ASSESSING THERMAL INDICES FOR MODELING GRAIN CORN PHENOLOGICAL DEVELOPMENT ON THE PRAIRIES

BY

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A Thesis Submitted to the Faculty of Graduate Studies of
The University of Manitoba
in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

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ABSTRACT

Zhanda, Justice. M.Sc., University of Manitoba, July, 2017.
Assessing Thermal Indices for Modeling Grain Corn Phenological Development on the Prairies
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Knowledge of growing season thermal units is essential for effective selection of corn (*Zea mays* L.) hybrids that can reach maturity within the short growing season on the Canadian Prairies. It is important to have adequate information about occurrence of phenological stages of corn so as to make effective management decision on seeding dates, chemical and fertilizer applications and anticipating harvest date. Therefore, a consistent index would aid with effective selection of corn hybrids for a given area. This study showed that the variation in the accumulation of the general thermal index (GTI) was consistently lower than that for the corn heat unit (CHU) but was not significant. The study also showed no significant differences in thermal heat unit accumulation required to reach physiological maturity by five corn hybrids with CHU ratings ranging from 2200 to 2700. The relative maturity (RM) rating determined by seed industries all showed a close relationship (r=0.75-0.99) with CHU rating. Therefore, the use of either tool would have similar results and thus RM would not be effective for selecting corn hybrids on the Canadian Prairies. There was an inverse relationship between cold night hours accumulated during the growing season and accumulated CHU from planting to maturity but no relationship between cold night hours and accumulated GTI. The GTI was not affected by cold night temperatures since the index calculation continues to accumulate thermal units at temperatures near 0°C. The relationship observed suggests that the current climate change trend for increasingly warmer overnight temperatures will also increase the number of CHU accumulated by corn hybrids from planting to maturity. The GTI showed an indication for accurate use as an alternative tool to CHU for selecting grain corn hybrids on the Canadian Prairies.

ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to my advisor Dr. Paul. R. Bullock for his much needed guidance and support during my entire graduate program. He played a significant role and I will continue to learn how to become a valuable asset to the scientific community through research. My co-advisor, Dr. Francis Zvomuya, has always been helpful with my data analysis as well as reviewing my project work from time to time. I am also thankful to members of my advisory committee: Dr. Don Flaten, Dr. Yvonne Lawley and from behind the scenes, Dr Lana Reid, for their valuable contributions during progress meetings and for taking their time to review my conference presentations. I am indebted to this team of experts who were always available for my progress meetings.

Our field study would not have been possible successfully without the great work performed by various collaborators from our study sites: Curtis Cavers, Craig Linde, Keith Murphy, Ryan Dyck, James Frey, Scott Chalmers and Geoffrey. These collaborators were responsible for all the agronomic work that was done on the phenology plots.

This project was financed by Manitoba Corn Growers Association, Western Grains Research Foundation, Canada and Manitoba Governments through Growing Forward 2 and The University of Manitoba's Faculty of Graduate Students that facilitated the Manitoba Government Scholarship. I am also grateful to the support given by all graduate students and technicians in the Soil Science department with special mention to Mick Runzika, Nicholson Jeke and Michael Cardillo.

Special thanks to my lovely wife Jane and my 2 daughters, Milcah and Peyton for being patient with me while I was doing my studies.

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1. INTRODUCTION

1.1 Significance of corn

Corn (*Zea mays* L.) is one of Canada's important resources for livestock feed, food, distillery and ethanol production. The C4 plant is among the most widely cultivated cereal crops in the world (Singh et al., 2014) and forms the staple food in most countries, including most African states, Mexico and the United States of America. In Canada, it is the third most valuable grain crop, after wheat and barley (Statistics Canada, 2014). Corn requires a warm and long growing season with adequate soil moisture in order to reach its maximum potential. According to Statistics Canada (2014), close to 94% of Canada's grain corn is produced in Ontario and Quebec, which have favorable conditions for corn growth and development, while the Canadian Prairies and other provinces produce the remaining 6%.

Historical data show that the Canadian Prairies experience a short frost-free period and low seasonal heat unit accumulation during the summer months (Bullock et al., 2010), conditions which are unfavorable for successful corn production. However, recent studies have shown positive shifts in seasonal heat units observed in some regions of western Canada (Nadler and Bullock, 2011). Furthermore, climate forecasts also predict a continual rise in temperature and subsequent increase in seasonal accumulation of heat units in the future (Pachauri and Intergovernmental Panel on Climate Change, 2008). As a result of these increased heat units, there is potential to expand grain corn production to previously unsuitable areas of the Canadian Prairies.

Successful production of corn requires selection of hybrids that are suitable for a given environment. Corn producers on the Canadian Prairies need corn hybrids that can mature in the short summer while at the same time producing high yields. Since corn development is mainly driven by temperature, selection of grain corn hybrids by producers is mainly based on temperature dependent indices that can be used to predict corn phenological development. The research reported in this thesis evaluated several thermal based indices as potential tools that could be used by Canadian Prairie grain corn producers to select appropriate corn hybrids for their locations. There is a dearth of information in this area of research as the majority of studies on heat unit evaluation have focused mostly on corn heat unit evaluation in warmer regions of Canada where corn is well adapted. Furthermore, most published research did not pay particular attention to heat accumulation requirements to reach earlier stages of corn development, such as the vegetative stages, under cool weather conditions that prevail on the Canadian Prairies. Therefore, new research is needed to explore alternative and effective tools that could assist corn producers to select grain corn hybrids that can reach maturity within the short growing season and before killing frost occurrence on the Canadian Prairies.

1.2 Influence of temperature on corn growth and development

Phenological stages of corn are controlled by its genetic traits and influenced by external environmental factors, which mainly determine morphological changes and function of plant parts (Slafer et al., 2015). Among the environmental factors that influence phenological processes, temperature is the major factor that affects growth and development of crops, including corn (Hall et al., 2014). Other factors such as availability of water, nutrients, CO_2 and solar radiation may influence phenological development of corn but their impacts are quantitatively negligible (Slafer et al., 2015). The influence of temperature on phenological development of corn is well documented and varies depending on its intensity and the crop's stage of development (Singh et al., 2014). During crop establishment, corn requires warm soil temperatures to help with activation of amylase enzymes, which are critical for successful initiation of the seed germination process. Temperature also affects phenological development of corn by changing the daily rate of metabolic processes (Rymen et al., 2007). Thus, growth and development events such as initiation and expansion of leaves, photosynthesis, stem elongation, initiation of tasseling, silking, grain filling and kernel dry down are largely influenced by temperature (Jame et al., 1999; Aslam et al., 2013). The Canadian Prairies, unlike Ontario and Quebec, frequently experience low temperatures overnight during the growing season (DePauw et al., 2011).In these conditions, corn plants suspend growth and development, then resume normal growth when favorable warm conditions prevail (Riva-Roveda et al., 2016). For corn, moderate temperatures during pollination enable effective transfer of pollen to the silks because high temperature stress during this time results in flower abortion and lower grain yield.

Corn development after physiological maturity, when dry matter accumulation in the kernel ceases, requires adequate heat to help with fast dry down of kernels to harvestable moisture levels (Kwabiah et al., 2003). Prolonged periods of low temperatures between physiological and harvest maturity may result in delayed harvesting as a result of delayed drying of corn kernels. The Canadian Prairies experience early fall frost (Qian et al., 2012); therefore, it would be ideal to have corn mature before that time to cut drying costs that are incurred as a result of use of artificial drying to meet the recommended storage moisture content of 12.5 to 14.5% (Setiawan et al., 2010). Knowledge of growing season temperature patterns for a given site will enable producers to make informed decisions on the choice of suitable corn hybrids for their area. Various temperature-based indices are used to characterize different environments for suitability of growing certain crops.

1.3 Indices used to rank corn hybrids

Thermal indices are temperature-based models used to predict phenological development of crops, including corn. In Canada, the major thermal indices used for modeling phenological development of corn are the growing degree day (GDD) and the corn heat unit (CHU) (Bootsma et al., 2005). The standard GDD model assumes a linear response of corn development from a base of 10°C and the modified GDD incorporates a maximum of 30°C beyond which a plateau is reached (Kumudini et al., 2014). However, previous studies have shown that the rate of phenological development of many plants, including corn, respond to temperature in a nonlinear pattern (Jame et al., 1999). Therefore, there is need to select a representative thermal index to accurately model the rate of plant development.

The CHU, sometimes called the Ontario heat unit system (Brown, 1969), defines corn phenological development using a quadratic function of daily maximum air temperature combined with a linear daily minimum air temperature function throughout the entire life cycle of the crop (vegetative and reproductive phases). Previous research has indicated that CHU accumulation lacks consistency in relation to corn phenological development rate and is unreliable, especially for the reproductive phase, because the thermal duration required by most hybrids to reach physiological maturity differs with the thermal environment (Stewart et al., 1998). Recent studies have attempted to evaluate a fairly new thermal index, the general thermal index (GTI), which uses two different non-linear temperature response functions for the vegetative and reproductive phases of corn development (Kumudini et al., 2014). However, there has been little research on the suitability of the GTI for the Canadian Prairies. The index uses daily mean temperature and requires prior knowledge of the silking date so as to change the response function from the vegetative to the reproductive function (Tojo Soler et al., 2005). In contrast to the CHU and GDD, GTI continues to accumulate heat units at low temperatures near 0°C and, therefore, accounts for useful heat early and late in the growing season (Dwyer et al., 1999a).

Cold night temperatures influence the total heat unit accumulation thereby affecting the rate of corn development. With few hours of cold temperatures during the nights, corn development tends to be fast, whereas more hours of cold temperatures prolong the life cycle of the crop. Previous research indicates that during the early and late development stages, when night temperatures are low, the CHU and GDD indices accumulate few or no heat units as a result of their higher minimum temperature thresholds of 4.4°C and 10°C, respectively, whereas the GTI continues to accumulate at temperatures below these thresholds (Kumudini et al., 2014). Cold night temperatures have been shown to impair chloroplast function, thereby altering translocation of photoassimilates within the corn plant (Rymen et al., 2007). This may result in the death of plant cells, hence reduction in plant growth and development. In another study, Riva-Roveda et al. (2016) showed that corn plants can undergo a standby or dormant mode due to chilling stress when temperatures persist near 4°C for one week but the plants will recover as a result of good tolerance of their photosynthetic machinery when warm conditions resume. This can be regarded as a tolerance mechanism and varies with the genetics of the corn hybrids; however, considering the Prairies experience a short growing season and low seasonal heat unit accumulation (Bootsma et al. 2005), there might not be adequate time for corn to recover and reach physiological maturity. In this study, physiological maturity is the end of the life cycle of grain corn at which no more translocation of assimilates occurs from the plant to the kernels. This stage is marked by the presence of a black or brown layer at the tip of corn kernels. Earlier studies found that at physiological maturity, kernel moisture content is between 31 and 35% depending on hybrid (Kwabiah et al. 2003).

Calendar days are one of the simplest indices that are used to predict crop development because they do not need complex calculations. However, they are not reliable for use to predict phenology events because the rate of growth and development of crops varies daily as a result of weather conditions, particularly temperature (Tojo Soler et al. 2005). Another index used to describe corn hybrids is the relative maturity rating (RM), sometimes referred to as the Minnesota Relative Maturity rating (Dwyer et al. 1999b). The RM value is assigned to a new hybrid by comparing harvest moisture content of kernels to a series of check hybrids (Wilkens et al. 2015).

