Impact of weather variability and climate change on grain yield of Sable wheat in Thunder Bay, Ontario

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by

Jannat Chauhan

Faculty of Natural Resources Management

Lakehead University

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Abstract

Cultivation of spring wheat varieties has expanded into northern areas where it is an integral part of the crop rotations followed by the farmers. Around Thunder Bay, in Northern Ontario, spring wheat is typically grown from May until September. Crop success or failure depends on critical stages of growth in spring wheat that include emergence and tillering (in May-June), stem elongation (jointing) and booting (in June-July), spike emergence, heading (mid July), anthesis, grain filling (July-August), and kernel hardening or maturity (in August). Weather plays a vital role at each of these stages. Here, analysis is presented of the role of weather during seeding, tillering, jointing, grain-filling and kernel-hardening stages on the grain yield of spring wheat (cultivar Sable) from 2003-2017 at the Lakehead University Agricultural Research Station (LUARS), Thunder Bay. The analysis was conducted using the CROP-SIM CERES model and weather records at the Thunder Bay Airport (~10 km from LUARS). Simulation of future yields followed with projected climate according to the Representative Concentration Pathway (RCP) 2.6, a greenhouse gas trajectory adopted by the Intergovernmental Panel on Climate Change (IPCC). The simulation predicted an average 26% lower grain yield by 2030. Sable grain yield was correlated to maximum ($R^2 = 0.69$) and minimum ($R^2 = 0.46$) temperature, but rainfall was not a factor that could predict wheat grain yield on its own. In the future, growers could experience a greater number of heat-stress days, and an increase in minimum temperatures during the jointing, grain filling and kernel-hardening stages that may limit future yields.

Keywords: grain yield, sable variety, spring wheat, weather, Lakehead University Agricultural Research Station, Thunder Bay.

Table of Contents

List of Tables

List of Figures

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Introduction

By 2050, the average annual temperature in Ontario will rise by 2.5–3.7 °C (Statistics Canada, 2016). The genetic makeup of plants in Ontario will be affected by this outcome, with some crops experiencing losses to genetic variation and others possibly facing extinction (Peters, 1990). Plants subjected to high stress, such as those at the edge of a range, will be more susceptible to insect-pests and pathogens (Colombo, 1998). Warmer and drier conditions expected in most of Ontario will favour species that are more tolerant of periodic drought (Schindler, 1998). Weather variables like temperature and precipitation also play an essential part synergistically and antagonistically in agricultural crops yields (Waggoner, 1983). Limiting or exceeding certain weather thresholds could limit crop growth. Prolonged drought and excessive rainfall affect specific aspects of a crop's growth cycle and associated field management. Extreme weather events can directly impact the physiological processes through physical damage, and can also affect the timing and conditions of field operations. Plants are often exposed to several stresses together, such as drought, flooding, and heat. It is necessary to understand the effect of these factors to facilitate regional yield forecasting and improve crop management.

The northern Ontario climate is characterized by a dry and warm summer and a cold and wet winter, with lower rainfall and a shorter growing season than in southern Ontario (Chapagain, 2017). Nevertheless, northern Ontario is home to 49,600 farms of the highest quality (Class 1) agricultural land, and the region contributes a significant component of Ontario's cultivation of oats (28 %), barley (15 %), hay (12 %), mixed grains (5 %), potatoes (5 %), silage corn (2 %), soybeans (1 %), and green peas (1 %; Ontario Ministry of Agriculture, Food and Rural Affairs, OMAFRA, 2017). Thunder Bay, in northwestern Ontario, experiences cooler summers and warmer winters relative to other parts of the region, due to Lake Superior's moderating effect.

The Thunder Bay area climate favours the cultivation of wheat, barley, rye, foxtail millet, soybeans, peas, canola, and forage crops like grasses, corn, and alfalfa.

Changing weather patterns with climate change in northern Ontario include less snow cover and less rain during May and June than in the past, resulting in drier soils, now less suitable for planting some of these crops than in the past. Multi-model climate change projections for 2031–2050 (relative to a 1986–2005 reference period) show that Thunder Bay will experience a 2.0 °C increase in summer mean temperatures in a low emission scenario (the Representative Concentration Pathway [RCP] 2.6, a greenhouse gas trajectory adopted by the Intergovernmental Panel on Climate Change; Bush and Lemmen, 2019). The growing season length could increase in Thunder Bay by 20 days. The annual highest daily maximum and minimum temperatures will also increase by 1.6 ºC and 4.0 °C, respectively.

This study is on the effect of daily, weekly, and monthly weather variations on the grain yield of the cultivar Sable of spring wheat (*Triticum aestivum* L.) in Thunder Bay. For this study, data were obtained on grain yield of Sable wheat from 2003–2017 from the Lakehead University Agricultural Research Station (LUARS). The Sable variety has been in the past recommended for cultivation throughout Canada. Other reasons for choosing this variety for this study is that it was grown in LUARS continuously from 2003-2017, a longer period than any other variety and a record unusual from the perspective of any other research station. In 2003 and 2004 it gave maximum yield as compared to the other spring wheat varieties grown in LUARS. The research question is how climate change forecasts related to temperature and precipitation will affect Sable wheat grain yield. The approach to answering this question is to model Sable wheat through its growth stages using the CROP-SIM CERES model (Hoogenboom et al., 2019a, 2019b; Jones et al., 2003). Forecasting Sable wheat grain yield using several years of variation in weather conditions can help farmers recognize what variation in grain yield they can expect, or what adjustments to crop management may help ensure a good harvest.

Physiology of Spring Wheat

There are eight critical stages of growth in spring wheat: (1) germination, (2) tillering (May-June), (3) jointing (stem elongation), (4) booting (end of stem elongation in June-July), (5) heading (spike emergence), (6) anthesis, (7) grain filling (July-August), and (8) kernel hardening or maturity (in August or early September; Bauer et al., 1992). Spring wheat development depends primarily on temperature at all stages, especially after the heading stage. Germination and growth begin when the soil temperature reaches 5 °C (Kobza et al., 1987). Spring wheat should be planted as early as possible, since cooler weather from emergence to the early reproductive stages generally benefits tiller formation and the development of larger heads. Increased growth during the early season typically results in higher yields.

The minimum temperature for spring wheat development is 0 °C and the maximum is 35 °C (Al-Khatib and Paulsen, 1999). The vegetative development of spring wheat has threshold temperatures of 20–30 °C depending on the cultivar (Kobza et al., 1987). Photosynthesis is maximized at 20–22 °C and inhibited at 30–32 °C. The optimum temperature for anthesis and grain filling is 12–22 °C, beyond which grain yield is significantly reduced (Tewolde et al., 2006). Spring wheat yield is lowered by 5-6 % with each one-degree rise in temperature (Asseng et al., 2014 and Innes et al., 2015). Global warming is expected to reduce spring wheat yield by at least this amount (Lobell et al., 2011). High temperature shortens the period of development of spring wheat (Van Dobben, 1962), depresses grain yield (Asseng et al., 2014; Hatfield et al., 2011; Yu et al., 2014), and greatly reduces grain number (Warrington et al., 1977).

Heat stress is a particular constraint to spring wheat productivity at the anthesis and grain-filling stages (Noorka et al., 2009). High temperature directly affects photosynthesis due to photosystem and enzyme impairment, leading to a reduction in yield (Al-Khatib and Paulsen, 1999). High temperature also disrupts pollen development, contributing to reduced seed set (Farooq et al., 2011), which induces early senescence and reduces the assimilates required for grain filling (Machado and Paulsen, 2001). Temperatures above 25 °C shorten the grain-filling stage and reduce wheat grain yield (Hatfield et al., 2011; Sofield et al., 1997). Wheat exposure to >30 °C pre- and post-anthesis reduces the grain-filling rate and decreases grain yield and quality (Barnabás et al., 2008). High temperature at the reproductive stage greatly reduces grain number (Warrington et al., 1977), grain growth and weight at the reproductive stage (Wiegand and Cuellar, 1981), causing a negative impact on grain number and grain filling (Chakrabarti et al., 2011). Increased variability of temperature also decreases spring wheat grain yield (Wheeler et al., 2000). For example, frost influences yield (Rezaei et al., 2015; Prasad and Djanaguiraman, 2014), reducing pollen quality and seed set (Hays et al., 2007). Seed size is influenced by high respiration rates that affect other qualitative losses, leading to 3–4 % loss in grain yield.

