissing were presented in Jing et al. (2016). The simulated biomass

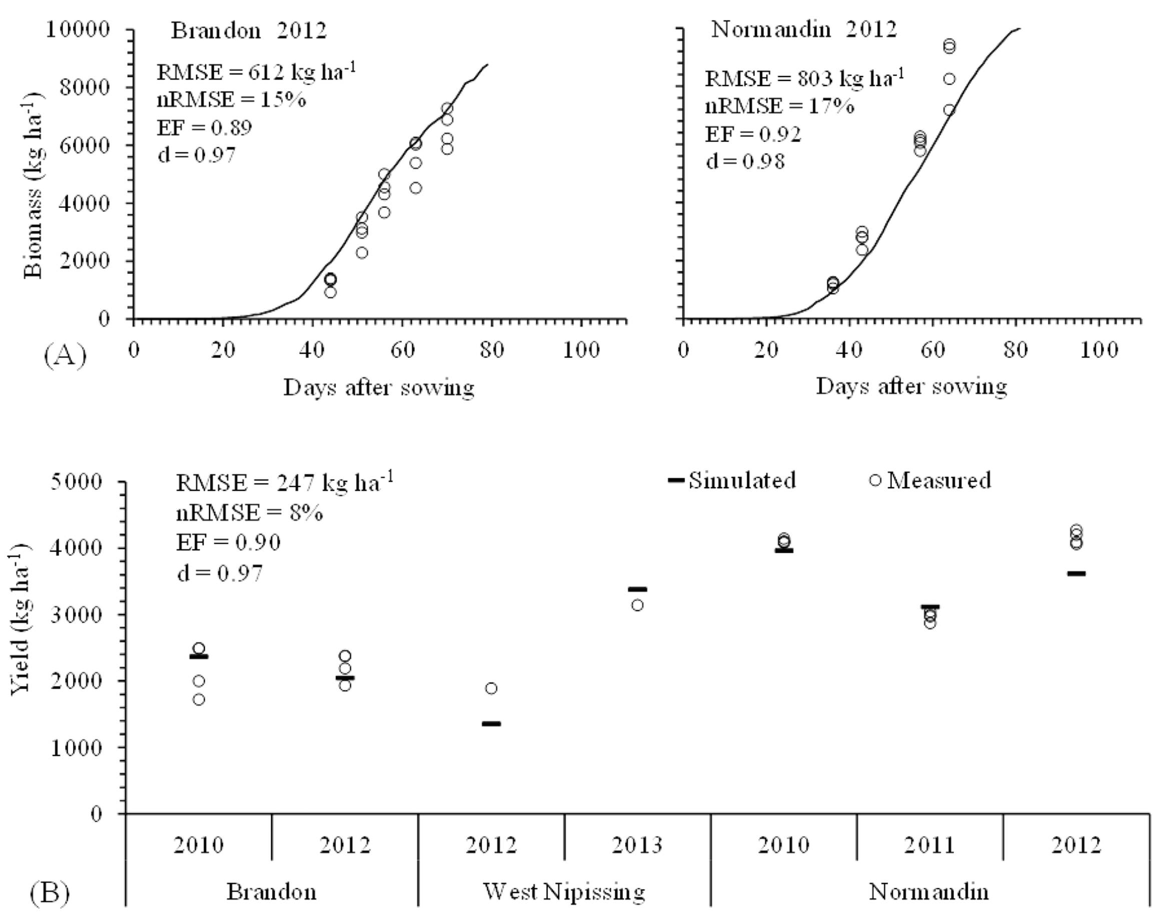

Fig. 3. (A) Simulated vs. measured (with replicates shown as circles) biomass at Brandon and Normandin in 2012, and (B) seed yields at three locations from 2010 to 2013. The data pairs of simulated biomass and yield vs. mean measured value of the replicates were used to calculate the root-mean squared error (RMSE), model simulation efficiency (EF) and index of agreement (d).

closely followed the observed values during the growing season for both sites (Fig. 3 A) with an nRMSE smaller than 17% and both EF and d close to 1.0. The evaluation results indicated good simulations for the dynamic growth of canola biomass. The model simulated the seed yields in the experiments well with an RMSE of 247 kg ha^{-1}, an nRMSE of 8% (Fig. 3 B) and both EF and d close to 1.0. All these statistics showed a very close match between the simulated yields and the measured values.