It has been reported that late maturing corn hybrids will normally have higher kernel moisture content at harvest than early maturing corn hybrids hence a positive correlation exists between RM and kernel moisture content at harvest. Previous studies have shown that selection of corn hybrids using the RM system requires that all hybrids be planted at the same time and harvested at the same time (Dwyer et al. 1999b). Ranking of these hybrids is then done in order of their grain moisture contents at harvest. Lower grain moisture content of a particular corn hybrid relative to another indicates earlier maturity and faster dry down rate while late maturity hybrids normally have higher grain moisture content at harvest (Tollenaar, 2013). Relative maturity rating assigned to a new hybrid, for example, 90 d RM hybrid, does not refer to calendar days but are days relative to check varieties. Therefore, corn hybrids with higher RM rating are full season or late maturity hybrids that normally require a longer growing season than lower RM rated hybrids such as 70 d RM (Wilkens et al. 2015).Grain moisture content at harvest is an important factor when choosing a corn hybrid to grow in a particular area.

1.4 Corn grain yield and yield components

Corn yield components are the plant organs that directly influence the final yield attained from the crop. When selecting corn hybrids for a particular environment, producers are not only concerned about the ability of their hybrids to reach maturity, but also, how much grain yield the hybrids can produce. Therefore, grain yield components such as the number of ears per unit area, kernel rows per ear and kernel weight are fundamental in determining final grain yield (Tsimba et al., 2013). In situations where nutrients and moisture are not limiting, temperature has a significant influence on final grain yield. High temperature stress during the silking stage may result in flower abortion, which will lead to poorly filled kernels and, eventually, fewer kernel rows per ear, which translates to reduced grain yield (Severini et al., 2011). Past research has shown that corn tends to roll its leaves as a mechanism of reducing water loss from the leaves under high temperature. However, if this occurs before or during critical stages, such as silking, pollination and grain filling, it might result in significant yield losses of about 1% for every 4 h of high temperature stress (Sindelar et al., 2010). In order to reach its grain yield potential, selection of early varieties is important because these can fully utilize the short growing season experienced on the Canadian Prairies.

1.5 Application of corn phenology models

Modeling phenological development of corn is an important tool that is used to predict events throughout the life cycle of corn. In corn phenology modeling, weather is the major input to the model (Yang et al., 2004; Kumudini et al., 2014). Automated weather stations, from which agrometeorology data for modeling are obtained, have become increasingly available in Canada and the rest of North America. In agrometeorology, phenology models are tools that can aid in finding solutions to the complexity of weather (Murthy, 2004) and for effective management of crops by producers. Murthy (2004) further indicated that phenology models are useful on-farm for determination of optimum seeding date, effective choice of suitable corn hybrids to grow, assessment of potential risks caused by weather and investment decisions. Reasonably accurate phenological models can also be used for prediction of crop performance (Kumudini et al., 2014) in geographic areas where production of that crop has previously not been successful. If producers have an accurate estimate of the amount of heat required for grain corn to reach certain phenological development stages, they can make informed decisions on the appropriate date of seeding as well as conducting other crop management aspects such as fertilizer and chemical application, projection of harvesting dates and yield estimation (Jame and Cutforth, 1996).

1.6 Overall thesis objectives and hypotheses

Different ecological zones on the Canadian Prairies accumulate different amounts of heat units seasonally; therefore, different corn hybrids that can reach maturity during the short growing season will be needed in each zone. This study evaluates heat unit accumulation required by different corn hybrids to reach specific stages of development across the Canadian Prairies (Chapter 2). Four different thermal indices were evaluated with the objective of establishing the most consistent and accurate index that can be used to estimate the rate of corn development on the Prairies. The expectation was that the ideal index could aid in the choice of corn hybrids that are most suitable for production in a specific location depending on weather conditions that prevail in that area. In addition, this research explored other factors including the relationship between RM and heat unit ratings as well as the effect of low temperature duration (cold nights) on seasonal heat unit accumulation on the Canadian Prairies (Chapter 3 and 4). Chapter 5 provides an overall synthesis of findings from this study. We hypothesized that a more consistent thermal index alternative to CHU does exist and if it can be identified, it could be used for more accurate modeling of phenological development to physiological maturity of different corn hybrids across site-years and to support improved decision-making by grain corn producers on the Canadian Prairies.

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2. PRECISION OF FOUR THERMAL INDICES AND CALENDAR DAYS FOR CORN PHENOLOGICAL MODELING ACROSS THE CANADIAN PRAIRIES

2.1 Abstract

Agroclimatic studies have shown positive trends in growing season heat unit accumulation, increasing the feasibility of corn (*Zea mays*) production on the Canadian Prairies. A reliable measure of heat requirements for corn development is necessary for assessing production risk on the Canadian Prairies. A 15 site-year field study was initiated in 2015 at eight locations, six in Manitoba and two in Alberta to quantify heat unit requirements and to identify a thermal index with a consistent accumulation for corn phenological development among five corn hybrids (2200 to 2700 CHU). The indices assessed included the corn heat unit (CHU), growing degree day (GDD_{10}), modified growing degree day ($mGDD_{10,\ 30}$), general thermal index (GTI) and calendar days (DAP). The experiment was laid out as a randomized complete block design with site-year as the replicate and therefore a random factor, and corn hybrid as a fixed factor. Daily air temperature data were obtained from onsite weather stations. Corn development from emergence to silking was monitored by time-lapse cameras set adjacent to each plot. Physiological maturity (R6) was defined by the presence of a black layer at the base of kernels. There were no significant differences in heat unit accumulation among the five corn hybrids.The five corn hybrids required more CHU than the numerical value of their ratings. At R6, all thermal indices had a coefficient of variation (CV) <10.5%, with GTI having the lowest CV (<5%). The low CV for GTI suggested that it may be indicative of an alternative and more consistent in predicting phenological development of corn. Further evaluation of heat unit requirements to reach R6 for commercial hybrids is required to assist producers in selecting appropriate grain corn hybrids for their locations.

2.2 Introduction

Recent studies have shown positive trends in growing season corn heat unit accumulation in some ecological regions of the Canadian Prairies (Nadler and Bullock, 2011). The observed warming in most locations, complemented by early maturing corn hybrids available through continued crop breeding, provides a potential for expansion of corn production to regions that had limited production of this crop in previous years (Nadler and Bullock, 2011; Qian et al., 2012). Although small increases in seasonal heat unit accumulation and frost free periods of 90 to 120 days on the Prairies (Nadler and Bullock, 2011) are masked by year to year variability, future climate forecasts also predict a continued rise in temperatures and a subsequent increase in seasonal heat unit accumulation (Pachauri and Intergovernmental Panel on Climate Change, 2008; Vincent et al., 2012). Therefore, it may become more feasible to expand corn production to locations that have not consistently produced this crop before on the Canadian Prairies. An increase in corn area means availability of more raw materials for use in the ethanol, feed and food industries.

Considering the projected positive shift in heat unit accumulation, corn producers are willing to take on the challenge to expand or substitute other crops for corn production area on the Canadian Prairies (Bootsma et al., 2005). However, corn producers require a reliable and consistent measure of both growing season heat accumulation and the heat requirements of corn hybrids for effective hybrid selection based on their location. Therefore, it is imperative to establish a consistent thermal index that can be used to model phenological development of grain corn under prevailing Canadian Prairie climatic conditions. Modeling phenological development of grain corn remains an important aspect in accurate prediction of growing season heat requirement to physiological maturity on the Canadian Prairies (Kumudini et al., 2014).

Although phenological development may be modified by other factors such as water and nutrients, thermal indices alone are generally acceptable because development of crops is mainly driven by temperature (Kwabiah et al., 2003).

There are various thermal indices that are used in modeling phenological development of corn in North America. In Canada, the major thermal indices that are used are the corn heat unit (CHU) system, growing degree days (GDD_{10}), modified growing degree days ($mGDD_{10, 30}$) and the general thermal index (GTI) (Kumudini et al., 2014). Almost all corn seed companies rate their hybrids using $mGDD_{10, 30}$ and CHU; no data are available to show corn hybrid maturity ratings based on GTI. Calendar days are among the simplest indices that have been used in corn phenology studies but they only provide an estimate on the total number of days required to reach each developmental stage. Corn rate of development is driven by temperature (Tojo Soler et al., 2005); therefore, calendar days alone may be insufficiently robust to quantify rate of development because of the significant variability in air temperature that is experienced on the Prairies. Temperature-based indices should be a more reliable measure for predicting phenological development of corn on the Canadian Prairies. Furthermore, heat unit risk maps should be a better tool for hybrid selection compared to calendar days. Currently most corn producers rely on government weather stations located at various locations around their production areas in order to get information of seasonal or historic heat units accumulated in their areas.

The GDD is an empirical linear model that was introduced by Reaumur around 1730 to aid in the description and prediction of phenological events of crops (McMaster and Wilhelm, 1997;

Kumudini et al. 2014; Anandhi, 2016). There are two approaches that can be used to calculate GDD for corn. The standard mean GDD (GDD_{10}) uses only mean daily temperature and a base temperature of 10°C below which phenological development of corn is assumed to be zero and which increases linearly with increasing mean daily temperature above 10°C. The modified growing degree day ($mGDD_{10,30}$) model also sets a base temperature of 10°C below which phenological development of corn is assumed to be zero; however, the daily maximum temperature is capped at 30°C above which it reaches a plateau (Qian et al. 2012). Seasonal GDD accumulation for corn using a base temperature of 10°C averages 1000 GDD in warmer ecoregions of the Canadian Prairies (Manitoba Agriculture, 2016).

The Ontario-based CHU system is the main thermal index that is used as a tool for selecting grain corn hybrids in Canada. It was developed in 1969 for use in eastern Canada which produces more than two thirds of grain corn in Canada (Brown, 1969; Statistics Canada, 2014). The system is an empirical nonlinear model based on maximum and minimum daily air temperature (Kumudini et al. 2014; Brinkman et al. 2016). The CHU model assumes that the rate of phenological development of corn increases proportionately in response to minimum daily temperature (usually experienced during the night) above 4.4°C (Kwabiah et al. 2003). The CHU model also assumes that the rate of development of corn increases quadratically with increasing maximum daily temperatures (usually experienced during the day) starting at 10°C, peaking at 30°C and decreasing quadratically above 30°C (Ma et al. 2004).

The GTI, developed more recently than the CHU, is another thermal function developed for USA and Canada for better prediction of phenological development of corn (Stewart et al. 1998). The index is an empirical nonlinear model that is estimated using mean daily air temperature and uses separate response functions for the vegetative and reproductive phases of corn development (Kumudini et al. 2014). The separate response functions between the vegetative and grain filling stages has potential to more accurately simulate thermal time requirements to physiological maturity than using one function for the two phenology phases combined (Tojo Soler et al. 2005). The use of GTI requires prior knowledge of transition date from tasseling to silking at which point its calculation changes from the vegetative to the reproductive function. The GTI assumes that corn development continues to take place as long as air temperatures stay above 0°C, which is a realistic assumption considering that corn continues to mature at very low temperatures late in the growing season as a result of some poorly understood plant processes (Qian et al. 2012). This trait may vary with different phenotypic and genetic characteristics between corn hybrids. In contrast, CHU and GDD models do not accumulate heat units beyond their minimum threshold levels when in fact there is some useful heat that helps corn to develop.