Precipitation during the vegetative stage is another determinant of grain yield in spring wheat (Yu et al., 2014). Rainfall is decreasing with climate change in many regions, leading to water deficiency for spring wheat in these regions, in turn having negative effects on germination (Rajaram, 2001), tillering (Larbi and Mekliche, 2004), and stem elongation (Eberhart and Russell, 1966). Delays in anthesis caused by low rainfall delay the milk development stage (Shamsi and Kobraee, 2011), resulting in reduced grain yield (Jatoi et al., 2011). On the other hand, excessive rainfall also affects early vegetative stage~~,~~ growth and grain yield of the wheat crop (Cannell et al., 1980), because flooding can reduce tiller number (Zhang et al., 2004), growth in the early reproductive stage and grain yield of wheat (Gardner and Flood, 1993). Excessive rainfall during later stages can reduce the number of grains per spike and grain weight (Musgrave and Ding, 1998).

Finally, water stress arising from a net moisture deficit, where evapotranspiration from plants and evaporation from soil exceeds precipitation, has a direct effect on spring wheat development. Morphological characters of wheat, such as root length, tillers, plant height, number of spikes, grains per spike, fertile tillers per plant, grain weight, peduncle length, spike weight, stem weight, awn length, main spike length, grain weight per spike, grain yield, biomass and harvest index, have low tolerance to water shortage (Blum, 2005). Water stress at heading and reproductive stages in spring wheat may lead to 58–91 % reduction in grain yield (Nawaz et al., 2015). Flowering is the most sensitive stage to water shortage (Farooq et al., 2012). Water stress inflicts a profound impact on shortening the grain-filling stage and altering enzymatic activities.

Spring Wheat in Thunder Bay

Spring wheat production in Thunder Bay has varied considerably from year to year during 2006–2018 (Table 1). Farmers are not always aware of mitigating practices, such as changes to sowing time, and as a result, lower yields can influence decisions to adopt different crop cultivation in a following year, rather than attempting another year of Sable wheat. If farmers are provided knowledge on the effect of weather changes on wheat grain yield, then they will be able to adopt agricultural practices to continue to grow the crop. Sable wheat is not a crop that is limited by growing degree days (GDD) in the Thunder Bay area; in fact, there is a significant negative relationship between GDD (above 5 ºC) and Sable wheat yields at LUARS (Table 1; Figure 1; Pearson correlation coefficient, $r = -0.54$; Student's $t = -2.32$; $P = 0.03$). Previous examination of weather trends by Mhetre and Sahota (LUARS Annual Report 2019, pages 3-11) also found evidence for higher Sable wheat yields at LUARS with lower total accumulated rainfall (Figure 2; $r = -0.49$; $t = -2.04$; $P = 0.06$). Thus, in general terms, the crop is neither heat limited nor drought limited in Thunder Bay.

Table 1. Sable spring wheat grain yield and production in the Thunder Bay area, 2006–2018 (Statistics Canada) and grain yield at the Lakehead University Agricultural Research Station (LUARS) 2003–2017.

Year	Area seeded (ha)	Area harvested (ha)	Area grain yield (kg/ha)	Area production (tonnes)	Grain yield at LUARS (kg/ha)
2003					6839
2004					7976
2005					5010
2006	222	202	500	101	3258
2007	567	567	1700	964	4216
2008	n/a				5237
2009	n/a				6309
2010	87	63	200	13	4880
2011	301	122	300	37	4594
2012	1066	1018	3900	3970	3175
2013	454	454	600	272	3476
2014	n/a				5846
2015	850	850	3600	3060	4370
2016	n/a				5899
2017	800	324	900	292	5200
2018	567	547	2000	1094	5776

Methods

Study variety

Sable wheat is a hard red spring wheat, derived from a cross (TG3S) x (B58-664HCH) produced at ACS-PZO-Pflanzenzucht Oberlimpurg, Germany, in 1989. Seeds are sown in May and harvested in the first or second week of September. Hard red spring wheat is one of the most tolerant crops to cold temperatures and frost events.

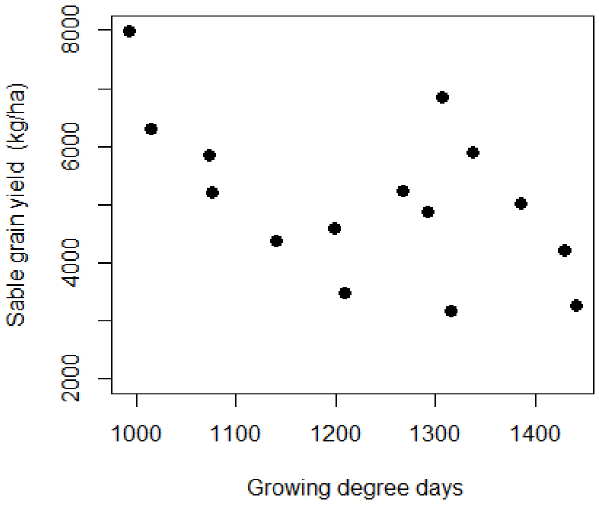

Figure 1. Relationship between Sable wheat grain yield at the Lakehead University Agricultural Research Station (LUARS) and growing degree days (>5 ºC) calculated from Environment and Climate Change Canada (ECCC) data from the Thunder Bay Airport, 2003–2017.

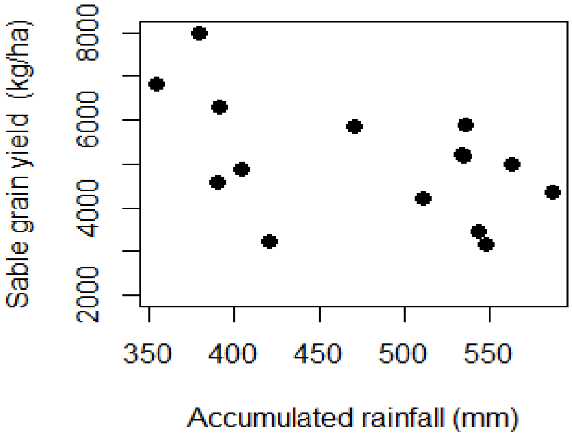

Figure 2. Relationship between Sable wheat grain yield at LUARS and accumulated rainfall May to September, 2003–2018 from ECCC data from the Thunder Bay Airport.

Study area

The Lakehead University Agricultural Research Station (LUARS) is located ~10 km from the Thunder Bay Airport, 48º 22′ 19.00″ N latitude and 89º 19′ 18.00″ W longitude, at an elevation of 199 m above mean sea level. The area experiences a warm-summer humid continental climate (Appendix 1). Average daily temperatures range from 17.7 °C in July to −14.3 °C in January, and average daily maximum temperature in July is 24.3 °C, in January, −8.0 °C.

The Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) established the Thunder Bay Agricultural Research Station (TBARS) in 1991 and passed on the research station to the University of Guelph in 1996. The University of Guelph-closed the research station in October 2002. Thunder Bay farmers protested the closure of the research station, organized themselves into Thunder Bay Agricultural Research Association (TBARA), a not-for-profit corporation, and reopened the research station in April 2003 with funding from the Northern Ontario Heritage Fund Corporation (NOHFC). TBARA operated the research station from 2003 to 2018, up to 2017 with funding from NOHFC and from 2017 to March 2018 with funding from

OMAFRA. OMAFRA offered $1.65 million funding in fall 2017 to Lakehead University to take over the research station beginning April 2018. Lakehead University changed the name of the research station from TBARS to LUARS (https://www.lakeheadu.ca/centre/luars) and has been operating it since April 2018.

