Impact of Climate Change on Wheat Production for Ethanol in Southern Saskatchewan, Canada

Hong Wang[1,*], Yong He[1,2], Budong Qian[3], Brian McConkey[1], Herb Cutforth[1], Tom McCaig[1], Grant McLeod[1], Robert Zentner[1], Con Campbell[3], Ron DePauw[1], Reynald Lemke[4], Kelsey Brandt[1], Tingting Liu[1,5], Xiaobo Qin[1,6], Gerrit Hoogenboom[7], Jeffrey White[8], Tony Hunt[9]

[1]*Semiarid Prairie Agricultural Research Centre, Agriculture and Agri-Food Canada, Box 1030, Swift Current, Saskatchewan, S9H 3X2, Canada*
[2]*Department of Soil and Water Sciences, Resources and Environmental Sciences College, China Agricultural University, Beijing, 100094, China*
[3]*Eastern Cereal and Oilseed Research Centre, Agriculture and Agri-Food Canada, Ottawa, Ontario, Canada*
[4]*Saskatoon Research Centre, Agriculture and Agri-Food Canada, Saskatoon, Saskatchewan, Canada*
[5]*Renmin University of China, Beijing, 100872, China*
[6]*Institute of Agro-Environment and Sustainable Development, Chinese Academy of Agriculture Sciences/The Key Laboratory for Agro-Environment and Climate Change, Ministry of Agriculture, Beijing, 100081, China*
[7]*Washington State University, 24106 North Bunn Road, Prosser, Washington 99350-8694, USA*
[8]*USDA ARS, ALARC, 21881 N Cardon Lane, Maricopa, AZ 85138, USA*
[9]*University of Guelph, Canada*
** Corresponding author. Tel: +1 3067787288, Fax: +1 3067783188, E-mail: hong.wang@agr.gc.ca*

Abstract: This study assessed the impact of climate change on wheat production for ethanol in southern Saskatchewan, Canada. The DSSAT-CSM model was used to simulate biomass and grain yield under three climate change scenarios (IPCC SRES A1B, A2 and B1) in the 2050s. Synthetic 300-yr weather data were generated by the AAFC stochastic weather generator for the baseline period (1961-1990) and scenarios. Compared to the baseline, all three scenarios increase precipitation every month except July and August and June (A2 only), when less rains are projected. Annual air temperature is increased by 3.2, 3.6 and 2.7 ^{o}C for A1B, A2 and B1, respectively. The model predicted increases in biomass by 28, 12 and 16% without the direct effect of CO_2 and 74, 55 and 41% with combined effect (climate and CO_2) for A1B, A2 and B1, respectively. Similar increases were found for yield. However, the occurrence of heat shock (>32^{o}C) will increase during grain filling under climate change conditions and could cause severe yield reduction, which is not simulated by DSSAT-CSM; therefore, the yield could be overestimated. Several measures such as early seeding must be taken to avoid heat damage and take the advantage of projected increase in precipitation.

Keywords: *Climate change, Wheat, Bioenergy crop, Heat shock, Seeding date*

1. Introduction

Because of the shortage of fossil fuels and the negative impact of fossil fuel consumption on global climate and environment, the production of bioenergy crops as an alternative to traditional fossil fuels has become much more attractive to the world. Approximately 44% of Canada's agricultural land is located in the province of Saskatchewan and the major (close to 40%) crop is wheat (*Triticum aestivum* L.), which is a potential bioenergy crop. No matter what measures are taken, global climate change will continue. Since the process of substituting energy crops for fossil fuels would occur gradually over several decades, climate change will affect its production. The objective of this study was to use the DSSAT-CSM model to assess the impact of climate change on the production of wheat as a bioenergy crop grown in southern Saskatchewan.