There is currently insufficient published data available to show thermal time duration to specific stages of corn development under the cool conditions frequently experienced on the Canadian Prairies. Previous studies in Canada also focused on the CHU requirements for corn hybrids to reach physiological maturity. In addition, there is currently insufficient published assessment of the GTI for modeling phenological development of corn on the Canadian prairies. Therefore, the objectives of this study were to (1) quantify corn heat unit accumulation required to reach specific phenological development stages of five corn hybrids with different corn heat unit ratings and (2) compare the accuracy of different thermal indices in predicting phenological development of different grain corn hybrids across site-years on the Canadian prairies. It was hypothesized that an alternate thermal index to CHU could provide a more consistent measure of corn hybrid heat unit requirements for development to specific phenology stages under weather conditions that prevail on the Prairies.

2.3 Materials and Methods

2.3.1 Study Sites

The study was set up at eight field locations on the Canadian Prairie provinces of Manitoba and Alberta during the 2015 and 2016 growing seasons (Figure 2.1). The study sites were spread across Manitoba and Alberta provinces to provide a range of weather conditions experienced on the Canadian Prairies. Site selection was limited to Manitoba and Alberta locations with the equipment to plant and harvest experimental corn trials. All study sites were co-located with Agriculture and Agri-food Canada’s (AAFC) prairie corn yield trials. The Manitoba sites were Fort Whyte (49º N, 97º W), Carman (49º 30ˈ 0" N, 98º 0ˈ 0" W), Carberry (49º 52ˈ 0" N, 98º 21ˈ 0" W), Portage la Prairie (49º 58ˈ 0" N, 98º 18ˈ 0" W), Roblin (51º 14ˈ 0" N, 101º 21ˈ 0" W) and Melita (49º 16ˈ 0" N, 100º 59ˈ 0" W) while the Alberta sites were Lethbridge (49º 42ˈ 0" N, 112º 50ˈ 0" W) and Vauxhall (50º 4ˈ 0" N, 112º 6ˈ 0" W). In 2015, plots at Melita site were completely destroyed by wild geese and was not considered for analysis. Corn at the Manitoba sites was grown under dryland conditions whereas the Alberta sites were grown under supplemental irrigation to prevent moisture stress. Soil texture at the sites ranged from sandy-loam to clay loam (Appendix I). Application of fertilizer at all sites was based on soil test results and crop nutrient requirements to meet target yields. The plots were 6 rows wide, with each row 8 m long x 0.76 m row spacing. Corn was planted by precision planters except at Fort Whyte. Seeding dates varied among locations in 2015 and 2016, and were slightly earlier in 2016 (Table 2.1). Plant density was 75 000 plants ha^{-1} at all sites.

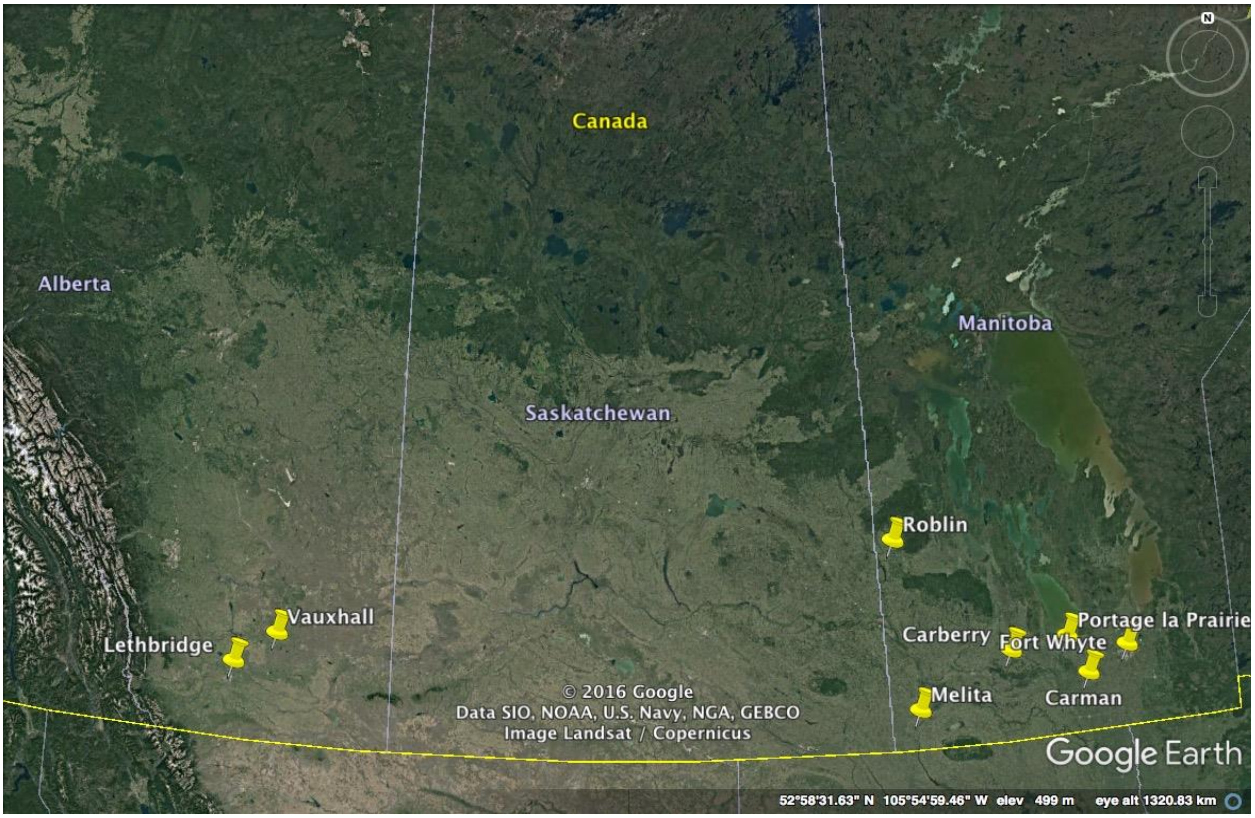

Figure 2.1 The 2015 and 2016 corn phenology study sites across the Canadian prairies.

Table 2.1 Corn seeding dates for the study sites in 2015 and 2016.

	Seeding dates	
Site	**2015**	**2016**
Carman	May 22	May 18
Carberry	May 25	May 18
Fortwhyte	May 7	May 6
Portage la Prairie	May 22	May 17
Roblin	May 26	May 25
Melita[z]	-	May 20
Lethbridge	May 6	May 3
Vauxhall	May 6	May 3

[z] Plots at Melita were completely destroyed by wild geese in 2015.

2.2.2 Corn Hybrids

In 2015, three corn hybrids, CM105xCL30, C0450xCL30 and C0450xC0442, which had different maturity ratings (Table 2.2), were evaluated at the seven locations described above. The hybrids were obtained from AAFC in Ottawa. In 2016, two additional hybrids, P7958AM and PrideA4408G2 were added to the evaluation to provide a comparison of low heat unit hybrids with the AAFC hybrids initially evaluated in 2015.

Table 2.2 Physiological maturity CHU ratings and sources of corn hybrids.

Hybrid	**Source**	**R6 CHU rating**[z]
P7958AM	DuPont-Pioneer	2275
CM105xCL30	AAFC	2550
C0450xCL30	AAFC	2600
C0450xC0442	AAFC	2700
PrideA4408G2	Pride seeds	2200

[z] R6 is the physiological maturity stage.

2.3.3 Experimental Design and Plot Layout

The study was laid out as a randomized complete block (RCBD) design with three treatments (corn hybrids) and seven blocks (replicates) in 2015, and five hybrids and eight blocks (replicates) in 2016. The design used in this study was not a traditional experimental design and instead of at least three replications at each location, site-years were the replicates and therefore random factors. Various blocking factors considered included differences in growing season heat units, soil texture, rainfall and orientation of the plots. Plot lay out was the same at each site except for Carman, Lethbridge and Vauxhall but this did not influence the results due to similar slopes at all the sites (Figure 2.2). For each hybrid at each site, a time-lapse camera was installed soon after seeding alongside each plot 1 m from the border row after seeding. Each camera was set to take pictures from the first two rows of each plot so as to enable accurate staging of corn plants. This was necessary because visibility of leaves would be difficult if the whole plot was captured as a result of the overlapping canopy of corn plants. The edge effect in this study was addressed by taking samples from the middle section of each plot. Camera height was adjusted as needed to keep the corn plants in the field of view during the season. The time-lapse cameras were set to photograph the centre section of each plot every 3 hours from 6:00 a.m. to 6:00 p.m. every day until physiological maturity.

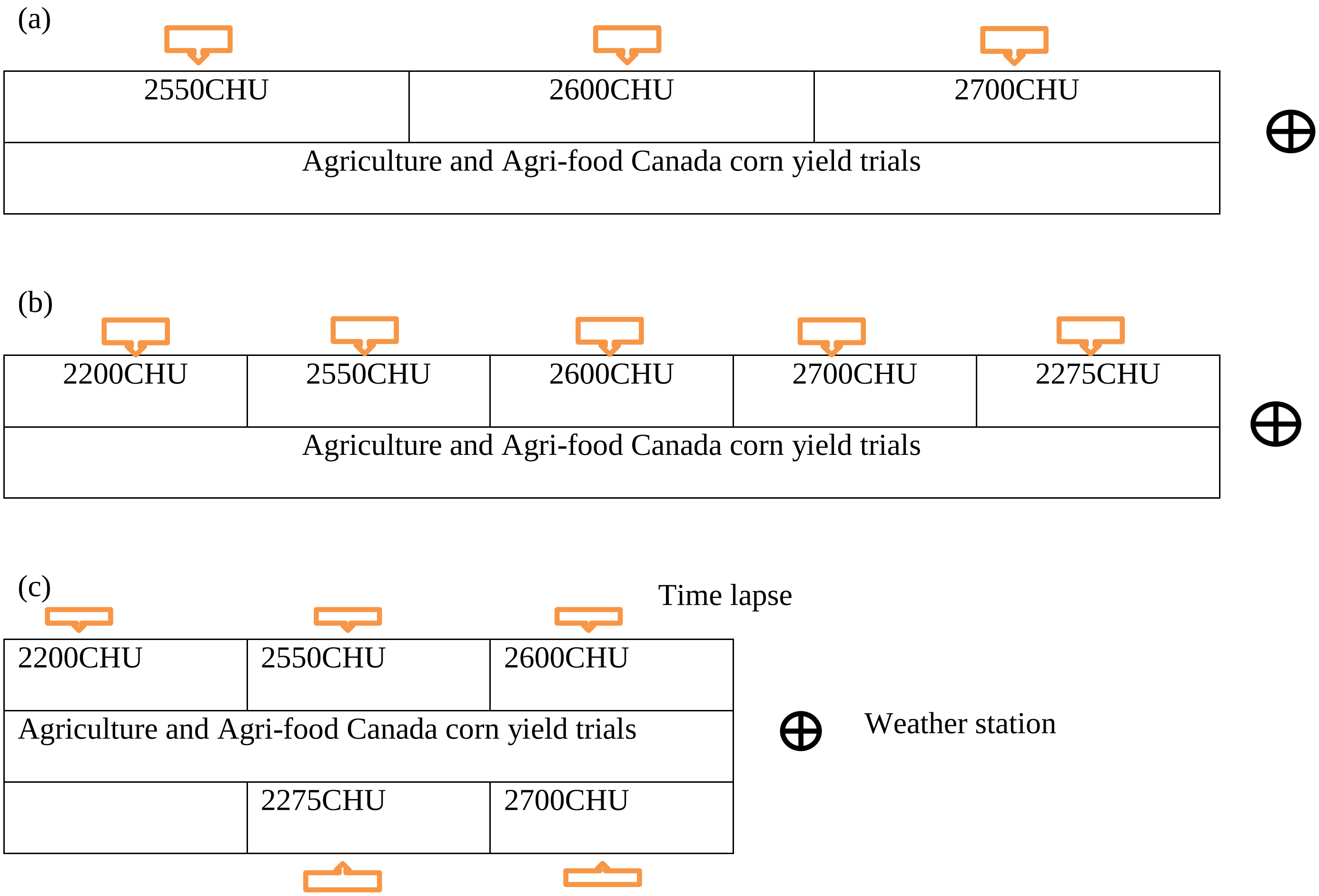

Figure 2.2 Plot layout with time lapse cameras and weather stations in 2015 (a), 2016 Manitoba sites (b) and 2016 Alberta sites and Carman (c).