Projected Climate Change

Air temperatures are projected to be much higher in the future than under the baseline climate conditions across all three locations (Table 2). Annual mean temperatures are projected to increase by 3.2 to 3.6°C and 3.7 to 4.1°C in the near future, and by 3.9 to 4.4°C and 6.3 to 7.2°C in the distant future, under forcing scenarios RCP4.5 and RCP8.5, respectively. Annual precipitation totals are also projected to increase but the range of the projected changes is large among the locations and scenarios. Increases of 10 to 14% for Brandon and 4 to 8% for West Nipissing are projected, while at Normandin, increases of more than 20% for all scenarios other than the near future under the RCP4.5 forcing scenario and as high as 32% in the distant future under the RCP8.5 forcing scenario are projected.

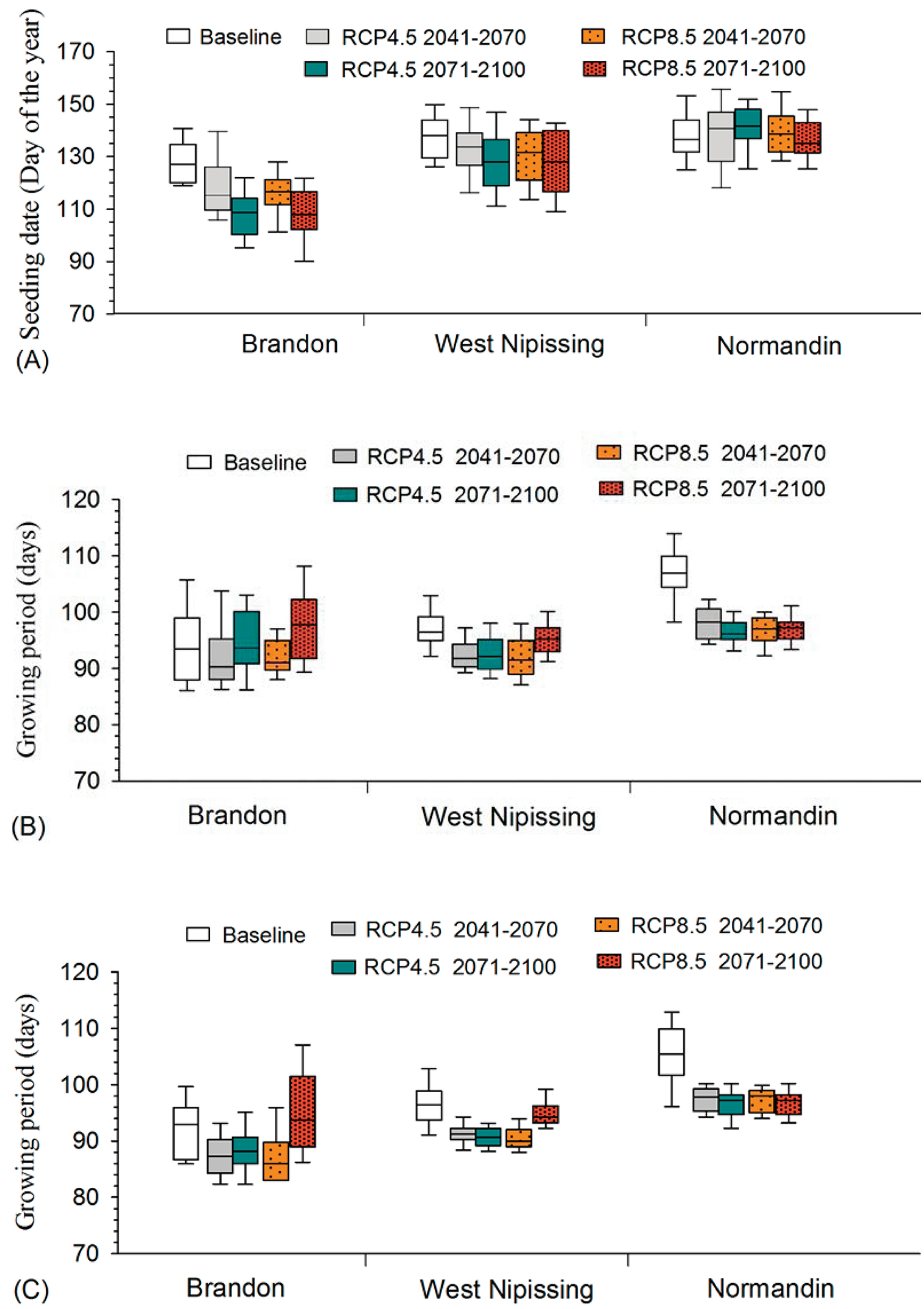

Fig. 4. (A) Estimated seeding date and (B) simulated growing period using estimated seeding dates, and (C) simulated growing period using fixed seeding date 15 May for cultivar InVigor5440 with a fertilizer rate of 100 kg ha^{-1} N applied at seeding at three sites under the baseline (1971–2000) and the climate scenarios RCP4.5 and RCP8.5 in 2041 to 2070 and 2071 to 2100. The lower end of the box indicates the 25th percentile; the solid line within the box marks the median; the upper end of the box indicates the 75th percentile; whiskers above and below the box indicate the 90th and 10th percentiles.