2. Methodology

2.1. Site Condition

The site selected for this study was located on a gently sloping Swinton silt loam (Typic Haploboroll) at the Semiarid Prairie Agricultural Research Centre, Swift Current, in southern Saskatchewan. Daily maximum and minimum air temperatures and precipitation were obtained from the weather station located on the research site. Daily solar radiation was calculated using the Mountain Climate Simulator [1]. Soil property inputs for DSSAT-CSM (organic carbon, total nitrogen, clay and silt in percent, cation exchange capacity, pH, soil lower, drained upper and saturated points, saturated hydraulic conductivity, and bulk density) were observed on the site. The management used for simulation was a continuous wheat rotation under no-till with a seeding depth of 5 cm. Nitrogen fertilizer was assumed to be applied at a rate of 100 kg ha^{-1} at planting time. Seeding dates were predicted with the model developed by Bootsma and De Jong [2], and subsequently modified by McGinn et al. [3].

2.2. The DSSAT-CSM Model

The Decision Support System for Agrotechnology Transfer-Cropping System Model (DSSAT-CSM), a widely used process-based modeling package [4], was selected for simulating the wheat production system. This model simulated wheat yield and biomass generally well in western Canada [5-7]. The wheat module of DSSAT-CSM (v4.0) was modified to improve the prediction of seedling emergence rate [8-9] and leaf appearance rate [10]. The spring wheat cultivar Biggar (Canada Prairie Spring Wheat class) was used for modeling because this wheat class has higher starch content and lower protein concentration in comparison to bread wheat class and is recognized as a viable feedstock for ethanol [11]. Genetic coefficients of Biggar were calibrated with the data collected by Jame and Cutforth [12] and tested using data from the New Rotation experiment at Swift Current [13]. In order to predict the long-term effect we used the Sequence Analysis of DSSAT to run the model.

2.3. Climate Change Baseline and Scenarios

Weather data during the period of 1961-1990 were treated as baseline climate. Climate change scenarios in 2050s (2040-2069) were projected by the third generation global climate model developed at Canadian Centre for Climate Modelling and Analysis (CGCM3) with the forcing of three greenhouse gas (GHG) emission scenarios (i.e., IPCC SRES A1B, A2 and B1) [14]. Synthetic 300-yr weather data were generated by the AAFC Stochastic Weather Generator (AAFC-WG) for the baseline period and each scenario [15]. These generated data were used to predict the climate effect on wheat production with the DSSAT model. Qian et al. [16] found that simulations of crop models with 30-yr observed and the 300-yr synthetic weather data generated by AAFC-WG with parameters calibrated from the same 30-yr observed data, in general, do not show significant differences, with regard to timing of biomass accumulation, crop maturity date, as well as final biomass and grain yield at maturity. The simulations were run with and without direct effects of increased atmospheric CO_2 levels. The CO_2 levels were 550 ppm for A1B and A2 and 450 ppm for B1 [14]. The hourly air temperature was calculated using the subroutine HTEMP of DSSAT-CSM [17].

2.4. Data Analysis

Statistical analyses were done by SAS [18]. Means, lower and upper limits of the 95% confidence interval and standard deviation of synthetic air temperature and precipitation were calculated and compared among baseline and climate change scenarios by PROC MEANS. Predicted and calculated variables were compared between scenarios with PROC MIXED [19].

3. Results

3.1. Climate Change Baseline and Scenarios

3.1.1. Precipitation

All the climate change scenarios increased annual precipitation compared to the baseline period (331 mm, Fig. 1). The most significant increase is scenario A1B (55 mm), followed by A2 (39 mm) and B1 (37 mm). All three scenarios increase precipitation every month except July and August and June (A2 only), when less rains are projected. Scenario A2 was similar to A1B in terms of precipitation distribution except that it was markedly (10 mm) less than A1B in June. Precipitation for scenario B1 was generally slightly less than that of A1B, except in July and August when B1 had more rain than A1B.