2.3.4 Corn Phenology and Staging

Five corn plants in view of the cameras were randomly selected and flagged in the field to track their phenological development from emergence to silking. The dates when the majority of corn plants (3 of 5) in view of the camera reached the emergence (VE), two leaf collar (V2), four leaf collar (V4), six leaf collar (V6), tassel (VT), and silk (R1) stages were recorded from the camera image. Indexing of phenological development of corn was done with the use of the Bayer, BASF, Ciba-Geigy and Hoechst (BBCH) leaf tip staging scale from the photos. The scale uses decimal codes which are grouped into primary and secondary development stages based on the Zadoks scale for cereals. The observations using this scale were converted to the collar method which is commonly used by corn breeders and producers in North America (Nielsen et al. 2002). This was necessary because it was not possible to observe leaf collars from the photos. Corn development post-silking was assessed by randomly selecting five cobs from each treatment in the field and assigning a stage on weekly basis. The post-silking development stage was defined when three or more cobs out of five fell in the same stage. Physiological maturity (R6) was defined when a black/brown dot was visible at the base of the majority of kernels sampled from five cobs. Kernel moisture content was measured weekly using a modified non-destructive MT808 moisture meter (www.electrophysics.on.ca) starting one week after silking and continuing until the black layer formation.

2.3.5 Agrometeorology Data

An automated weather station, Watchdog 2000 series model 2900ET (Spectrum Technologies Incorporation), was installed at each site to record site specific weather data. The data recorded at hourly intervals included; air temperature, soil temperature at the 5-cm depth, dew point temperature, wind speed and direction, rainfall and solar radiation. All the stations were initially deployed adjacent to each other at the University of Manitoba for several days for calibration. The data from the weather stations were checked to ensure that all the sensors had similar readings (data not shown). The weather data from each site were downloaded to a data shuttle every 30 days before configuration with Specware 9 Pro software (Spectrum Technologies Incorporation). Daily maximum and minimum air temperatures were used to estimate the accumulated CHU (Eq. 1) and $\mathrm{mGDD}_{10,\ 30}$ (Eq. 2) while mean daily temperature was used to calculate GDD_{10} (Eq. 3) and GTI (Eq. 4).

Daily CHU = $(CHU_{min} + CHU_{max})/2$ [1]

(i) $CHU_{min} = 1.8(T_{min}-4.4°C)$, when $T_{min} < 4.4°C$ then $T_{min}=4.4°C$

(ii) $CHU_{max}= 3.33(T_{max}-10°C) - 0.084(T_{max}-10°C)^2$, if $T_{max} < 10°C$ then $T_{max} = 10°C$

$mGDD_{10, 30} = (T_{max}+ T_{min})/2-[T_{base}]$, if T_{max} is $> 30°C$ then $T_{max}=30°C$, [2]

if $T_{min}<T_{base}$ then $T_{min}=T_{base}$

$GDD_{10} = T_{mean}-T_{base}$, if $T_{mean}<T_{base}$ then $T_{mean}=T_{base}=10°C$ [3]

GTI (i) $GTI_{veg} = 0.043177 (T_{mean})^2 - 0.000894 (T_{mean})^3$ [4]

(ii) $GTI_{rep} = 5.3581 + 0.011178 (T_{mean})^2$

where CHU_{min} is the CHU based on minimum temperature, CHU_{max} is the CHU based on maximum temperature, T_{min} is the daily minimum temperature, T_{max} is the maximum temperature, T_{mean} is the mean temperature, T_{base} is 10°C (base temperature for corn development), GTI_{veg} is the daily GTI during the vegetative stage and GTI_{rep} is the daily GTI from the reproductive phase until physiological maturity.

2.3.6 Statistical Analysis

Analysis of variance (ANOVA) of heat unit accumulation data was performed with PROC GLIMMIX in SAS 9.3 (SAS Institute Incorporation, 2011) to test for effects on grain yield and heat accumulation units required to reach selected crop development stages. The AAFC hybrids were initially compared for the combined 2015 and 2016 growing seasons and later compared together with two commercial hybrids in 2016 alone. The corn hybrids were fixed factors while site-years were modeled as random factors. Differences between corn hybrids were deemed significant at $\alpha = 0.05$ using Tukey's adjustment for multiple comparisons. Thermal time required to reach each phenological development stage was analyzed as a gamma distribution. Test for homogeneity of coefficients of variation (Zar, 1999) was performed for heat unit accumulation required to reach each phenological stage to determine consistency of thermal indices. The most reliable index was considered to be the one with the lowest coefficient of variation across sites and all stages of development.

2.4 Results

2.4.1 Growing Season Weather

Mean daily soil temperature at the 5-cm depth 7 d after planting was lowest at the Portage la Prairie (4.4°C) and Carberry (4°C) locations in 2015 (Figure 2.3). On the same DAP, the soil at the Lethbridge site was 6.3°C warmer than at the Carberry location. During the same DAP, in 2016, mean soil temperature at the Fort Whyte location was 1°C lower than that at the Carberry site (Figure 2.4). All locations recorded soil temperatures of more than 10°C 15 d after planting in both years.

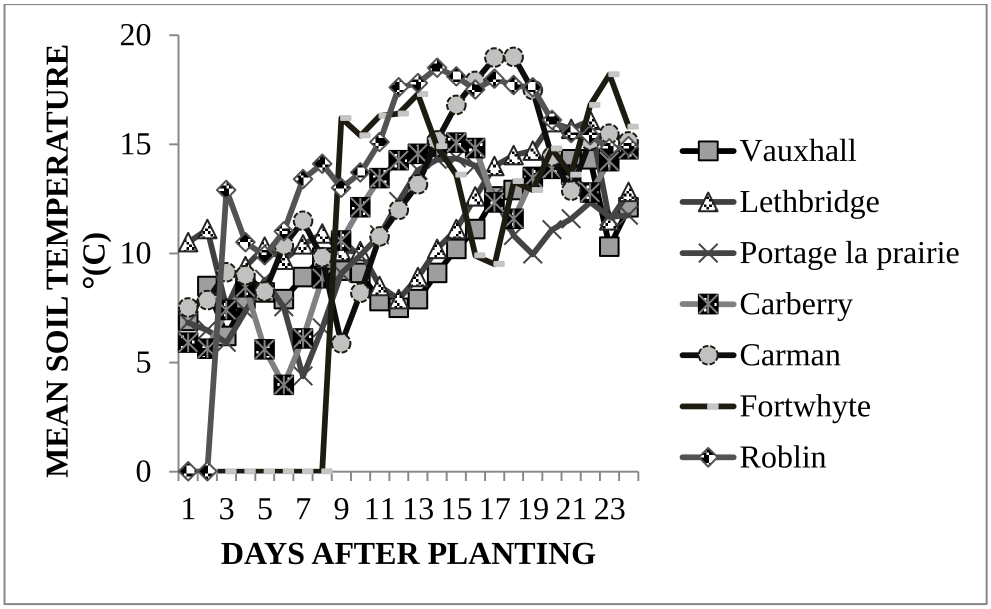

Figure 2.3 Mean daily soil temperature at the 5-cm depth at seven Prairie locations from 1 to 24 DAP in 2015.

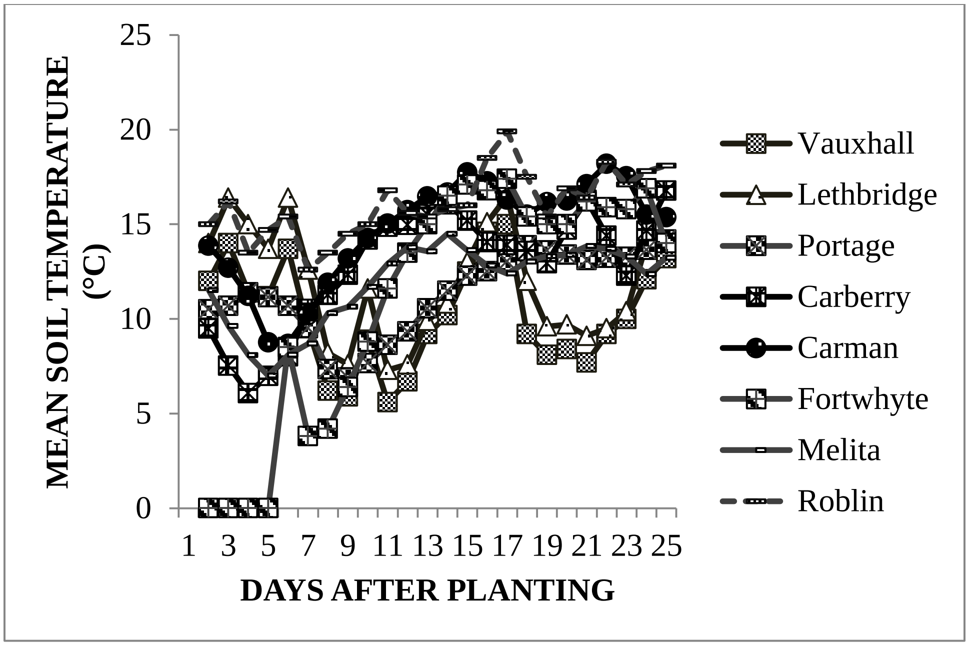

Figure 2.4 Daily mean soil temperature at the 5-cm depth at eight Prairie locations from 1 to 25 DAP in 2016.

The highest monthly mean maximum air temperatures occurred in August at all the locations in 2015. Carman, Carberry, Vauxhall and Lethbridge all recorded maximum temperatures above 35°C on at least one day in that month. Freezing temperatures (< 0°C) were recorded at most of the sites during the first week of seeding in May and towards the end of the growing season in late September. The highest mean monthly temperatures were recorded in either July or August at each location and ranged from 18-20°C.