The projected changes vary from season to season and changes within a growing season could differ from those projected for annual mean temperature and precipitation totals. For example, while annual precipitation at Brandon is projected to increase by 14% in the distant future under RCP8.5, the growing season precipitation would decrease by 5% (Table 2). Growing season mean temperatures and growing degree days are projected to increase across all three locations under all four scenarios. Furthermore, the number of days with a daily maximum temperature exceeding 29.5°C is projected to increase, especially in the distant future under RCP8.5 (Table 2). These projected changes suggest that a canola crop would likely be exposed to much greater heat stresses in the future than under the baseline conditions.

Potential Changes in Seeding Date and Crop Development

Seeding dates were estimated to be 10 to 21 d earlier at Brandon due to an increase in air temperature, 5 to 11 d earlier at West Nipissing, and almost unchanged (2 d earlier to 3 d later) at Normandin under the four future climate scenarios compared to the baseline climate (Fig. 4A).

Changes in seeding date accompanied by increasing temperatures would alter the growing period of canola (Fig. 4B). The growing period of canola from seeding to physiological maturity would be 2 to 5 d shorter in West Nipissing and 8 to 9 d shorter in Normandin in eastern Canada due to projected temperature increases and the limited opportunity to shift seeding date. However, it might not change at Brandon on the Canadian Prairies due to the potential for earlier seeding. We also used a fixed seeding date based on the baseline climate in the simulations. It appears that the growing period would also be shortened at Brandon (Fig. 4C) due to increasing temperatures in all scenarios except for the distant future under RCP8.5. The extended growing period in the distant future under RCP8.5 is projected to be due to delays in crop development associated with increasing water stress.

Changes in Seed Yield

Hastened crop development in a shortened growing period could result in a reduction in canola yield under the projected climate change if other factors such as water availability and fertilizer applications are not improved (Anwar et al., 2015; Gan et al., 2007). A seed yield reduction of 42, 21, and 24% was simulated with a fertilizer application of 100 kg N ha^{-1} for the near future and of 37, 27, and 23% for the distant future, under RCP4.5, compared to the baseline climate for Brandon, West Nipissing, and Normandin, respectively (Fig. 5A). Under RCP8.5, the simulated reductions were 44, 33, and 25% for the near future and 74, 50, 26% for the distant future at Brandon, West Nipissing, and Normandin, respectively. The reduction in yield was partially compensated for by increasing the N fertilizer application to 150 kg N ha^{-1}. The increased N fertilization was projected to compensate for more than one-half of the