Barley, spring wheat, winter wheat, soyabean, oats, beans, spring peas, lentil, linseed, canola, rye, mustard, forage crops, alfalfa, and galega are grown experimentally at the station. Sable wheat is one of the spring wheat varieties that was grown at LUARS from 2003 to 2017. During 2003–2005, Sable wheat produced the highest grain yield among the spring wheat cultivars at LUARS.

CROP-SIM CERES wheat model

Many studies have analysed the impact of weather variation and climate change on wheat yield using crop growth models (e.g., Wang et al., 2012; Asseng et al., 2011; Qian et al., 2012; Jones et al., 2003). These models divide the life cycle of the wheat plant into the eight growth stages. Details on the CROP-SIM CERES wheat model are reported by Hoogenboom et al., 2019a, 2019b; Jones et al., 2013) and are found in Thorp et al. (2010). The CROP-SIM CERES model uses maximum and minimum temperature and rainfall. When temperature exceeds the base temperature for wheat, the growth increment for that day is calculated as a function of the daily minimum and maximum temperature, while a one-dimensional soil water balance calculates soil water flow through all modelled soil layers, from which the model calculates daily evapotranspiration and soil evaporation. As soon as the characteristic number of biological days for any growth stage is reached, the next stage is entered, and the process continues until the end of the grain-filling stage. The crop stages and the morphological development of the model plants are simulated as a function of temperature, day length, leaf area calculated as potential leaf size, and available dry matter. Stem and spike areas are calculated from stem and spike weights, and grain number is estimated as the difference between the aboveground dry matter at the end of anthesis. Grain yield is estimated as a coefficient of grains per spike and maximum grain growth rate.

In this study, daily minimum and maximum temperatures and rainfall for May to September from 2003–2017 were downloaded from Environment and Climate Change Canada's website, matching the Sable wheat grain yield dataset from the Lakehead University Agricultural Research Station. These weather data, along with soil and crop cultivar information, followed by soil type, planting date, planting method, planting distribution, the number of plants at seeding and emergence, and spacing and direction of the planted rows, were entered into the CROP-SIM CERES model. Fertilizer doses were inputted for each year according to LUARS records; irrigation applications were kept at zero for each year, as wheat is grown rainfed (not irrigated) in the Thunder Bay area and irrigation is not used at LUARS. Initial field conditions were entered, including information on the previous season's crop, which for legumes also included the weight of the nodules and the concentration of nitrogen in the soil. Extreme events like drought will be less frequently experienced in Thunder Bay by 2030, according to Environment and Climate Change Canada, and there is a predicted increase in precipitation by 10 % in the RCP 2.6 Climate Change Scenario (Bush and Lemmen, 2019). Water stress was thus reviewed in a qualitative way.

Data analysis

The modelled Sable wheat grain yields for each year were compared to observed yields at LUARS using the normalized root mean square error, NRMSE, which is the RMSE of the model divided by the simulated yield and multiplied by 100. It evaluates the average relative deviation between real and simulated values as a percentage. Model performance is considered excellent at an NRMSE value of less than 10 %, good at 10 to 20 %, and fair at 20 to 30 % (Nouri et al., 2017). The CROP-SIM CERES model output includes performance measures for simulated yield based on four models: one including only maximum temperature, a second only minimum temperature, a third only rainfall, and a fourth the full model using all three variables. The reported statistics are R^2, F and the associated probability, P, in an analysis of covariance (ANCOVA) in each of the four model cases.

Weather for the RCP 2.6 Climate Change Scenario was simulated using the same weather data for Thunder Bay between 2003 and 2017, but adjusted daily according to the projected changes reported by Environment and Climate Change Canada (Bush and Lemmen, 2019). These are maximum temperature increases of 1.0–2.4 °C, minimum temperature increases of 1.0–3.0 °C, and a 30 % increase in the number of rainy days. The RANDBETWEEN function in Microsoft Excel was used to add to the maximum and minimum temperatures a randomly chosen value each day within the projected ranges of increase, and the RAND function generated an additional number of days with average rainfall, by choosing a random number between 1 and 10.

If maximum temperature, minimum temperature, and rainfall are significantly above or below optimum conditions for just a few days, Sable wheat could experience lower grain yields. To explore potential effects of such variation, Pearson (r) correlation coefficients were calculated to identify the strongest relationship between the number of days exceeding a range of defined optimum conditions for each growth stage and the final Sable wheat grain yields at LUARS, or the same number of days by each stage in an RCP 2.6 Climate Change Scenario and the final simulated Sable wheat grain yields in CROP-SIM CERES. To calculate the number of days above the optimum maximum temperature, a threshold was set at 25 ºC, following Hatfield et al. (2011) and Sofield et al. (1997), which is also one degree above the historical mean for maximum temperatures in July in Thunder Bay; one-degree increments to 31 ºC were tested as thresholds, about halfway to the published maximum temperature of 35 °C for Sable wheat (Al-Khatib and Paulsen, 1999). A summary of the number of days above each maximum temperature threshold is shown in Appendix 2.

The minimum temperature optimum for Sable wheat grain yield will vary with the growth stage, with some evidence that lethal minimum temperatures near freezing can affect hardening during the germination stage, while relatively cooler temperatures during the stem elongation stages (jointing and booting) may benefit seed production and yield (Hunt and Pararaiasingham, 1995). Therefore, for exploring correlations between Sable wheat grain yield and the number of days of minimum temperature, a threshold was set at 1 ºC, to increase in one-degree increments to 6 ºC. A summary of the number of days below each minimum temperature threshold is shown in Appendix 3. Finally, total rainfall was calculated for each stage in Sable wheat development according to the crop calendar developed for North Dakota (Bauer et al., 1992), and Pearson correlation coefficients, r, were calculated for the amount of rainfall during each grain development stage and the total observed and modelled Sable wheat grain yields at the end of the observed and RCP 2.6 Climate Change Scenario growing seasons, respectively.

A correlation was considered significant between each of the three weather variables (maximum temperature, minimum temperature and rainfall) and observed and modelled grain yield at different stages for $P < 0.05$ for Student's t-test statistics associated with r (Appendices 4 and 5). All statistics were calculated in R-Studio using the Tidyverse and ggplot packages. The strongest correlations are presented as graphics.

Results

Sable wheat grain yield simulated by the CROP-SIM CERES model was closely mapped to observed yields at LUARS (Figure 3). NRMSE values were in the fair range for the fitted data on wheat grain yield (27 %), maximum temperature (20 %), minimum temperature (29 %) and rainfall (25 %). The order of influence of variables on wheat yield was, from stronger to weaker, maximum temperature, minimum temperature, and rainfall (Table 2). Models with RCP 2.6 projected weather (Figure 4) were also in fair range for wheat grain yield (25 %), maximum temperature (22 %), minimum temperature (27 %) and rainfall (27 %). The same general model statistics were recorded for the wheat grain yields projected for the climate differences in the RCP 2.6 scenario, but in this case, rainfall alone was not a significant contributor to modelled grain yield (Table 2). RCP 2.6 wheat grain yields were on an average 26 % lower than for the model using historic weather records from 2003 to 2017 (Figure 4).