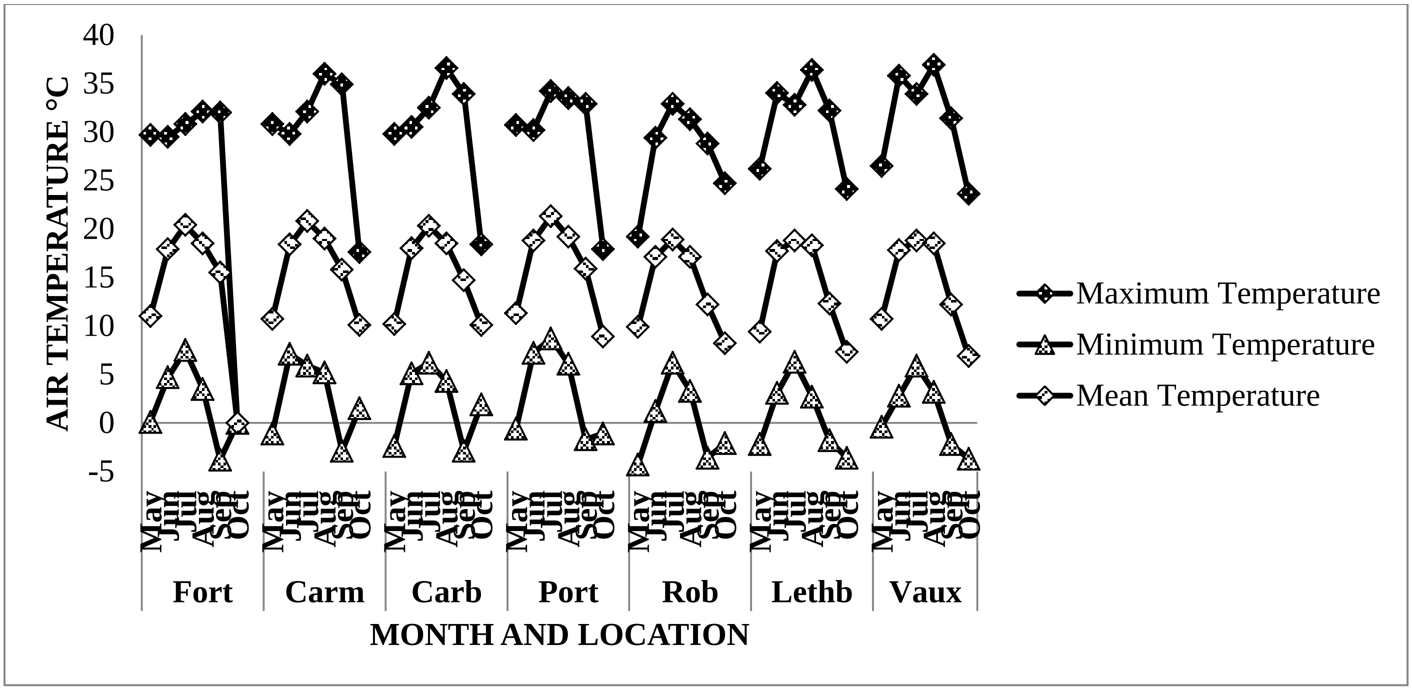

Figure 2.5 Monthly maximum, minimum and mean air temperature recorded at Fort Whyte (Fort), Carman (Carm), Carberry (Carb), Portage la Prairie (Port), Roblin (Rob), Lethbridge (Lethb) and Vauxhall (Vaux) from May to October 2015.

Air temperature data in 2016 (Figure 2.6) showed similar trends as observed in 2015. However, highest temperature occurrence at the sites varied from June to August and the maximum temperatures were about 1°C lower than in 2015. The highest mean monthly temperature in 2016 (19.9°C) was recorded at the Melita location in July. The lowest mean monthly minimum temperature (-10.6°C) was recorded at Lethbridge in September.

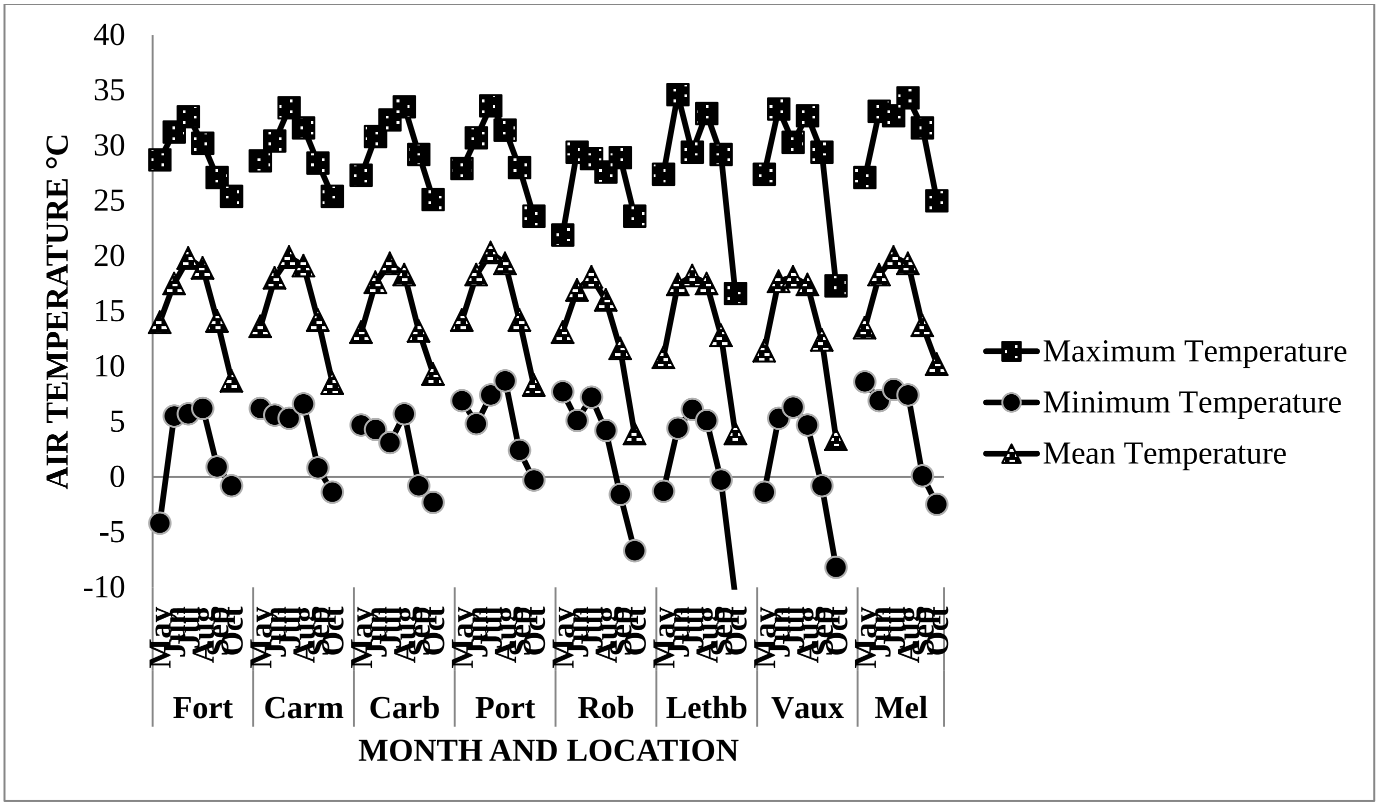

Figure 2.6 Monthly maximum, minimum and mean air temperature recorded at Fortwhyte (Fort), Carman (Carm), Carberry (Carb), Portage la Prairie (Port), Roblin (Rob), Lethbridge (Lethb), Vauxhall (Vaux) and Melita (Mel) from May to October 2016.

Figure 2.7 presents precipitation and irrigation data recorded at the seven study locations in 2015. Lethbridge and Vauxhall locations received low rainfall compared to the other locations with highest precipitation occurring in July (75.1 mm) and June (62.5 mm), respectively. These locations received supplemental irrigation in May, June and July. The largest amount of irrigation (101.6 mm) was applied in July at each location. Precipitation records also show that, at all locations, the largest amount of rainfall was recorded in July. Portage la Prairie received 165.2 mm in that month. During the month of May, the Carman site received the largest amount of rainfall (98.8 mm) and Vauxhall received only 11.7 mm.

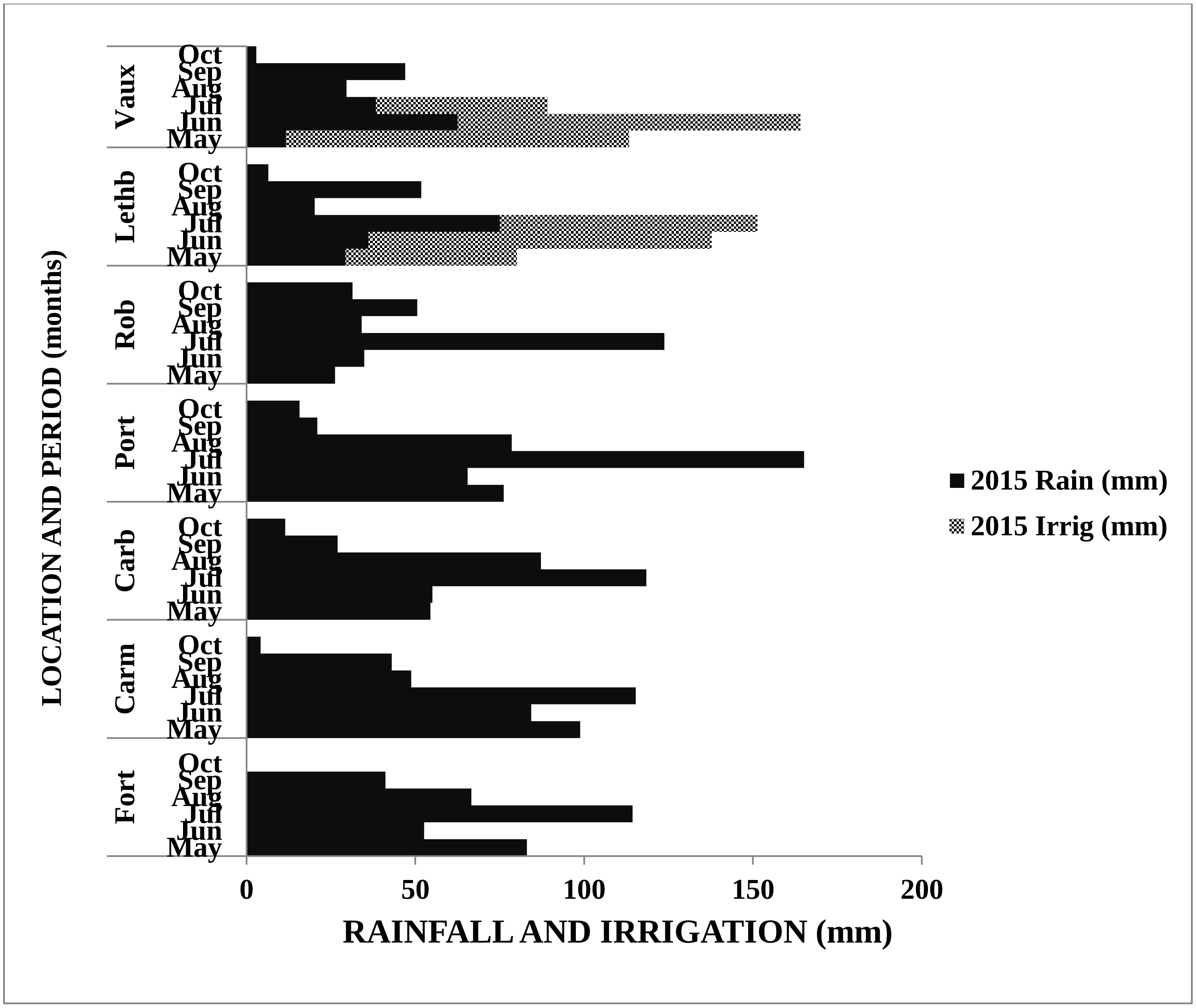

Figure 2.7 Rainfall and irrigation amounts recorded at Fort Whyte (Fort), Carman (Carm), Carberry (Carb), Portage la Prairie (Port), Roblin (Rob), Lethbridge (Lethb) and Vauxhall (Vaux) from May to October 2015.