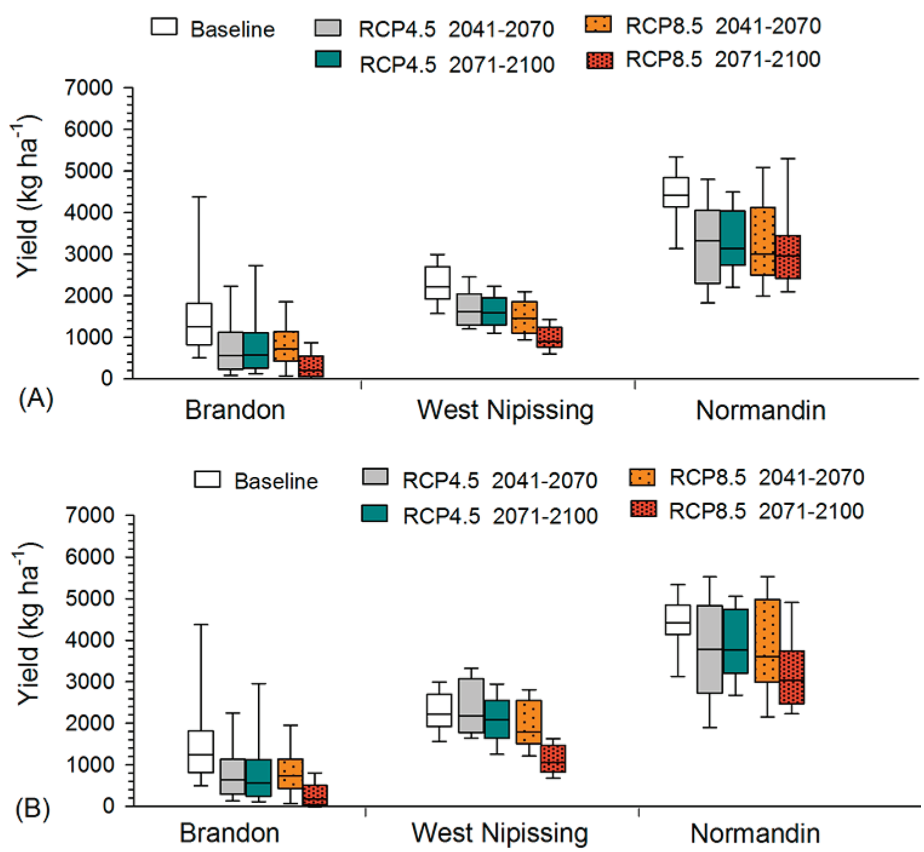

Fig. 5. Simulated seed yields of canola (cultivar InVigor5440) (A) with N fertilizer rates of 100 kg ha^{-1} applied at seeding for the baseline and future climate scenarios same as in Fig. 4, and (B) with N fertilizer rates of 100 kg ha^{-1} for baseline and 150 kg ha^{-1} applied at seeding for future climate scenarios at three sites. The lower end of the box indicates the 25th percentile; the solid line within the box marks the median; the upper end of the box indicates the 75th percentile; and whiskers above and below the box indicate the 90th and 10th percentiles.

yield reduction at West Nipissing and approximately one-half at Normandin, but only marginally at Brandon depending on the climate change scenarios (Fig. 5B).

DISCUSSION

Heat Stress and Changes in Crop Harvest Index, Water Use Efficiency and Nitrogen Use Efficiency

Heat stress can significantly affect canola growth, development, and yield (Morrison and Stewart, 2002). The number of days with daily maximum temperatures exceeding 29.5°C (high temperature) is expected to increase at all three locations (Table 2). Severe heat stress would therefore be expected in the future, not only on the Canadian Prairies, but also in eastern Canada. Heat stress at different growth stages may have different effects as discussed by Morrison and Stewart (2002). The values of the heat stress index for the simulated different growth stages are shown in Table 4. It can be clearly seen that heat stress would increase at all three growth stages under future climate scenarios, especially at the critical flowering and seed development stages.

The simulated reduction in seed yield is likely associated with a reduction in HI under increased temperature during the growing period. The simulated HI for the three locations under future climate scenarios was much lower in the future compared to the baseline (Fig. 6A). Furthermore, the simulated HI in the distant future under RCP8.5 was the lowest, this being the scenario in which higher temperatures are projected. High temperatures put stress on seed filling during the reproductive stage of many crops and thus usually reduce the HI (Porter and Semenov, 2005; Unkovich et al., 2010). A growth chamber experiment for canola indicates that high temperature during the reproductive phase significantly reduces the HI (Angadi et al., 2000), and that is consistent with a field experiment that showed that HI decreased with high temperature during the seed filling of canola (Faraji et al., 2009).

Achieving high aboveground biomass is essential for canola to construct a favorable canopy profile and to build sufficient numbers of pod and seed for high yield (Zhang and Flottmann, 2016). Temperature has evident impacts on canola seed formation during the reproductive phase when the seed yield is strongly correlated to air temperature (Faraji et al., 2009). Kutcher et al. (2010) reported that canola yields were negatively correlated with the number of days with a daily maximum air temperature above 30°C on the Canadian Prairies. Very high temperature reduces seed yield by more than 50% through decreasing seed weight during reproduction (Aksouh-Harradj et al., 2006; Aksouh et al., 2001; Gan et al., 2004), especially during pod development when high temperature can severely reduce the number of fertile pod and seed numbers per pod (Gan et al., 2004). Morrison et al. (2016) pointed out that temperature exceeding 33°C may reduce canola pollen germination and eventually leading to raceme sterility which reduces seed number. The impact of temperature stress on yield components is simulated in the CSM-CROPGRO-Canola model in which the number of pod and seed and seed weight are reduced when temperature stress occurs (Hoogenboom et al., 2015; Deligios et al., 2013).

Corresponding to the projected lower HI under the future climate scenarios, both WUE and NUE in seed production would decrease under future warmer climates (Fig. 6B, 6C), although these efficiencies for biomass production could remain at their baseline level or slightly decrease (not shown). These reductions are very likely the causes for the simulated reductions in seed yield.