The significant correlations with grain yield of Sable wheat and number of days above a maximum temperature occurred only for the observed grain yields at LUARS (Table 3). These were a negative correlation, $r = –0.57$ ($t = –2.53$, $P = 0.02$), between grain yields and the number of days >25 °C during the grain-filling stage (Figure 5), and a positive correlation, $r = 0.82$ ($t = 5.18$, $P < 0.01$), between grain yields and the number of days >29 °C during the kernel-hardening stage (Figure 6). In contrast, there were several significant correlations with observed grain yields of Sable wheat at LUARS and

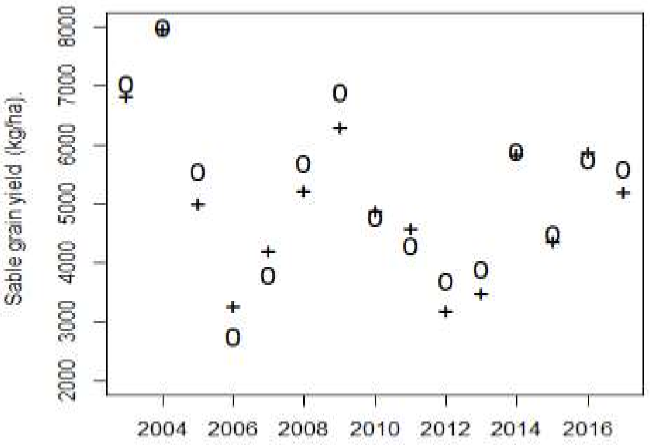

Figure 3. Actual (crosses) and simulated (open circles) Sable wheat yield at LUARS from 2003–2017. Simulation of yield used the CROP-SIM CERES model (Hoogenboom et al., 2019a, 2019b; Jones et al., 2013).

the number of days below a minimum temperature, occurring both for the actual grain yields at LUARS and projected grain yields with simulated weather in an RCP 2.6 Climate Change Scenario (Table 4). These included a positive correlation, $r = 0.49$ ($t = 2.07$, $P = 0.05$), between projected grain yields and the number of days <1 °C during the tillering stage (Figure 7), and positive correlations between LUARS grain yields and the number of days <1 °C (*r* = 0.56, *t* = 2.48, *P* =0.02), and between projected grain yields and the number of days <4 °C (*r* = 0.54, *t* = 2.34, *P* =0.03) during the jointing stage

Table 2. Model statistics matching observed Environment Canada weather for the Thunder Bay Airport to observed Sable wheat grain yields at LUARS, and matching simulated weather in an RCP 2.6 Climate Change Scenario to modelled grain yields. Modelled period was from 2003–2017.

Model	LUARS grain yields			Modelled grain yields		
	R^2	*F*	*P*	R^2	*F*	*P*
Maximum temperature	0.93	166	<0.001	0.69	21	0.002
Minimum temperature	0.83	60	<0.001	0.46	5.9	0.05
Rainfall	0.30	5.4	0.04	0.05	0.2	0.69
All three variables	0.98	1194	<0.001	0.89	1183	<0.001

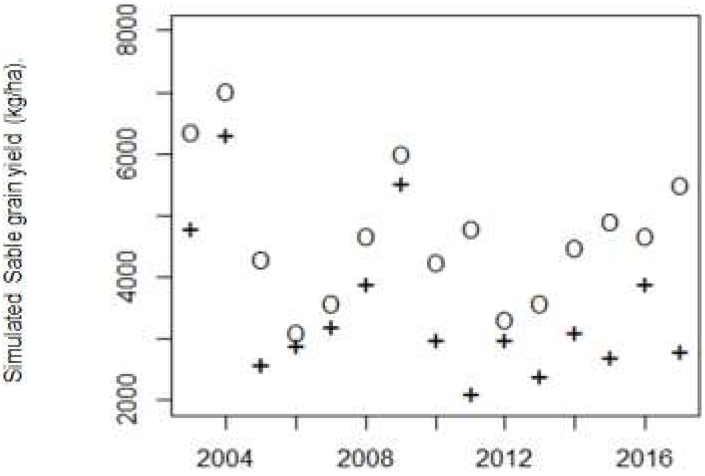

Figure 4. Modelled Sable wheat grain yield using observed weather (open circles) and weather projected in an RCP 2.6 Climate Change Scenario (crosses).

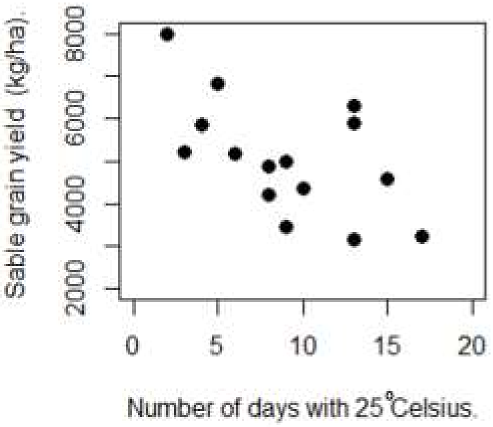

Figure 5. Sable grain yield at LUARS against the number of days with maximum temperatures in the grain-filling stage >25 °C.

(Figure 8). In the grain-filling stage, the strongest of the significant positive correlations with observed grain yields and the number of days with low minimum temperatures occurred for the number of days <4 °C ($r = 0.78$, $t = 4.52$, $P < 0.01$), and a significant positive correlation occurred between modelled grain yields in an RCP 2.6 Climate Change Scenario and the number of days <6 °C ($r = 0.52$, $t = 2.23$, $P = 0.04$; Figure 9). In the kernel-hardening stage, the strongest of the significant positive correlations with observed grain yields and the number of days with low minimum temperatures occurred for the number of days <5 °C ($r = 0.70$, $t = 3.56$, $P < 0.01$), and a significant positive correlation occurred between projected grain yields and the number of days <4 °C ($r = 0.61$, $t = 2.81$, $P = 0.01$; Figure 10). Finally, a significant correlation with amount of rainfall occurred during the germinating stage (Table 5), and higher rainfall in this stage was negatively related to Sable wheat grain yields at the LUARS site (Figure 11).

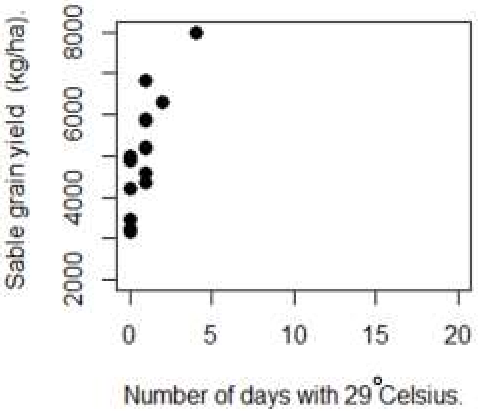

Figure 6. Sable grain yield at LUARS against the number of days with maximum temperatures in the kernel-hardening stage >29 °C.

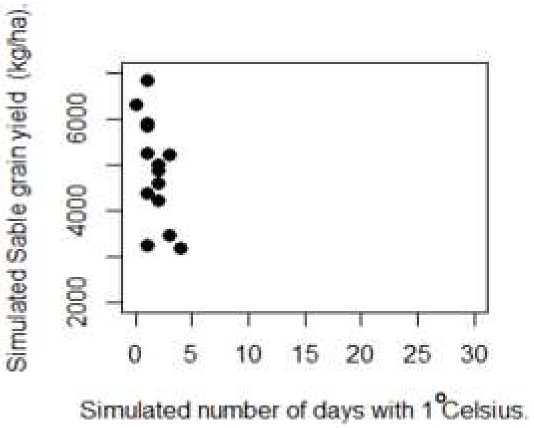

Figure 7. Projected Sable grain yield with simulated weather in an RCP 2.6 Climate Change Scenario against the number of days with minimum temperatures in the tillering stage <1 °C.