Just like in 2015, Lethbridge and Vauxhall locations received supplemental irrigation for three months during the 2016 growing season (Figure 2.8). A total of 228.6 mm of irrigation was equally distributed among the three months at Vauxhall, while Lethbridge received 25.4, 127 and 76.2 mm in May, June and July, respectively. All the other locations did not require supplemental irrigation as rainfall was sufficient and evenly distributed throughout the growing season. During the month of May, the Carman site received 52.6 mm more rainfall than the Roblin site, which received 55.6 mm during that month. During the month of August, the Melita site was the only one that received less than 25 mm of rainfall; all the other sites received more than 38 mm of rainfall during the same month.

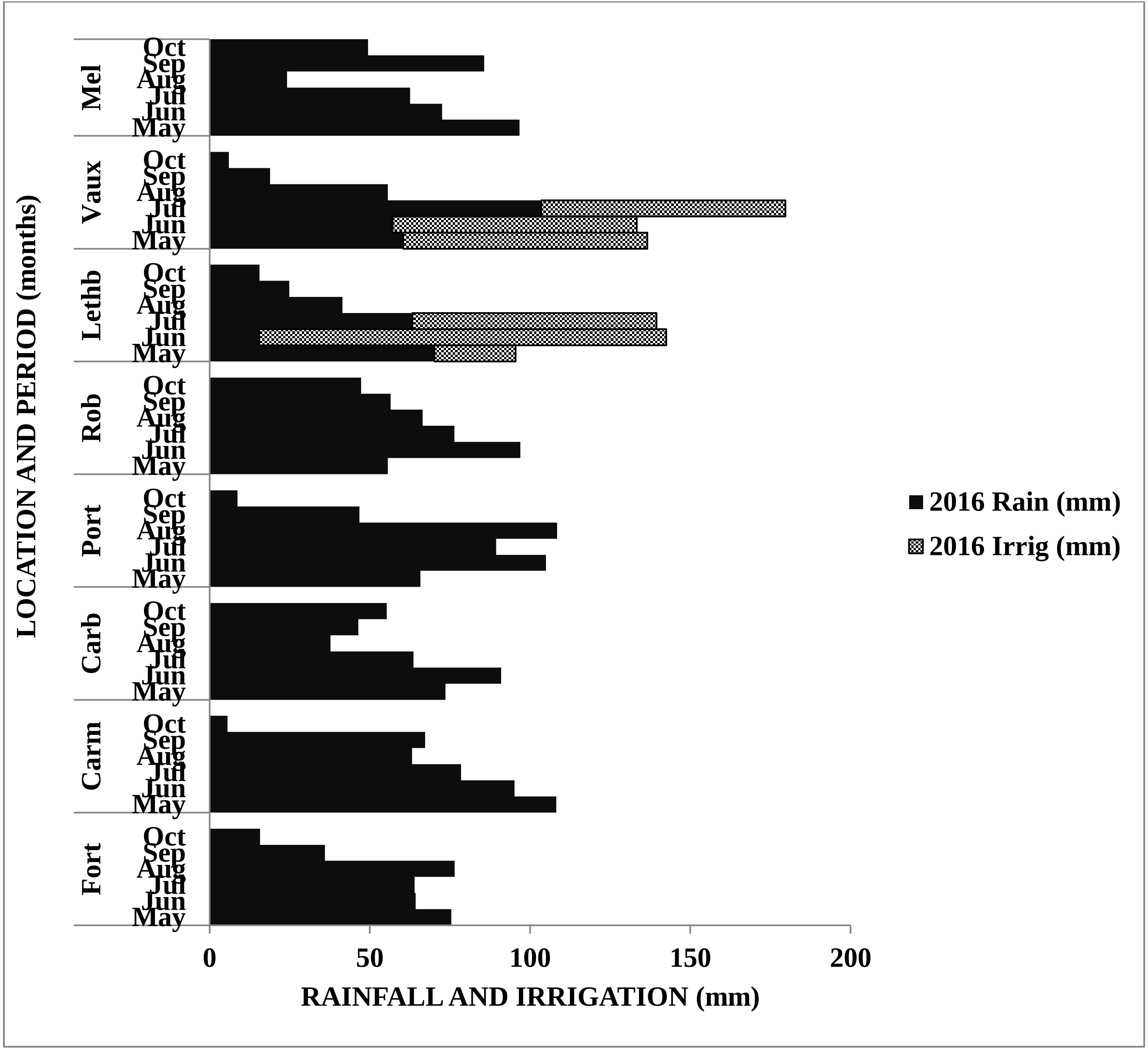

Figure 2.8 Rainfall and irrigation amounts recorded at Fort Whyte (Fort), Carman (Carm), Carberry (Carb), Portage la Prairie (Port), Roblin (Rob), Lethbridge (Lethb), Vauxhall (Vaux) and Melita (Mel) from May to October 2016.

In both 2015 and 2016, the Lethbridge location had more frost free days while the Roblin location had the fewest frost free days (less than 136 d) (Table 2.3). The last dates of spring frost varied among locations in 2015 but they were similar for most locations in 2016 except for the Roblin and the Melita sites, which experienced their last spring frost at the end of April.

Table 2.3 Dates of last spring frost, first fall frost and frost-free days for study site locations in 2015 and 2016.

Site	**2015** **Last spring frost date**	**Fall frost date**	**Frost free days[z]**	**2016** **Last spring frost date**	**Fall frost date**	**Frost Free days**
Carman	May 12	September 29	130	May 14	October 12	148
Carberry	May 19	September 29	127	May 14	October 8	143
Portage	April 25	October 15	146	May 14	October 16	148
Fortwhyte	May 19	September 29	145	May 14	October 16	157
Lethbridge	May 18	October 5	152	May 11	October 10	160
Vauxhall	May 12	September 28	145	May 11	October 6	156
Melita	-	-	-	April 30	October 7	140
Roblin	May 19	September 29	125	April 26	October 8	136

[z] Frost free days at each location were calculated from date of seeding to first killing frost in fall in order to characterize growing season length.

There were variations in heat units accumulated between the Alberta and Manitoba sites (Table 2.4 and 2.5). In both years, the Roblin site accumulated fewer heat units than the other sites. The Portage la Prairie site accumulated more heat units from seeding to first killing frost than all the other sites in 2015 while the Fort Whyte site accumulated more than the other sites in 2016, although there was not great variation from the Portage la Prairie. Characterization of all the locations in the two growing seasons showed that in both years, the mean CHU accumulated from the same starting and ending dates ranged from 2288 to 2750, with Roblin, Vauxhall and Lethbridge accumulating low CHU in both years (Table 2.5). There was not much variation (mean CV 7%, n = 8) in CHU accumulated from the latest seeding date to the earliest physiological maturity date among the sites.

Table 2.4 Heat units accumulated at each study site from seeding date until first killing frost in 2015 and 2016.

	Heat units accumulated in 2015				**Heat units accumulated in 2016**			
Site	**CHU**	**GTI**	**$mGDD_{10,30}$**	**GDD_{10}**	**CHU**	**GTI**	**$mGDD_{10,30}$**	**GDD_{10}**
Carman	2734	1205	1155	1101	2950	1294	1146	1085
Carberry	2575	1142	1073	998	2738	1213	1045	979
Portage	2913	1287	1199	1148	3011	1306	1160	1109
Fortwhyte	2792	1226	1139	1075	3023	1324	1168	1090
Lethbridge	2548	1185	1072	905	2643	1208	1025	881
Vauxhall	2483	1152	1044	908	2610	1192	1030	876
Roblin	2285	1035	890	805	2347	1065	842	734
Melita[z]	-	-	-	-	2823	1224	1112	1054

[z] No data was available in 2015 as a result of destruction of the plots by wild geese.

Table 2.5 Range of CHU accumulation across sites from 26 May to 30 September in 2015 and 2016.

	Seasonal corn heat unit accumulation[z]		
Site	**2015**	**2016**	**Mean**
Carman	2666	2682	2674
Carberry	2571	2501	2536
Portage la Prairie	2764	2735	2750
Fort Whyte	2613	2654	2634
Lethbridge	2335	2378	2357
Vauxhall	2325	2344	2335
Roblin	2289	2288	2289
Melita	.	2629	2629
Mean	**2509**	**2526**	**2525**
Range	**2289-2764**	**2288-2735**	**2289-2750**
SD	**190**	**172**	**176**
CV (%)	**8**	**7**	**7**

[z] The same starting and end dates of CHU accumulation was used to facilitate comparisons between sites, regardless of planting dates and dates of killing frost.

2.4.2 Calendar days and heat unit accumulation to different phenological development stages of three AAFC corn hybrids in 2015

The number of days required to reach phenological development stages VE to V4 did not differ significantly among the three corn hybrids averaged across 15 site-years (Figure 2.9). Although there were notable differences between hybrids from V6 to R6, these were not statistically significant at $\alpha = 0.05$. The mean total number of days required from seeding to physiological maturity was 135±5.71 SEM, 139±5.98 SEM and 148±6.36 SEM for CM105xCL30, CM450xCL30 and C0450xC0442 respectively.

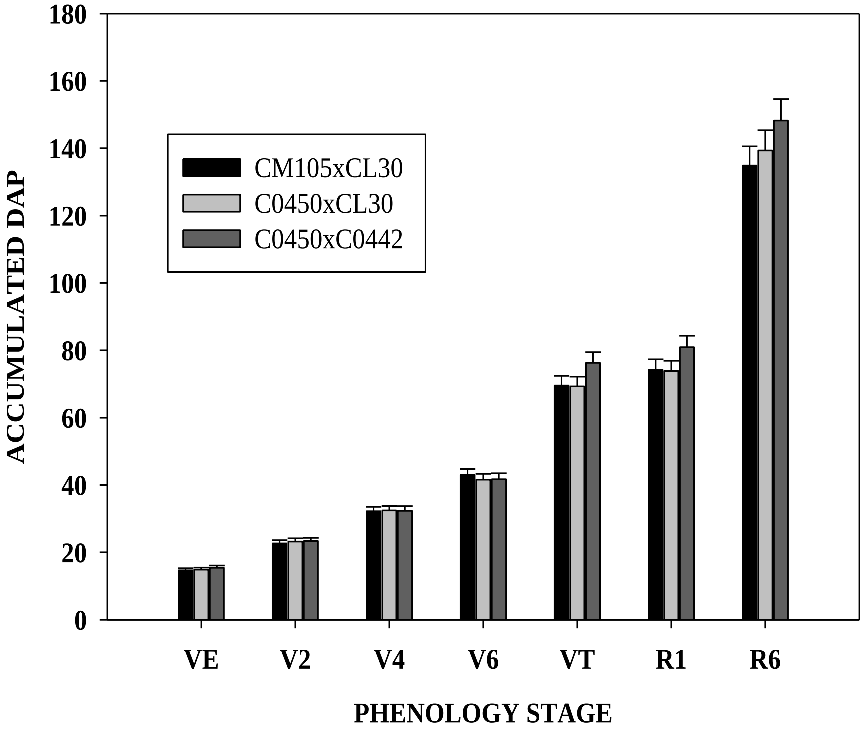

Figure 2.9 Mean cumulative days after planting (DAP) for three corn hybrids across 15 site-years. Bars represent standard error of the mean at the 95% confidence interval.