Water Stress

Water stress is also known to be a critical factor limiting the yield of spring crops on the Canadian Prairies (Qian et al., 2009). The projected higher temperatures during the growing period may increase soil evaporation and result in more severe water stress. The simulated potential seed yield of canola (Y_P) under future climate scenarios is shown in Fig. 7A, in comparison with the baseline as well as the water-limited yield Y_{WL}. A higher Y_P is always seen at Normandin compared to the other two locations. This is likely related to the lower

Table 4. Heat stress index† [$\sum(T_{max} - 29.5°C)\Delta t$] during three growth stages at three locations under baseline (1971–2000) climate conditions and projections based on the CanRCM4 climate model under scenarios RCP4.5 and RCP8.5 for the near (2041–2070) and distant (2071–2100) future.

Location	Scenario		Growth stage: Vegetative	Flowering	Seed development
Brandon	Baseline	1971–2000	7.8	9.0	14.0
	RCP4.5	2041–2070	17.8	33.0	51.6
		2071–2100	18.8	44.2	75.4
	RCP8.5	2041–2070	14.5	47.2	95.9
		2071–2100	32.0	88.9	205.5
West Nipissing	Baseline	1971–2000	1.1	2.4	0.6
	RCP4.5	2041–2070	4.3	12.4	6.9
		2071–2100	9.3	13.1	9.8
	RCP8.5	2041–2070	10.7	16.0	12.4
		2071–2100	23.2	46.6	40.1
Normandin	Baseline	1971–2000	4.1	2.0	1.8
	RCP4.5	2041–2070	15.7	14.8	7.5
		2071–2100	14.1	15.3	10.0
	RCP8.5	2041–2070	17.0	19.7	13.7
		2071–2100	31.7	67.3	36.6

† T_{max} is daily maximum air temperature, Δt is time step.

temperatures at Normandin. It is interesting to see that the simulated Y_P for Brandon was higher than or close to the simulated Y_P for West Nipissing but simulated Y_{WL} was much lower (Fig. 7B). It implies that water stress may be a key factor limiting canola yield on the Canadian Prairies. Yield loss due to water stress at Brandon could be close to 60% of the potential yield in more than 50% of the years under the baseline climate and it would increase to above 80% of the potential yield in the future (Table 5). In extreme (10%) years, yield loss due to water stress is projected to be more than 80% under the baseline climate and more than 90% under future climate scenarios. It may be worthwhile to mention that yield loss due to water stress could also be related to the water holding capacity of the soil. Thus, the yield loss on a different soil at Brandon could be different from the results in this study. In contrast, water stress did not seem to be a limiting factor under the baseline climate at West Nipissing and Normandin, even under the projected future climate scenarios. A slight increase of yield loss due to water stress was simulated for extreme years at Normandin under some scenarios, mainly in the distant future under RCP4.5 and the near future under RCP8.5.

Adaptation to Climate Change

Canola planted on optimal seeding dates can avoid unfavorable hot and dry weather during the flowering period on the Canadian Prairies (Gan et al., 2004), thus improving seed set (Morrison and Stewart, 2002). Earlier seeding in the field experiments also significantly increased canola yield in eastern Canada (Ma et al., 2016). Therefore, earlier seeding would likely be used to reduce heat stress at critical growth stages