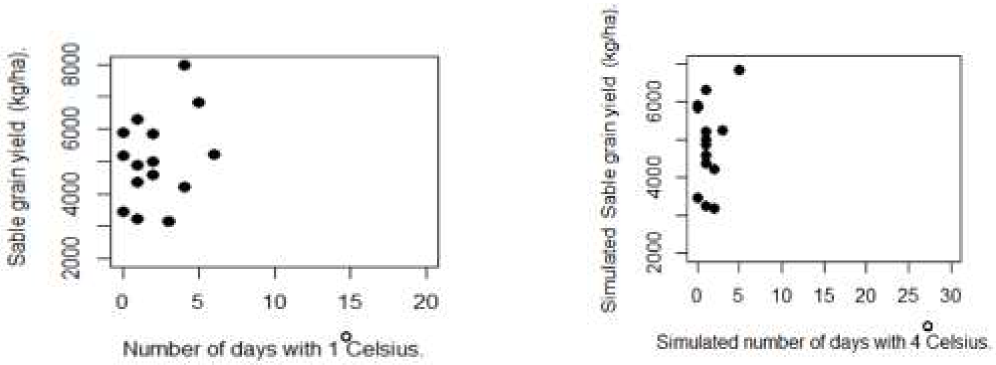

Figure 8. Sable grain yield against the number of days with minimum temperatures in the jointing stage <1 °C (left), and projected Sable grain yield with simulated weather in an RCP 2.6 Climate Change Scenario against the number of days with minimum temperatures in the jointing stage <4 °C (right).

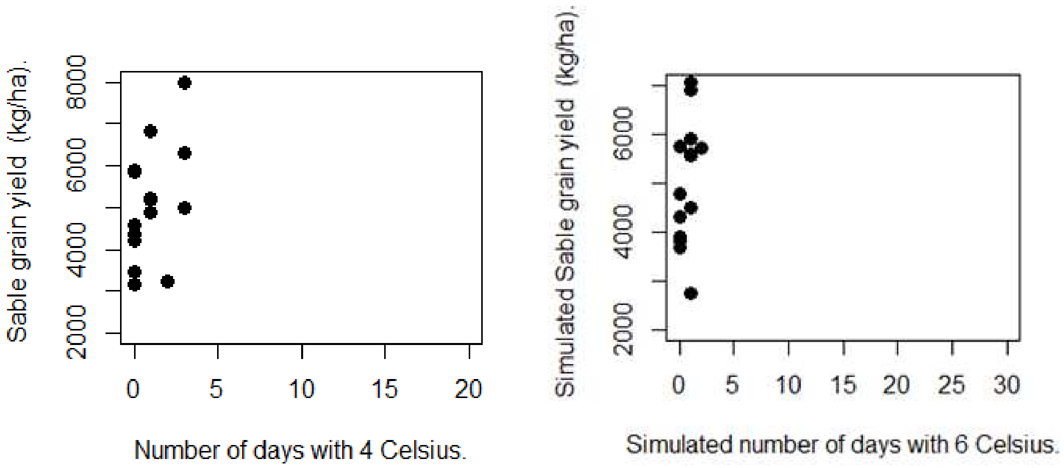

Figure 9. Sable grain yield against the number of days with minimum temperatures in the grain-filling stage <4 °C (left), and projected Sable grain yield with simulated weather in an RCP 2.6 Climate Change Scenario against the number of days with minimum temperatures in the grain-filling stage <6 °C (right).

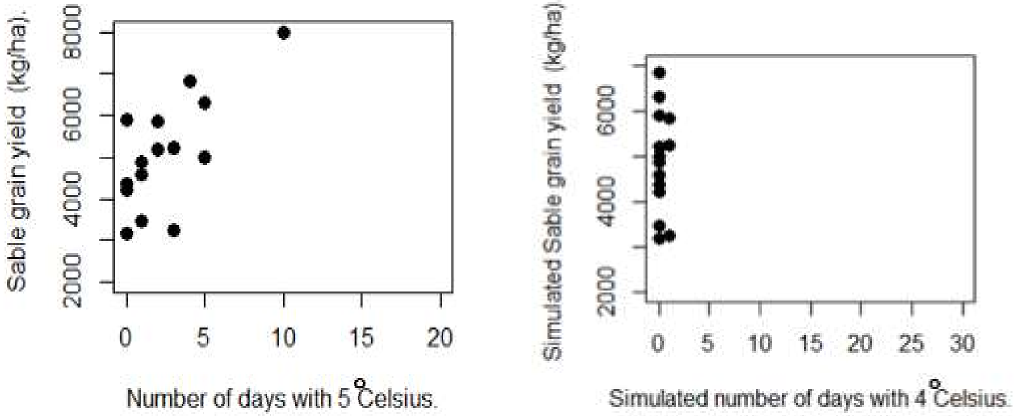

Figure 10. Sable grain yield against the number of days with minimum temperatures in the kernel-hardening stage <5 °C (left), and projected Sable grain yield with simulated weather in an RCP 2.6 Climate Change Scenario against the number of days with minimum temperatures in the kernel-hardening stage <4 °C (right).

Table 3. Pearson (r) statistics for correlations between the total rainfall during 2003–2017 in five spring wheat growth stages and (a) Sable wheat grain yields at LUARS and (b) modelled yields using an RCP 2.6 Climate Change Scenario. Simulation of grain yield used the CROP-SIM CERES model. Test statistic is Student's t and statistics in boldface are significant at P < 0.05.

	(a) LUARS grain yields			(b)Modelled grain yields		
Rainfall (mm)	*r*	*t*	*P*	*r*	*t*	*P*
Germinating stage	-0.69	-3.45	<0.01	-0.30	-1.17	0.26
Tillering stage	-0.20	-0.74	0.46	-0.38	-1.48	0.16
Jointing stage	-0.05	0.19	0.84	-0.05	-0.18	0.85
Grain-filling stage	-0.13	-0.47	0.64	-0.04	-0.15	0.87
Kernel-hardening stage	0.16	0.59	0.56	-0.11	-0.42	0.67

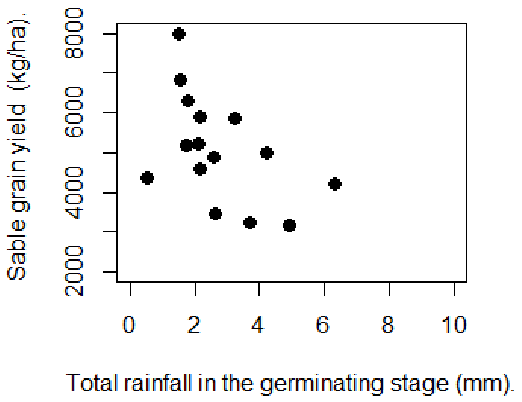

Figure 11. Sable wheat grain yield at LUARS graphed against total rainfall during the germinating stage.

Discussion

This study analysed a sixteen-year dataset recorded at the Lakehead University Agricultural Research Station (LUARS) to assess the impacts of weather change in Thunder Bay on Sable wheat grain yield. The LUARS study is the first to estimate weather change impacts on Sable wheat production in Thunder Bay using CROP-SIM-CERES models. Consistent with worldwide studies, the prediction is for grain yield reductions for spring wheat that appears to be more related to higher maximum temperatures, especially under future climate trends (Bassu et al., 2014; Zhao et al., 2017).

Rainfall alone was not considered a significant factor in determining the grain yield. This result was not different from several, including from a study in Australia, suggesting that most variation in spring wheat grain yield is due to the effect of temperature-driven physiological mechanisms (Asseng et al., 2011). The forecast of grain yields at LUARS with simulated Thunder Bay weather in an RCP 2.6 scenario suggests a decrease in Sable wheat grain yield due to an increased number of days with the maximum temperature above the optimum range during the later growth stages; in the historic record, a higher number of days with maximum temperatures in the grain-filling stage >25 °C is associated with lower grain yields. The result matches published work, which shows that an increase of just 1 ºC above the optimum threshold shortens the grain-filling stage by 5 % (Lawlor and Mitchell, 2000). Although earlier planting benefits spring wheat, we also found that cooler minimum temperatures during tillering and jointing stages corresponded to better grain yield, matching published benefits of cooler temperatures on tiller formation and the development of larger heads (Kobza et al., 1987). Lower minimum spring temperatures coupled with wet soil conditions in Thunder Bay likely led farmers to delay their seeding dates by 1–2 weeks, resulting in lower Sable wheat grain yields.