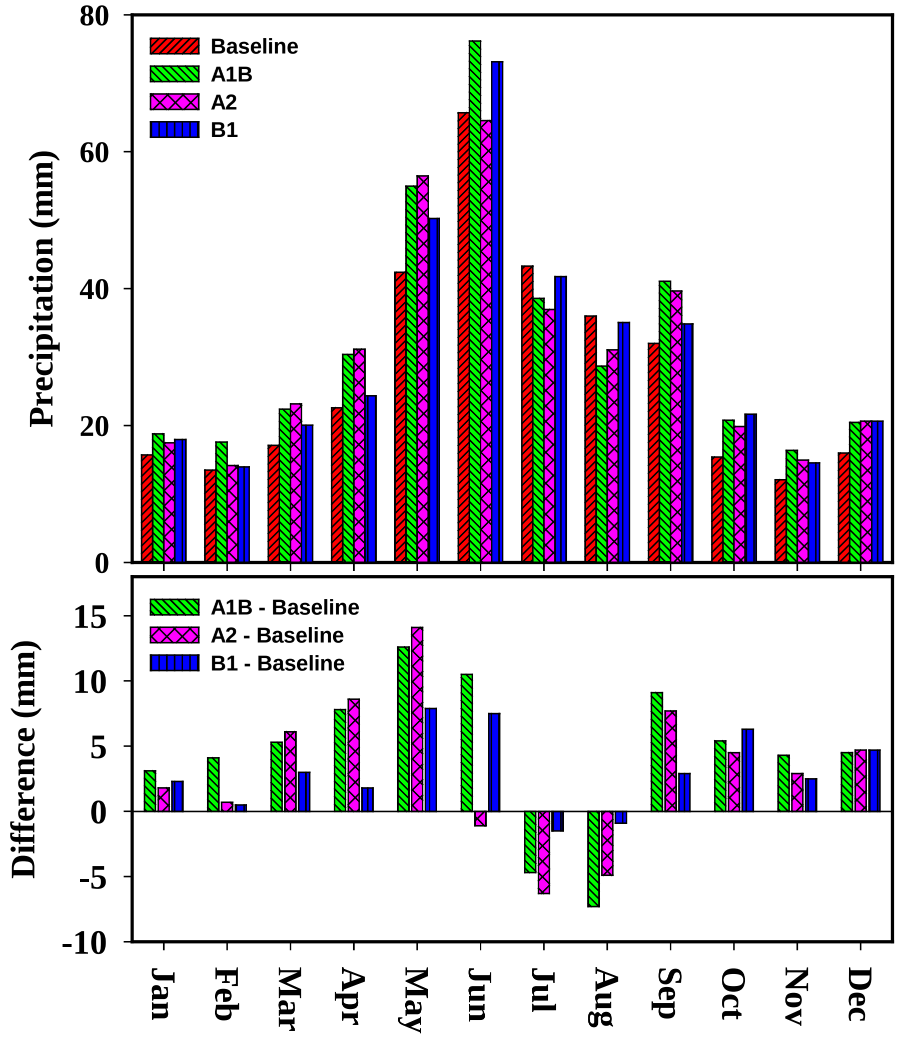

Fig. 1. Monthly precipitation under baseline and three scenarios and difference between baseline and scenarios.

3.1.2. Air temperature

Air temperature in all climate scenarios was increased compared to the baseline climate (Fig. 2). Scenarios A1B, A2 and B1 had 3.2, 3.6 and 2.7 ^{0}C higher annual mean air temperatures than the baseline, respectively. The highest differences in temperature occurred in the winter, followed by summer, and relatively small differences occurred in the spring and fall. Scenario

A2 had the highest temperature in most of the days of the year. The change in pattern and difference between scenarios in daily maximum and minimum air temperatures were similar to that in daily mean temperature (data not shown).