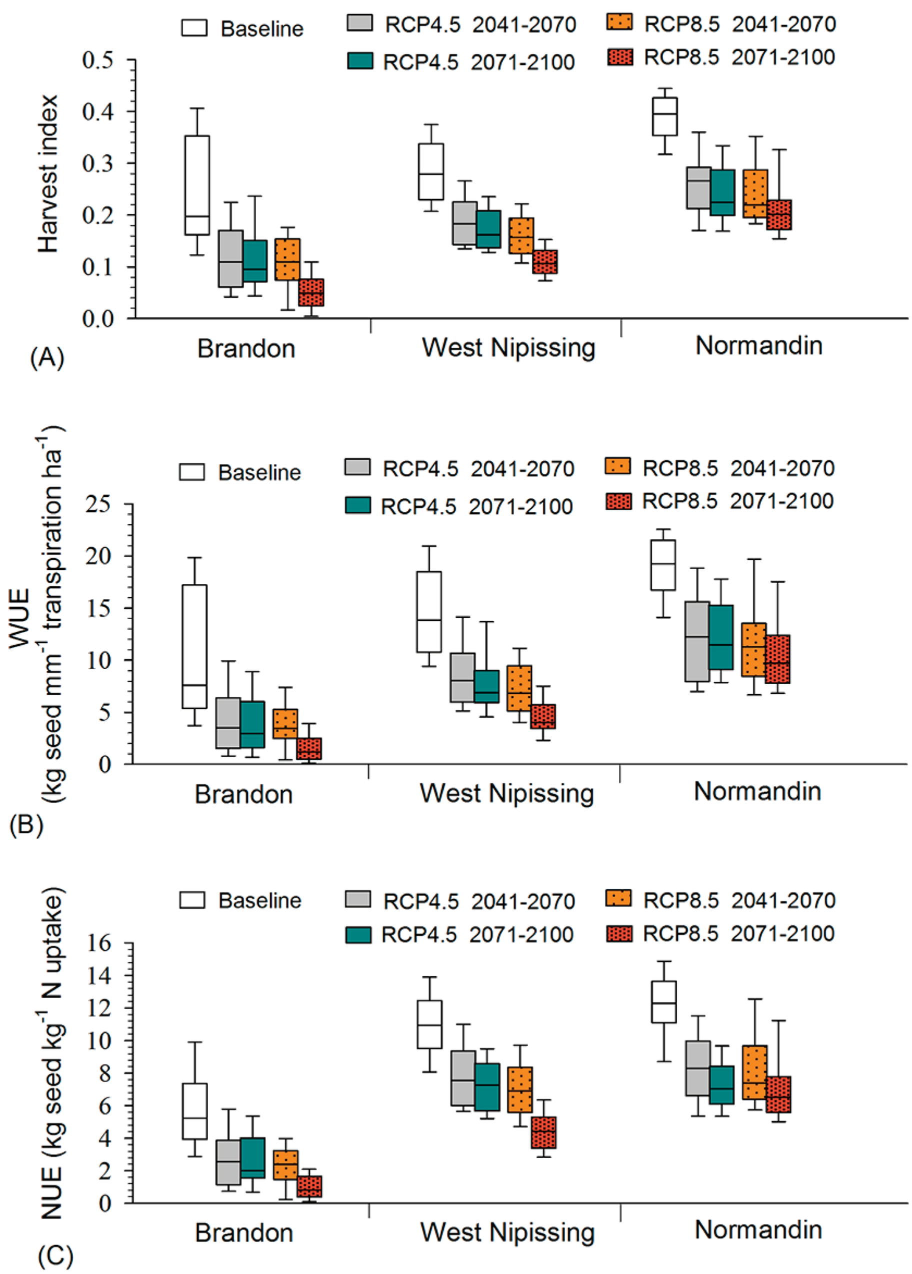

Fig. 6. (A) Simulated canola harvest index, (B) water use efficiency (WUE), and (C) nitrogen use efficiencies (NUE) of canola cultivar InVigor5440 averaged over 30 yr under the baseline and future climate scenarios same as in Fig. 4 with a fertilizer rate of 100 kg ha^{-1} N applied at seeding. The lower end of the box indicates the 25th percentile; the solid line within the box marks the median; the upper end of the box indicates the 75th percentile; and whiskers above and below the box indicate the 90th and 10th percentiles.

such as flowering in a warmer future. However, an increase in annual precipitation may limit earlier seeding due to poor soil trafficability related to excessive moisture (Qian et al., 2013). It is clear that seed yield at Brandon could decrease under future climate scenarios due to increased heat and water stress even when earlier seeding was used as an adaptation measure compared to fixed seeding dates, as indicated in Fig. 8. Increasing fertilizer application would not help mitigate the adverse impacts of climate change in this case, showing very limited options for adaptation, unless new drought and heat-tolerant cultivars could be developed. In eastern Canada, water stress might not be a big problem in most years but the increased heat stress would result in yield loss. Increasing N fertilizer applications might partially compensate for the yield loss due to higher temperature in the future. Overall, negative impacts on canola seed yield were simulated by the CSM-CROPGRO-Canola model. Our results agree well with a recent study (Anwar et al., 2015) that reports canola yield would decrease by about 15 to 30% in the middle of the 21st century and by 30 to 50% at the end of this century at four locations in Australia.

Based on previous studies in field and laboratory experiments and this modeling study, heat stress is very likely the greatest challenge to canola production in Canada under projected future warmer climates. In addition to heat stress, water stress will remain as a key limiting factor on the Canadian Prairies. Moreover, earlier seeding may not be an effective adaptation measure to mitigate the adverse effects of increasing temperatures on canola production. Therefore, developing canola cultivars that are tolerant of both heat and water

Table 5. Drought stress index (DSI)† based on simulations for cultivar InVigor 5440 at three locations under baseline (1971–2000) climate conditions and projections based on the CanRCM4 climate model under scenarios RCP4.5 and RCP8.5 for the near (2041–2070) and distant (2071–2100) future.