Generally, there is an adverse impact of high maximum temperatures (>30 ºC) during floret development that can cause complete sterility; elevated temperatures have been shown to reduce grain weight for every 1 °C above 15–20 °C (Streck, 2005). An increase in temperature from 30 to 38º C lessened the main stem grain weight by 20–44 % at the reproductive stage (Tahir and Nakata, 2005). Temperatures above 18–22 ºC cause yield reduction by decreasing starch biosynthesis (Spiertz et al., 2006). Heat stress decreases the activity of starch synthase, reducing grain growth (Prakash et al., 2003). Effects are not limited to high temperatures during the reproductive stages alone; even small increases in evapotranspiration from increased maximum temperatures at the vegetative growth stages reduce soil moisture availability, and therefore induces significant yield losses from water shortage during grain filling (Kirkegaard et al., 2007). The predicted drop in the grain yield was 7 % per 1 ºC increase in air temperature between 18 and 21 ºC plus 4 % per 1 ºC above 21 ºC for wheat-growing regions of the Great Plains of Australia (Asseng et al., 2014). In Australia, climate change effects are already being documented, as rising temperatures have resulted in decreased grain yield at a majority of the wheat-growing locations.

One drawback of using the CROP-SIM CERES model is that we cannot address the adverse effects of local climatic extremes on more minor scales over short periods, such as heat extremes, extreme precipitation, droughts, and floods. Heat shock, especially in June and early July, can negatively affect grain yield (McCaig, 1997). Heat shock also represses pollen germination, creating sterility and grain abortion, inhibiting kernel development, and cause significant grain yield reductions. Cooler weather from emergence to early reproductive stages generally benefits tiller formation, and the development of larger heads; increases in minimum temperatures during tillering and heading stages cause yield loss. Higher seasonal temperatures quicken the time to anthesis, resulting in less time to accumulate biomass, by making less water available for grain filling due to higher evapotranspiration, and increasing the possibility of facing detrimental temperatures above 34 °C (Asseng et al., 2011). Temperatures >20 °C in the spike-initiation and anthesis stages speed the growth of the spike, but reduce the number of spikelets and grains per spike (Saini and Aspinall, 1982; Semenov, 2009). Development of an anther after three days of heat stress at the anthesis stage, or an increase of 5 °C in temperatures >20 °C during the grain-filling stage, forms structurally abnormal and non-functional florets (Hedhly et al., 2009; Yin et al., 2009). Grain number and weight are sensitive to elevated temperatures (Ferris et al., 1998). An inverse relationship occurs between duration of heat stress and grain number per spike (Rawson and Bagga, 1979). Earlier, many studies supported lower rainfall as a cause of variation in spring wheat yield, ignoring the possible temperature impacts (Hammer et al., 1996). More recently, the effects of temperature increase across the growing season confirm the predictions of Van Ittersum et al. (2003) about the complexities of future temperature changes, in particular the increased frequency of extreme temperature events, rather than water stress related changes (Asseng et al., 2011).

Alternative crop models have different simulation algorithms for dealing with leaf development, light interception, yield formation, crop phenology, etc. (Palosuo et al., 2011). For example, in the CERES-Wheat model, the growth stage depends on thermal time, and ignores the potential stresses of drought and higher wind speeds. Many studies include the impact of water stress on wheat during reproductive stages, which resulted in about 10 % decrease in grain yield, but moderate stress during the early vegetative period had essentially no effect on grain yield (Bauder, 2001). An average grain yield loss of 17–70 % due to water stress has been forecast (Edmeades et al., 1994). Water stress at the vegetative stage causes stomatal closure, loss of leaves, reduced tillering and sheath development, and inhibition of some tillers from producing spikes. At the flowering stage, drought stress affects grain filling, the number of seeds per spike and kernel weight. At the reproductive stage, a decline in transpiration and delayed period of maturation causing reduced number~~,~~ and weight of grains, spikes and yield (Zulkiffal et al., 2021). A strong relationship in many variables determining yield exists with drought tolerance, such as flag leaf persistence, leaf rolling, canopy temperature, and stomatal conductance. The amount, duration, frequency, and timing of rain-related to crop growth stages are primary determinants of the levels of terminal drought stress under rainfed conditions.

Precipitation in the Thunder Bay area is forecast to increase by 10 %, and fewer drought periods will be observed (Bush and Lemmen, 2019). In the future, more importance should be given to establishing new genotypes that are adapted to a wider range of critical temperatures and more temperature extremes during flowering and grain-filling stages of spring wheat development. Extending the early development stages, especially from ear initiation to flowering, may increase the number of grains. This kind of management response is a positive one to predicted climate change. Disease incidence of both fungal and viral pathogens is a growing concern in recent years in northwestern Ontario, and increase in temperature and precipitation could create environmental conditions that will increase disease incidence in Thunder Bay. Examples of diseases of spring wheat are Fusarium head blight, net blotch, and rust and leaf spot disease. Disease management can occur by increasing a focus on disease resistance in breeding goals, scouting fields early for disease, practicing crop rotation, performing conservation tillage, using certified seeds, and using fungicides.

Conclusions

In this study, the changes to expected Sable wheat grain yield due to differences in maximum and minimum temperatures and rainfall under an RCP 2.6 Climate Change Scenario were described for Thunder Bay area farmers. Projected changes to weather showed that area farmers are likely to experience lower grain yields due mostly to changes in maximum daily temperatures. The most critical periods, according to the CROP-SIM CERES model, will be during the jointing and grain-filling stages. Interaction between agronomic techniques and genetic innovation can help in improving resistance to abiotic changes, and farmers can adapt to changes in weather variability by adjusting planting times and optimizing plant densities. They can opt for precision management of nutrients and use fungicides to protect spring wheat.

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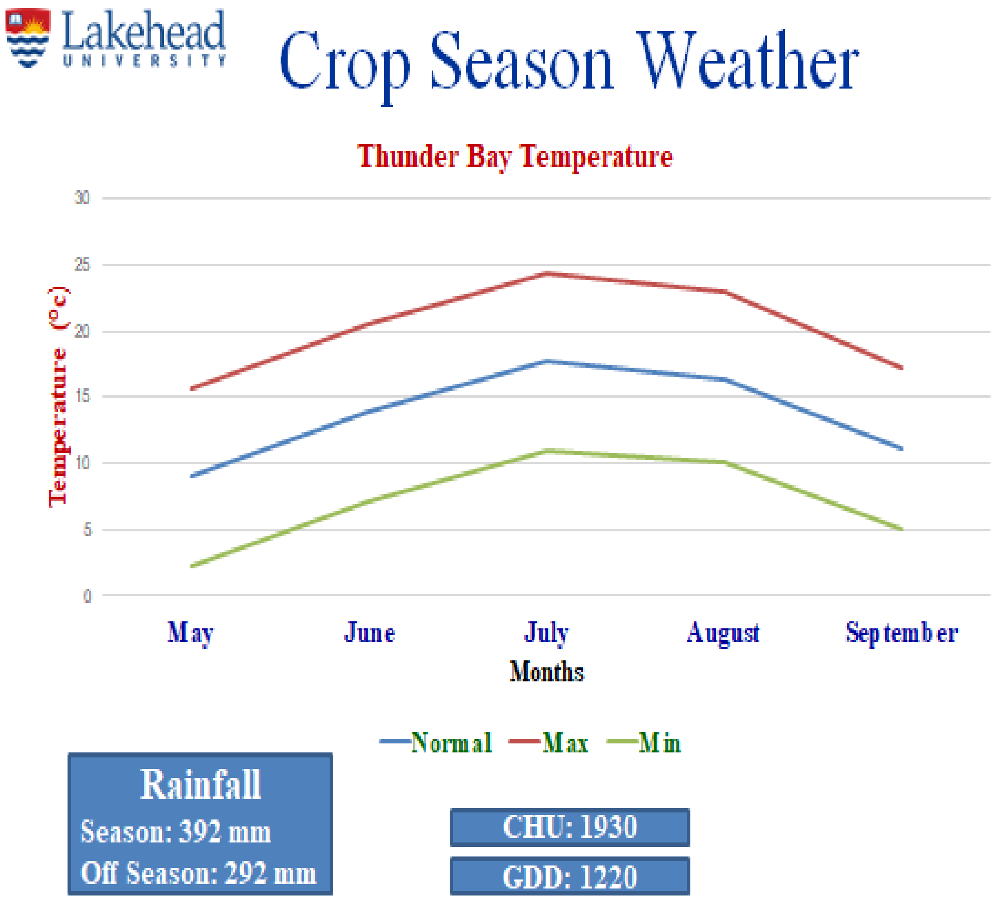
Appendices

1. Thunder Bay weather analysis report from 2003–2018 which examined weather extremes for each growing season (Mhetre and Sahota (LUARS Annual Report 2019). Thunder Bay Weather Analysis (2003–2018) at https://www.lakeheadu.ca/centre/luars/articles.