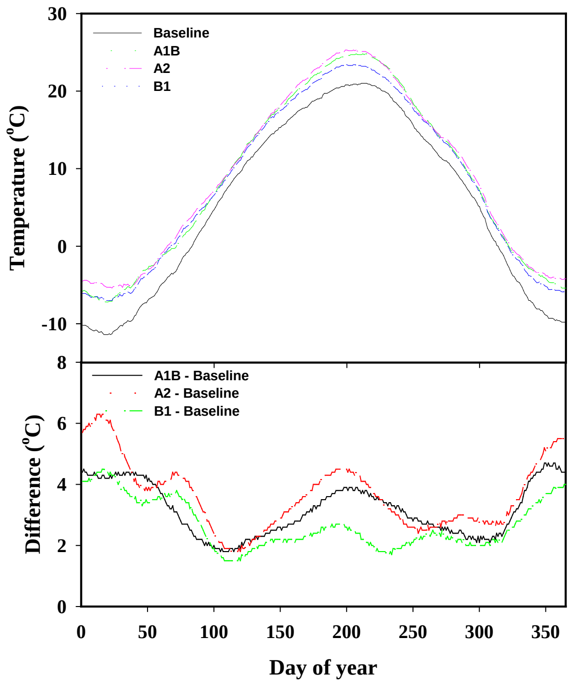

Fig. 2. Daily mean air temperature under baseline and three scenarios and difference between baseline and scenarios.

3.2. Phasic Development

The predicted seeding dates under all climate change scenarios are six days earlier than the prediction under the baseline climate (Day 124, May 10) (Table 1). Because of the earlier seeding and higher temperatures, predicted dates of anthesis and maturity averaged nine and 13 d earlier than simulations based on the baseline climate, respectively. The vegetative (from emergence to anthesis) and grain filling stages were shortened by 2-3 and 3-5d, respectively. The total time to maturity was shortened by 6-9 d. Among the three climate scenarios, the scenario that reduced days to plant maturity the most was scenario A2, which is associated with its higher temperature.

Table 1. Effects of climate change on phasic development of wheat

	Day of year			Duration (days)			
Scenario	Seeding	Anthesis	Maturity	Seeding to emergence	Emergence to anthesis	Grain filling	Seeding to Maturity
Baseline	123.5a[z]	185.2a	218.4a	11.3a	50.4a	33.1a	94.8a
A1B	118.0b	176.7bc	205.5c	10.9ab	47.9c	28.7c	87.5c
A2	117.8b	175.7c	203.8d	10.7b	47.1d	28.1d	86.0d
B1	118.1b	177.5b	207.5b	10.9ab	48.6b	30.0b	89.4b

[z] Within columns and depth, values followed by the same letter are not significantly different at the 0.05 level of probability.

3.3. Biomass and Grain Yield

Without the direct effect of CO_2, the model predicted that all three climate change scenarios significantly increases biomass production compared to the baseline (Table 2), with A1B increasing the most (28%) followed by B1 (16%) and A2 (12%). The combined effect (climate and CO_2) increased biomass production much more, with A1B increasing the most (74%) and A2 (55%) and B1 (41%) being similar. Increased CO_2 concentrations of 220 and 120 ppm resulted in increased biomass production of 43-45% and 25%, respectively. The effect of the climate change scenarios on grain yield shows the same trend as biomass with a slightly higher increase rate.

Table 2. Effects of climate change on biomass and grain production of wheat.

Scenario	CO2 ppm	Biomass kg ha-1	Grain Yield kg ha-1
Baseline	330	5039f[z]	2467f
A1B	330	6463d	3167d
A1B	550	8753a	4349a
A2	330	5651e	2834e
A2	550	7813b	3978b
B1	330	5856e	2880e
B1	450	7104c	3520c

[z] Within columns and depth, values followed by the same letter are not significantly different at the 0.05 level of probability.