Location	Scenario		DSI_{med}	DSI_{90}
Brandon	Baseline	1971–2000	57.6	81.6
	RCP4.5	2041–2070	82.6	93.2
		2071–2100	83.6	93.6
	RCP8.5	2041–2070	81.3	96.3
		2071–2100	86.6	97.4
West Nipissing	Baseline	1971–2000	0.0	5.8
	RCP4.5	2041–2070	0.0	6.0
		2071–2100	0.2	9.4
	RCP8.5	2041–2070	0.0	4.1
		2071–2100	0.1	11.5
Normandin	Baseline	1971–2000	0.6	7.6
	RCP4.5	2041–2070	1.9	38.1
		2071–2100	0.4	7.3
	RCP8.5	2041–2070	1.2	23.1
		2071–2100	0.1	3.6

† $DSI = (Y_P-Y_{WL})/Y_P \times 100$. Y_P is the simulated potential seed yield without water and N stress. Y_{WL} is the simulated seed yield under the water-limited (rainfed) conditions and without N stress. DSI_{med} and DSI_{90} are the median and the 90th percentile of the values of DSI over a 30-yr period, respectively.

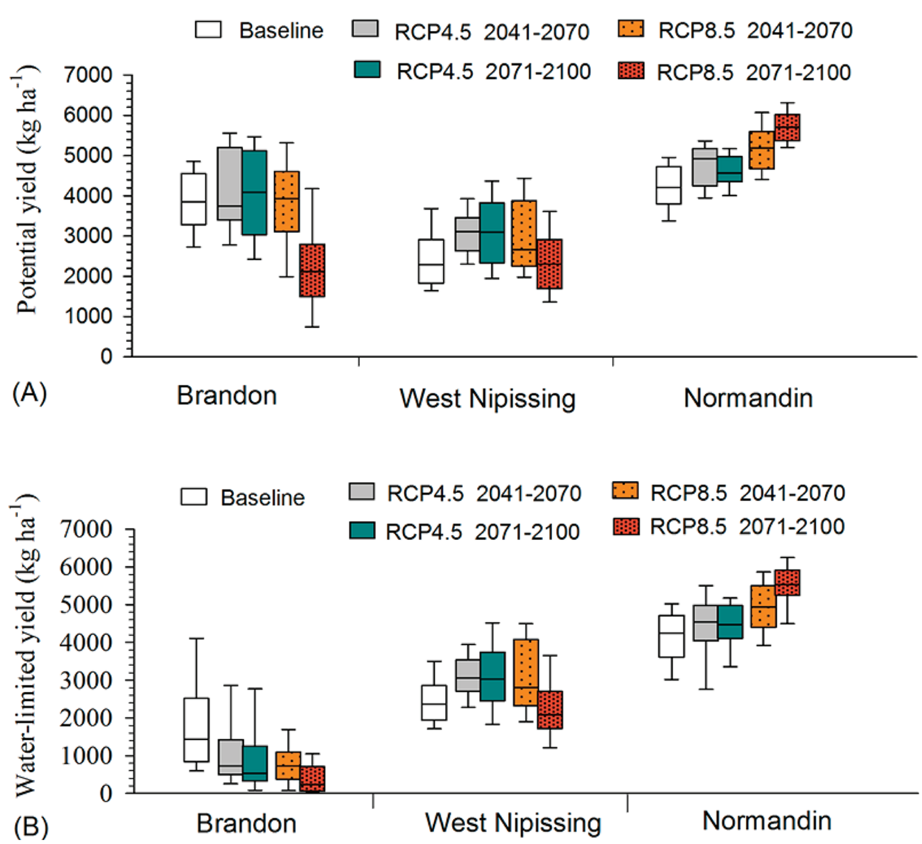

Fig. 7. (A) Simulated potential and (B) water-limited seed yields of canola (cultivar InVigor 5440) at three sites under the baseline and future climate scenarios same as in Fig. 4. The lower end of the box indicates the 25th percentile; the solid line within the box marks the median; the upper end of the box indicates the 75th percentile; and whiskers above and below the box indicate the 90th and 10th percentiles.