2. Number of days at or above threshold during the (a) germination, (b) tillering, (c) jointing, (d) grain-filling, and (e) kernel-hardening stages with maximum temperature from Environment and Climate Change Canada (ECCC) data from the Thunder Bay Airport, 2003–2017.

Maximum Temperature

(a) Number of days at or above threshold during the germinating stage.

Years	**25 °C**	**26 °C**	**27 °C**	**28 °C**	**29 °C**	**30 °C**	**31 °C**
2003	1	1	0	0	0	0	0
2004	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	0
2006	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0
2008	2	2	2	2	2	2	1
2009	2	2	2	1	1	0	0
2010	0	0	0	0	0	0	0
2011	3	2	1	0	0	0	0
2012	0	0	0	0	0	0	0
2013	1	1	1	0	0	0	0
2014	0	0	0	0	0	0	0
2015	1	0	0	0	0	0	0
2016	0	0	0	0	0	0	0
2017	1	0	0	0	0	0	0

(b) Number of days at or above threshold during the tillering stage

Years	**25 °C**	**26 °C**	**27 °C**	**28 °C**	**29 °C**	**30 °C**	**31 °C**
2003	2	2	1	1	0	0	0
2004	0	0	0	0	0	0	0
2005	1	0	0	0	0	0	0
2006	1	1	1	1	0	0	0
2007	1	0	0	0	0	0	0
2008	2	1	1	1	1	1	1
2009	2	2	2	0	0	0	0
2010	0	0	0	0	0	0	0
2011	1	1	1	1	1	1	0
2012	0	0	0	0	0	0	0
2013	2	2	2	2	1	1	0
2014	3	3	3	2	1	1	0
2015	4	3	2	1	0	0	0
2016	3	3	2	1	0	0	0
2017	0	0	0	0	0	0	0

(c) Number of days at or above threshold during the jointing stage

Years	**25 °C**	**26 °C**	**27 °C**	**28 °C**	**29 °C**	**30 °C**	**31 °C**
2003	5	2	0	0	0	0	0
2004	1	1	0	0	0	0	0
2005	9	7	6	5	3	3	3
2006	2	2	2	1	0	0	0
2007	3	2	1	0	0	0	0
2008	6	6	4	4	2	2	0
2009	3	0	0	0	0	0	0
2010	5	3	3	1	1	1	0
2011	6	5	2	2	2	0	0
2012	2	2	1	1	0	0	0
2013	1	1	1	0	0	0	0
2014	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0
2016	2	2	2	0	0	0	0
2017	3	2	0	0	0	0	0

(d) Number of days at or above threshold during the grain-filling stage

Years	25 °C	26 °C	27 °C	28 °C	29 °C	30 °C	31 °C
2003	5	2	0	0	0	0	0
2004	2	2	2	1	0	0	0
2005	9	7	6	5	3	3	3
2006	17	14	10	5	2	2	1
2007	8	7	6	2	1	1	0
2008	3	2	1	0	0	0	0
2009	13	12	9	6	3	2	1
2010	8	6	6	4	3	2	1
2011	15	10	7	7	1	0	0
2012	13	8	7	4	2	1	0
2013	9	4	1	1	1	0	0
2014	4	3	1	1	0	0	0
2015	10	9	7	3	2	1	0
2016	13	10	7	3	2	0	0
2017	6	4	3	2	1	1	0

(e) Number of days at or above threshold during the kernel-hardening stage

Years	25 °C	26 °C	27 °C	28 °C	29 °C	30 °C	31 °C
2003	18	14	14	10	5	3	0
2004	16	11	7	5	3	2	0
2005	16	11	8	8	6	4	2
2006	21	19	17	12	4	1	1
2007	16	10	6	2	1	0	0
2008	7	5	5	3	2	2	1
2009	20	15	11	9	5	2	2
2010	26	20	17	13	10	6	0
2011	15	13	9	9	3	0	0
2012	10	7	5	4	3	2	0
2013	10	5	3	2	0	0	0
2014	15	7	3	1	0	0	0
2015	18	14	10	8	6	4	2
2016	21	18	13	11	7	4	1
2017	15	14	10	5	3	1	1

3. Number of days at or above threshold during the (a) germination, (b) tillering, (c) jointing, (d) grain-filling, and (e) kernel-hardening stages with minimum temperature from Environment and Climate Change Canada (ECCC) data from the Thunder Bay Airport, 2003-2017.

Minimum temperature (℃)

(a) Number of days at or below each temperature during the germinating stage

Year	**0 ℃**	**1 ℃**	**2 ℃**	**3 ℃**	**4 ℃**	**5 ℃**	**6 ℃**
2003	1	1	2	2	5	5	5
2004	2	2	3	4	4	4	4
2005	1	2	3	4	5	5	5
2006	1	2	3	4	5	5	5
2007	0	1	1	1	3	3	3
2008	1	4	5	5	5	5	5
2009	0	1	2	4	6	7	7
2010	0	0	0	0	3	7	8
2011	1	2	3	4	5	5	6
2012	2	1	3	3	3	5	6
2013	0	0	1	1	3	6	6
2014	0	1	1	6	6	6	6
2015	0	2	3	4	5	5	5
2016	2	2	2	3	4	5	5
2017	2	2	2	2	2	2	2

(b) Number of days at below each temperature during the tillering stage

Year	**0 ℃**	**1 ℃**	**2 ℃**	**3 ℃**	**4 ℃**	**5 ℃**	**6 ℃**
2003	3	5	7	8	9	11	11
2004	2	4	6	6	7	9	10
2005	1	2	3	7	11	17	24
2006	1	1	2	2	3	4	5
2007	2	4	8	10	10	11	11
2008	1	6	10	10	11	13	14
2009	0	1	2	3	5	6	6
2010	1	1	1	1	1	4	5
2011	1	2	3	5	6	7	9
2012	1	3	5	7	9	10	0
2013	0	0	1	3	7	10	11
2014	0	2	3	5	6	11	13
2015	1	1	2	3	3	5	6
2016	0	0	2	3	5	5	5
2017	1	0	3	7	7	9	0

(c) Number of days at or below each temperature during the jointing stage

Year	**0 ℃**	**1 ℃**	**2 ℃**	**3 ℃**	**4 ℃**	**5 ℃**	**6 ℃**
2003	0	4	6	7	10	13	14
2004	1	2	4	5	6	7	7
2005	0	0	0	0	0	3	4
2006	0	1	3	6	7	8	10
2007	0	1	1	2	3	4	7
2008	0	0	0	0	1	4	7
2009	0	1	1	1	1	1	1
2010	1	1	4	6	6	7	8
2011	0	0	0	0	2	2	4
2012	0	0	0	0	2	3	6
2013	0	0	1	1	2	2	2
2014	0	0	1	4	7	7	7
2015	1	1	1	3	5	5	7
2016	1	1	2	3	4	4	5
2017	0	1	1	1	3	3	4