4. Discussion and Conclusions

The estimated increase in yield under climate change is consistent with the study by Arthur [20] who predicted an increase in wheat yield under four climate change scenarios in Saskatchewan. However, caution must be exercised when interpreting the model-simulated results as the effect of heat stress on wheat growth is not well described by the model. Heat stress occurs often in wheat on the Canadian Prairies especially during reproductive growth, which has markedly negative impacts on yield [21]. At the grain growth stage (anthesis to maturity), heat stress is divided into two types according to Wardlaw et al. [22]: chronic stress (20–32°C) and heat shock (>32°C). Chronic stress involves a progressive decrease in kernel weight with increasing temperature because the increase of grain filling rate associated with the increase of temperature does not compensate enough for the reduction of grain filling duration [23]. In southern Saskatchewan, McCaig [21] found that the cumulative maximum daily air temperature >20°C during and after anthesis was negatively correlated with the yield of wheat. Heat shock can inhibit pollen growth, cause sterility and abortive grain, trigger premature senescence, inhibit kernel development and cause significant reduction in yield [24-25].

The occurrence of chronic stress increased for all the climate change scenarios compared to baseline (data not shown). Significant and more obvious increase of heat shock incidence was found for all scenarios (Table 3). Under the baseline climate, heat shock (>32 ^{o}C) occurred for only 30 hours during the first 20 days of grain filling. Heat shock occurred for 73, 87 and 56 hours during this same period under climate change scenarios A1B, A2 and B1, respectively, which are 1.8-2.9 times of that under the baseline climate. Note that if daily temperature is used, increases of heat shock are significant, but not as tremendous as calculated by using hourly results. This means that under climate change conditions heat shock will occur longer in a day than under the baseline climate. It is obvious that heat shock will damage the kernel development and reduce grain yield if the future cultivars are not improved in heat shock resistance. This is not predicted by the model because the DSSAT-CSM model, like many other models, does not simulate the yield loss caused by heat shock [26]. Therefore, grain yield, and probably biomass, is likely overestimated.

Table 3. Effects of climate change on duration of air temperature surpassing 32 °C during the first 20 days of grain filling.

Scenario	Day	Hour
Baseline	5.0d[z]	30.1d
A1B	9.3b	72.8b
A2	10.9a	87.3a
B1	7.6c	55.5c

[z] Within columns and depth, values followed by the same letter are not significantly different at the 0.05 level of probability.

Adaptation measures must be taken in regards to the high temperature under climate change. One possible strategy is early seeding. This would allow wheat to mature earlier, avoiding heat shock which will mostly occur in July. The prediction of seeding dates in this paper (Table 1) was calculated by an empirical model [3] which is based on observations from 1956 to 1984 [2]. In recent years, the adoption of no-till and stubble mulch tillage systems allows seeding even earlier. Therefore, if this technique is used in the 2050's the seeding dates could be significantly earlier than the predicted dates. Early seeding of wheat on the Canadian Prairies may have other advantages, such as reducing the application of herbicides for weed control [27], and could possibly reduce the incidence of some insects and diseases and improve the timeliness of planting operations in the spring. Dormant-seeding in the fall or winter is another method to be considered. This is already practiced by some farmers and some research has been conducted [28].

Two other strategies to cope with the heat stress are breeding heat resistant cultivars [29] and adopting improved tillage methods. The surface residue and standing stubble in a no-till and stubble mulch system act as insulation and impede the exchange rate of thermal energy between the soil and atmosphere. The slightly higher soil moisture under this system can also help buffer the extremes in daily soil temperatures and reduce near-surface root heat stress. Merrill et al. [30] and Wang et al [25] observed that no-till mitigated heat stress of wheat and improved growth and yield.

Although the projected increase of air temperature, especially the increase of heat shock, may cause yield loss, all three climate change scenarios projected an increase in precipitation. Proper management methods are needed to capitalize on this advantage. Fortunately, one of the strategies is also to seed wheat early which allows wheat to take advantage of the wetter spring while avoiding the drier period in July [31-32].

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