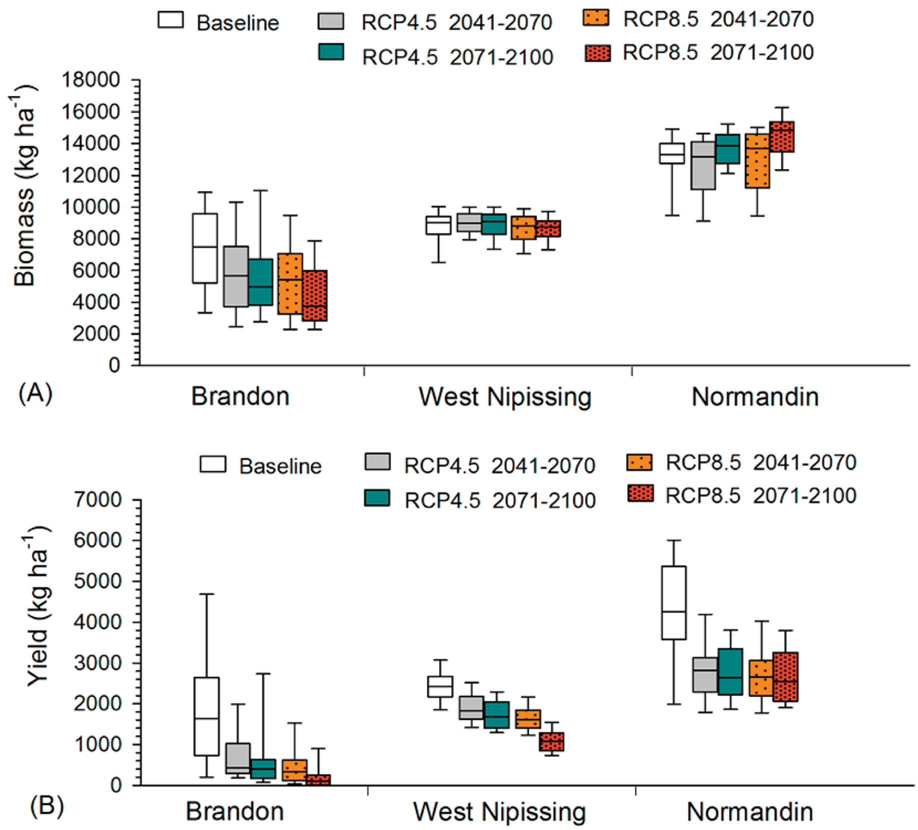

Fig. 8. (A) Simulated biomass and (B) seed yields with fixed seeding dates for canola (cultivar InVigor5440) with N fertilizer rates of 100 kg ha^{-1} applied at seeding for baseline and future climate scenarios same as in Fig. 4 at three sites. The lower end of the box indicates the 25th percentile; the solid line within the box marks the median; the upper end of the box indicates the 75th percentile; and whiskers above and below the box indicate the 90th and 10th percentiles.

stress is an urgent need for adaptation of canola production to climate change. For example, a study based on a yield trial in western Canada shows that the mustard species [*B. juncea* (L.) Czern. & Coss.] has more heat tolerance than other canola species (*B. napus* L. and *B. rapa* L.) (Woods et al., 1991). The *B. juncea* canola varieties might become more important in the future. In addition to the development of new spring cultivars, winter canola currently limited to southwestern Ontario (OMAFRA, 2017) may also become suitable for other regions to reduce the impacts of summer heat stress. Introduction of irrigation on the Prairies, especially at critical growth stages such as flowering, may be necessary for maintaining canola production. However, further studies are required to investigate water availability for irrigation and its economic potential (Lewis, 1989; Kulshreshtha, 2014).

This study is the first attempt at assessing climate change impacts on canola growth and yield in Canada using a crop growth model. It is also worthwhile to mention that pests and diseases related to climate and crop management practices, as well as the impacts of excessive water on harvest, are not simulated by the CSM-CROPGRO-Canola model. Further studies are warranted, as uncertainties associated with crop models and climate scenarios are large (Asseng et al., 2013). Using multiple crop growth models and more climate scenarios will assist in estimating uncertainty and in developing rigorous adaptation measures to climate change for canola production.

CONCLUSIONS

Simulations with four projected future climate scenarios showed an overall negative impact of climate change on canola seed yield across three locations, due to increased heat and/or water stress. Both heat and water stresses would be critical on the Canadian Prairies even if earlier seeding is taken into account as a potential adaptation measure. Water stress would not be critical in eastern Canada but increased heat stress might not be avoidable by shifting seeding to an earlier date due to poor soil trafficability in humid regions. Therefore, the effects of earlier seeding of canola could be very limited as a measure of adaptation to climate change. However, later seeding and winter cultivars might have potential, from this point of view, and it would be interesting to have a further study, given that the growing season is projected to end later with milder winters in the future.

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