The four thermal indices presented in Figure 2.10 show no statistically significant differences among the three corn hybrids in heat unit accumulation required to reach different phenological stages of development. Although not significantly different, C0450xC0442 hybrid required numerically more heat units to reach the VT, R1 and R6 phenology stages than CM105xCL30 and CM0450xCL30. There was a high variation (CV>18%) for all indices at the VE and V2 developmental stages (Table 2.6). Regardless of the hybrid assessed, the GTI showed the lowest variation (CV<3.3%) at R6 but the variation was not significantly different (p>0.24) from the other indices tested (CV 4.4% to 10.4%), especially at physiological maturity. In all treatments, GDD_{10} was highly variable at all phenological development stages as compared to the other indices.

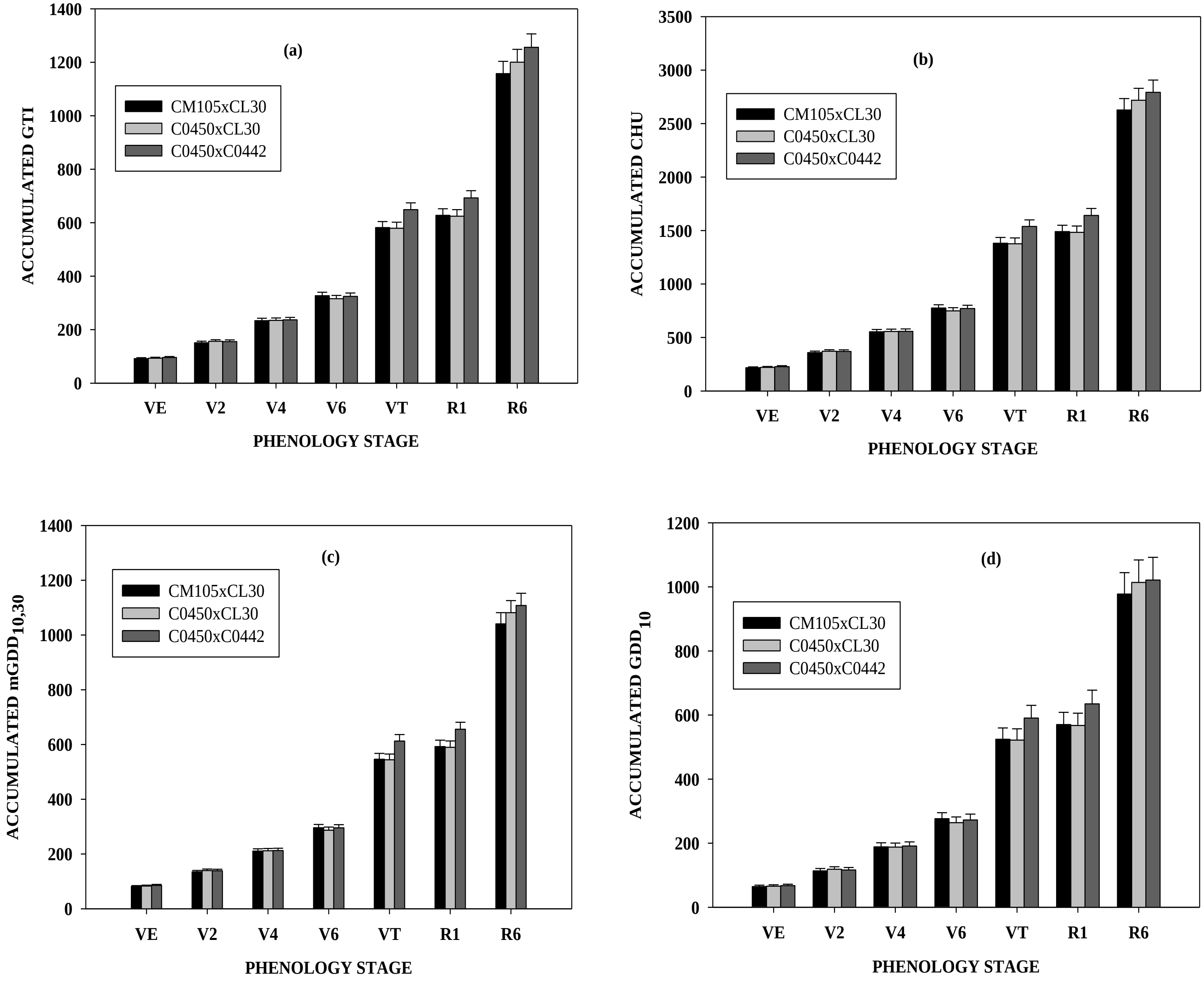

Figure 2.10 Mean cumulative general thermal index (a), corn heat units (b), modified growing degree days (c) and growing degree days (d) for three AAFC corn hybrids over 15 site-years. Bars represent standard error of the mean at the 95% confidence interval.

Table 2.6 Coefficient of variation of thermal indices and days after planting for three AAFC corn hybrids at different phenological development stages across 15 site-years ($P > 0.05$).

Hybrid	Index[z]	CV (%) at different phenological development stages						
		VE	V2	V4	V6	VT	R1	R6
CM105xCL30	CHU	19.2	17.2	10.4	8.4	5.0	4.9	6.1
	GTI	19.3	16.4	9.6	7.6	4.4	4.1	3.3
	GDD_{10}	32.5	27.8	16.1	14.1	7.5	8.0	10.4
	$mGDD_{10,30}$	18.7	16.8	10.1	8.2	4.8	5.3	8.8
	DAP	23.0	19.5	16.0	11.8	10.2	9.1	5.4
C0450xCL30	CHU	19.4	18.7	11.2	9.0	6.7	5.8	5.1
	GTI	19.2	17.8	9.9	7.8	6.2	4.9	3.3
	GDD_{10}	32.6	29.2	17.3	14.4	9.5	8.9	8.8
	$mGDD_{10,30}$	18.6	18.4	10.4	9.0	6.9	6.1	4.7
	DAP	22.1	19.3	14.8	12.0	10.2	8.5	6.6
C0450xC0442	CHU	16.6	17.4	9.9	9.6	3.8	3.9	5.0
	GTI	16.2	16.7	8.3	8.5	2.8	3.0	2.2
	GDD_{10}	30.4	30.4	15.7	13.8	6.1	6.5	9.4
	$mGDD_{10,30}$	16.0	16.7	9.2	9.0	3.1	3.8	4.4
	DAP	22.2	17.7	14.2	13.8	9.6	9.5	5.2

[z] CHU (corn heat units), GTI (general thermal index), GDD_{10} (standard growing degree days), $mGDD_{10, 30}$ (modified growing degree days), DAP (days after planting).

2.4.3 Calendar days and heat unit accumulation to different phenological development stages of five corn hybrids across eight sites in 2016

Five corn hybrids were compared with respect to the number calendar days and heat unit accumulation required to reach different phenological development stages in 2016. Seven of the eight locations were analyzed from VE to R6 while the Roblin location was analyzed from VE to R1 due to frost. There were no statistically significant differences in the number of days (Figure 2.11) and heat unit accumulation (Figure 2.12) required to reach different phenological development stages among the five corn hybrids.

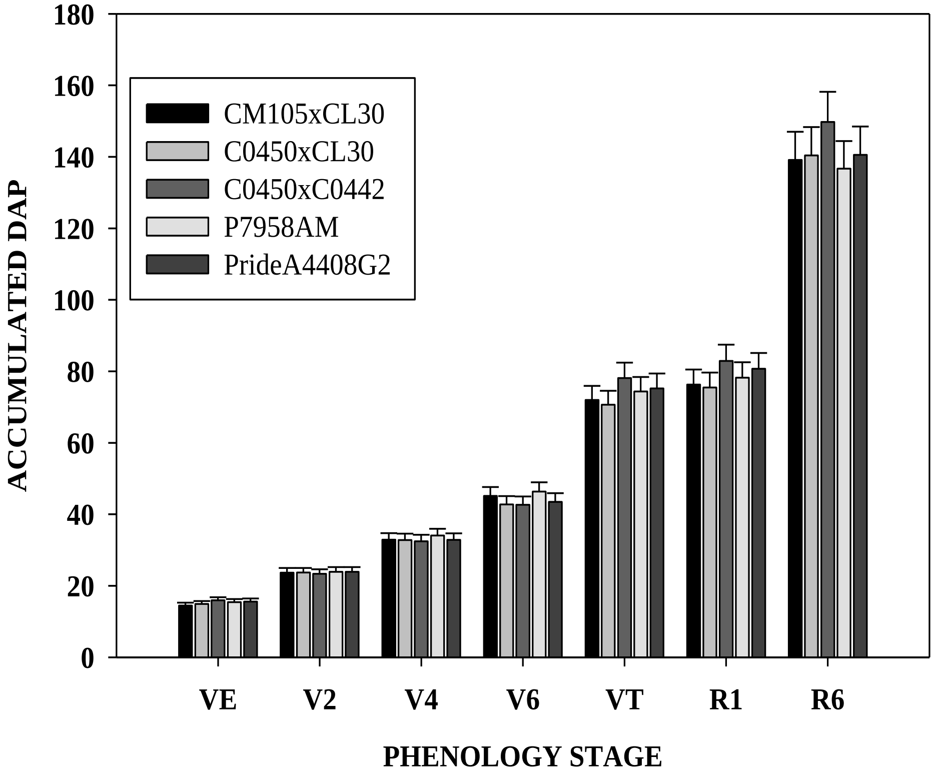

Figure 2.11 Accumulated days after planting for five corn hybrids across 8 (VE to R1) and 7 (R6) study sites in 2016. Bars represent standard error of the mean at the 95% confidence interval.

Five corn hybrids were compared to quantify heat unit accumulation required to reach different phenological development stages. All the eight locations were analyzed from VE to R1 while only seven locations were analyzed at R6 as a result of frost before maturity at one of the locations. Hybrid C0450xC0442 accumulated numerically more heat units to reach VT, R1 and R6 than the other four hybrids. However, there were no statistically significant differences (Figure 2.12) in heat unit accumulation required to reach each stage of development by the five corn hybrids.