(d) Number of days at or below each temperature during the grain-filling stage

Year	0 °C	1 °C	2 °C	3 °C	4 °C	5 °C	6 °C
2003	2	3	3	4	6	7	8
2004	0	0	2	2	7	9	11
2005	0	0	0	1	1	2	3
2006	0	0	0	0	0	2	4
2007	0	0	0	0	0	0	5
2008	0	0	0	2	2	7	8
2009	0	0	0	0	1	5	6
2010	0	0	0	0	0	2	5
2011	0	0	0	0	0	0	1
2012	0	0	0	0	1	1	3
2013	0	0	0	0	0	0	3
2014	1	1	1	2	2	4	6
2015	0	0	0	1	1	1	2
2016	0	0	0	0	1	1	1
2017	0	0	0	0	0	1	1

(e) Number of days at or below each temperature during the kernel-hardening stage

Year	0 °C	1 °C	2 °C	3 °C	4 °C	5 °C	6 °C
2003	0	0	0	2	3	4	9
2004	0	0	2	3	6	10	14
2005	0	0	1	2	5	5	9
2006	0	0	1	1	3	3	3
2007	0	0	0	0	0	0	1
2008	0	0	1	1	2	3	7
2009	0	0	0	0	3	5	5
2010	0	0	0	0	1	1	1
2011	0	0	0	0	0	1	2
2012	0	0	0	0	0	0	3
2013	0	0	0	1	1	1	2
2014	0	0	0	1	1	2	2
2015	0	0	0	0	0	0	1
2016	0	0	0	0	0	0	1
2017	0	0	0	0	1	2	3

4. Pearson (*r*) statistics for correlations between the number of days above threshold maximum temperatures during 2003-2017, using Environment Canada data and LUARS grain yields, and simulated weather in an RCP 2.6 Climate Change Scenario and projected grain yields, during the (a) germination, (b) tillering, (c) jointing, (d) grain-filling, and (e) kernel-hardening stages. Simulation of grain yield used the CROP-SIM CERES model. Test statistic is Student's *t* and statistics in boldface are significant at $P < 0.05$.

Threshold maximum temperature (°C)	LUARS grain yields			Projected grain yields		
	r	*t*	*P*	*r*	*t*	*P*
(a) Correlations with days above threshold during the germinating stage						
25	-0.05	-0.18	0.85	0.06	0.24	0.81
26	0.00	0.03	0.97	0.27	1.04	0.31
27	0.04	0.16	0.86			
28	0.14	0.52	0.60			
29	0.14	0.52	0.60			
30	0.03	0.11	0.91			
31	0.03	0.11	0.91			
(b) Correlations with days above threshold during the tillering stage						
25	0.06	0.25	0.80	0.19	0.73	0.47
26	0.13	0.50	0.62	0.14	0.53	0.59
27	0.06	0.24	0.80	0.07	0.27	0.78
28	-0.14	-0.53	0.59	0.05	0.20	0.84
29	-0.13	-0.50	0.62	0.00	0.02	0.98
30	-0.13	-0.50	0.62	-0.07	-0.28	0.78
31				0.01	0.05	0.95
(c) Correlations with days above threshold during the jointing stage						
25	0.03	0.13	0.89	-0.21	-0.78	0.44
26	-0.13	-0.47	0.64	-0.35	-1.38	0.19
27	-0.23	-0.87	0.39	-0.16	-0.59	0.56
28	-0.15	-0.57	0.57	-0.42	-1.67	0.11
29	-0.05	-0.21	0.83	-0.44	-1.78	0.09
30	0.00	-0.02	0.98	-0.34	-1.30	0.21
31	0.00	-0.05	0.95	-0.33	-1.27	0.22
(d) Correlations with days above threshold during the grain-filling stage						
25	**-0.57**	**-2.53**	**0.02**	-0.36	-1.43	0.18
26	-0.43	-1.74	0.10	-0.40	-1.78	0.09
27	-0.40	-1.61	0.12	-0.42	-1.70	0.11
28	-0.32	-1.22	0.24	-0.27	-1.05	0.31
29	-0.34	-1.33	0.20	-0.46	-1.87	0.08
30	-0.28	-1.05	0.31	-0.33	-1.27	0.22
31	-0.06	-0.24	0.81	-0.14	-0.53	0.59
(e) Correlations with days above threshold during the kernel-hardening stage						
25	0.21	0.77	0.45	-0.01	-0.43	0.96
26	0.34	1.33	0.20	0.00	0.01	0.99
27	0.45	1.86	0.08	0.02	0.09	0.92
28	0.45	1.84	0.08	0.03	0.12	0.89
29	**0.82**	**5.18**	**<0.01**	-0.01	-0.04	0.96
30	0.37	1.47	0.16	-0.10	-0.38	0.70
31	-0.04	-0.14	0.88	-0.04	-0.14	0.88

5. Pearson (*r*) statistics for correlations between the number of days below threshold minimum temperatures during 2003-2017, using Environment Canada data and LUARS grain yields, and simulated weather in an RCP 2.6 Climate Change Scenario and projected grain yields, during the (a) germination, (b) tillering, (c) jointing, (d) grain-filling, and (e) kernel-hardening stages. Simulation of grain yield used the CROP-SIM CERES model. Test statistic is Student's *t* and statistics in boldface are significant at $P < 0.05$.

Threshold minimum temperature (°C)	LUARS grain yields			Projected grain yields		
	r	*t*	*P*	*r*	*t*	*P*
(a) Correlations with days below threshold during the germinating stage						
0	0.21	0.78	0.44	-0.14	-0.53	0.60
1	0.15	0.58	0.57	0.28	1.06	0.30
2	0.01	0.07	0.94	0.47	1.92	0.07
3	0.23	0.87	0.39	0.19	0.71	0.48
4	0.30	1.17	0.26	0.36	1.14	0.17
5	0.01	0.04	0.96	0.15	0.57	0.57
6	0.10	0.38	0.79	0.40	1.60	0.13
(b) Correlations with days below threshold during the tillering stage						
0	0.27	1.02	0.32	0.47	1.96	0.07
1	0.30	1.16	0.26	**0.49**	**2.07**	**0.05**
2	0.24	0.92	0.41	0.42	1.67	0.11
3	0.14	0.52	0.60	0.21	0.79	0.44
4	0.07	0.28	0.78	0.09	0.33	0.74
5	0.09	0.35	0.72	0.22	0.82	0.42
6	0.06	0.21	0.83	0.31	1.20	0.24
(c) Correlations with days below threshold during the jointing stage						
0	0.32	1.29	0.24	0.14	0.51	0.61
1	**0.56**	**2.48**	**0.02**	0.12	0.44	0.66
2	0.48	1.97	0.06	-0.02	-0.07	0.93
3	0.34	1.30	0.21	0.24	0.90	0.38
4	0.31	1.21	0.24	**0.54**	**2.34**	**0.03**
5	0.35	1.35	0.19	0.23	0.86	0.40
6	0.14	0.54	0.56	-0.41	-1.63	0.12
(d) Correlations with days below threshold during the grain-filling stage						
0	0.40	1.59	0.13	-0.33	-1.27	0.22
1	0.40	1.57	0.13	0.14	0.52	0.61
2	**0.68**	**3.42**	**<0.01**	0.21	0.78	0.44
3	**0.60**	**2.76**	**0.01**	0.20	0.74	0.46
4	**0.78**	**4.52**	**<0.01**	0.14	0.53	0.60
5	**0.77**	**4.45**	**<0.01**	0.31	1.19	0.25
6	0.49	2.03	0.06	**0.52**	**2.23**	**0.04**
(e) Correlations with days below threshold during the kernel-hardening stage						
0						
1				-0.19	-0.70	0.49
2	0.34	1.33	0.20	0.01	0.04	0.96
3	**0.52**	**2.22**	**0.04**	0.17	0.63	0.53
4	**0.55**	**2.37**	**0.03**	**0.61**	**2.81**	**0.01**
5	**0.70**	**3.56**	**<0.01**	0.40	1.61	0.12
6	**0.65**	**3.09**	**<0.01**	0.19	0.69	0.49