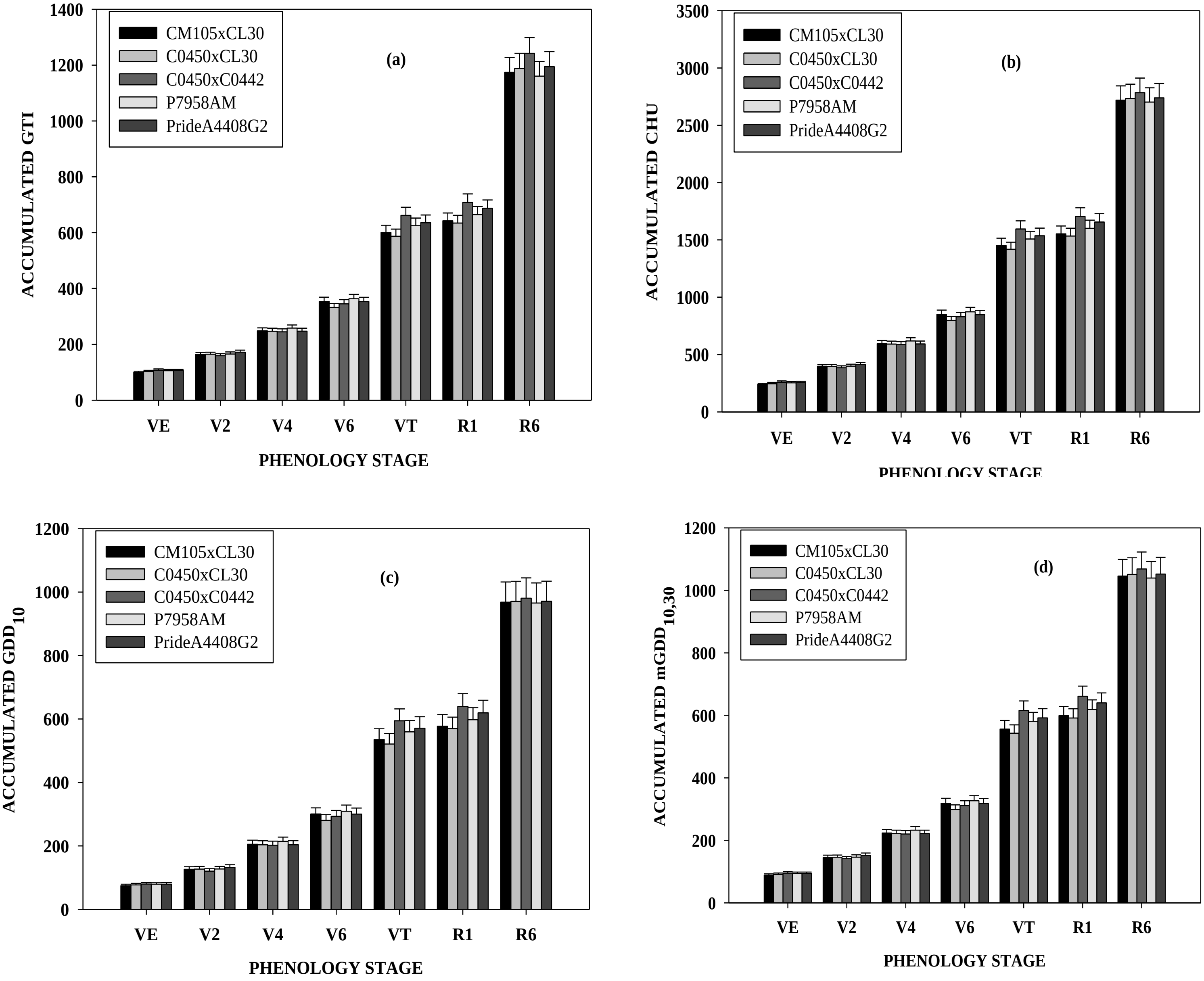

Figure 2.12 Accumulated general thermal index (a), corn heat units (b), standard growing degree days (c) and modified growing degree days (d) by five corn hybrids across 8 (VE to R1) and 7 study sites in 2016. Bars represent standard error of the mean at the 95% confidence interval.

Although the GTI appeared to have the lowest CV (less than 5%) at R6 in 2016, there were no significant differences when compared with the other indices (CV 5.2 to 10% at physiological maturity) regardless of the hybrid considered in the analysis (Table 2.7).

Table 2.7 Coefficient of variation of four thermal indices and calendar days for five corn hybrids at different phenology stages across eight Canadian Prairie locations in 2016 ($P > 0.05$).

Hybrid	**Index**	**CV (%) at different phenological development stages of corn**						
		VE	**V2**	**V4**	**V6**	**VT**	**R1**	**R6**
CM105xCL30	CHU	18.8	17.9	11.3	6.9	5.2	4.9	7.0
	GTI	18.2	17.8	11.7	8.2	5.0	4.6	5.1
	GDD10	27.2	25.0	13.9	9.6	8.1	8.4	10.1
	mGDD$_{10,30}$	19.9	19.8	13.2	9.7	6.0	6.1	6.5
	DAP	17.9	21.4	19.5	16.9	10.2	9.0	5.9
C0450xCL30	CHU	18.6	20.2	12.1	9.8	8.0	7.6	6.3
	GTI	17.3	19.7	12.3	10.5	8.0	7.5	4.0
	GDD$_{10}$	26.6	26.5	14.5	12.1	11.3	11.1	9.8
	mGDD$_{10,30}$	18.7	21.5	13.9	12.1	8.8	8.6	5.9
	DAP	15.9	21.8	19.9	18.2	10.5	9.1	7.1
C0450xC0442	CHU	17.5	17.2	12.5	10.4	3.4	2.7	4.2
	GTI	16.9	15.9	11.2	9.9	3.4	4.3	3.0
	GDD$_{10}$	26.1	27.4	14.2	9.0	5.9	7.1	4.8
	mGDD$_{10,30}$	19.2	17.4	12.8	10.2	4.9	5.8	4.4
	DAP	21.3	18.4	17.9	19.7	10.5	10.5	6.1
P7058AM	CHU	22.1	18.6	12.0	8.1	2.9	3.2	6.3
	GTI	20.9	18.5	12.2	9.2	3.2	3.5	4.0
	GDD$_{10}$	30.1	26.1	15.4	10.8	6.6	6.7	9.7
	mGDD$_{10,30}$	22.0	20.5	13.8	10.8	4.8	5.1	5.9
	DAP	22.2	20.6	18.8	16.7	9.9	9.9	7.3
PrideA4408G2	CHU	18.2	19.9	12.2	7.5	4.3	5.5	5.5
	GTI	17.4	19.6	13.7	6.9	5.4	6.6	2.4
	GDD$_{10}$	26.9	27.3	15.6	9.0	6.7	7.6	9.5
	mGDD$_{10,30}$	18.4	21.1	15.2	8.0	6.1	7.6	5.2
	DAP	20.8	19.6	20.5	17.5	11.8	12.6	8.3

2.4.4 Comparison of Corn Grain Yield

Three AAFC corn hybrids were compared for grain yield differences over 12 site-years (Table 2.8). Hybrid C0450xC0442 resulted in significantly more grain yield (7.8±0.5 Mg ha^{-1}) than CM105xCL30. There were no significant differences between hybrid C0450xC0442 and C0450xCL30, and CM105xCL30 and C0450xCL30 (Table 2.8).

Table 2.8 Analysis of variance and least square means of corn grain yield by three AAFC hybrids over 12 site-years.

Effect	Num DF	Den DF	F	Pr>F
Hybrid	2	22	4.29	0.03

Hybrid	Grain yield±SEM (Mg ha^{-1})^{z}	
C105xCL30	6.6±0.5b	<.0001
C0450xCL30	7.3±0.5ab	<.0001
C0450xC0442	7.8±0.5a	<.0001

^{z}Grain yields with the same letter in the same column are not significantly different at α=0.05 using the Tukey method.

Comparison of grain yield of five corn hybrids, including the three AAFC hybrids, in 2016 resulted in hybrid P7958AM producing significantly more grain (8.65±0.67 Mg ha^{-1}) than CM105xCL30 (7.11±0.67 Mg ha^{-1}) (Table 2.9). Grain yields of the other corn hybrids were not significantly different, regardless of them having different maturity ratings.

Table 2.9 Analysis of variance and least square mean for corn grain yield of five hybrids across 6 sites in 2016.

Effect	Num DF	Den DF	F	Pr>F
Hybrid	4	19.3	2.99	0.04

Hybrid	Grain yield±SEM (Mg ha^{-1})[z]	
P7958AM	8.65±0.67a	<.0001
C105xCL30	7.11±0.67b	<.0001
C0450xCL30	7.52±0.67ab	<.0001
C0450xC0442	7.97±0.67ab	<.0001
PrideA4408G2	8.03±0.66ab	<.0001

[z] Grain yields with the same letter are not significantly different at α=0.05 using the Tukey method.

All the corn hybrids appeared to require more heat unit accumulation than their ratings (Table 2.10). The mean CHU accumulation at R6 did not differ across hybrids for both 12 and 6 site-year analyses (Table 2.10). Grain yield significantly increased with numerical increase in mean CHU accumulation at R6.

Table 2.10 Corn heat unit rating, mean CHU accumulated from seeding to physiological maturity (R6) and grain yield

		12 site-years		6 site-years	
Hybrid name	**Hybrid CHU rating**	**Mean CHU at R6**	**Grain yield (Mg ha^{-1})[z]**	**Mean CHU at R6[y]**	**Grain Yield (Mg ha^{-1})**
CM105xCL30	2550	2628	6.6b	2702	7.11b
C0450xCL30	2600	2718	7.3ab	2719	7.52ab
C0450xC0442	2700	2792	7.8a	2723	7.97ab
P7958AM	2275	-	-	2784	8.65a
PrideA4408G2	2200	-	-	2784	8.03ab
P value		0.6	0.03	0.7	0.04

[z] Grain yields with same letters in the same column are not significantly different at α=0.05 using the Tukey method. [y] R6 is the physiological maturity.

2.5 Discussion

2.5.1 Heat Unit Accumulation and Calendar Days from Seeding to Physiological Maturity

The mean number of days from planting to physiological maturity varied numerically, but not significantly, by about 10 days among the hybrids. All hybrids required an average of 15 days to emerge after seeding. This was to be expected, considering the low soil temperatures recorded for several days after seeding at most locations. At two of the coolest locations (Vauxhall and Lethbridge) in this study, corn was seeded during the first week of May, but it took more than 20 days for the seedlings to emerge. According to Brown et al. (2009), corn seedling emergence takes between 6 to 21 d as a result of varying environmental conditions. In the present study, the delay in emergence may be attributed to cool temperatures in spring, which inhibited imbibition of water by seeds as a result of non-activation of amylase enzymes responsible for seed germination (Farooq et al., 2009). Furthermore, soil crusting as a result of wet soils at Portage la

Prairie, resulted in uneven crop emergence, was probably another factor that might have contributed to delay in seedling emergence.

In ideal conditions of warm soil temperature (12-15°C for corn), good seed quality, adequate soil moisture and optimum seeding depth, it is expected that corn emergence takes between 5 and 7 d (Nielsen et al., 2002; Farooq et al., 2009). On the Canadian Prairies, low spring temperatures may slow down phenological development, rendering the use of calendar days questionable for use in accurate prediction of corn phenology (Brinkman et al., 2016). For the critical R1 stage, regardless of the number of days that it takes to reach this stage; the duration is mainly influenced by temperature. As a result of cool soil temperatures in spring on the Canadian Prairies, there is little difference in emergence date whether seeding is done during the first half or the second half of May because seed germination with early seeding is frequently delayed under such conditions and may take up to four weeks in some cases. A possible solution to the situation in this cool region is the availability of corn hybrids that can emerge at soil temperatures in the range of 7°C to 8°C, which are typical of Canadian Prairies in spring. On the other hand, a combination of good timing of planting (into warm soils) and corn hybrids that can mature in a short growing season may play a significant role in the successful production of grain corn on the Canadian Prairies.

Across the 15 site-years, corn required slightly fewer heat units than expected from seeding to emergence probably due to low temperatures during the first week of seeding (Figure 2.2 and 2.3). As expected, due to cool temperatures early in the growing season, there was little heat unit accumulation during the first week of seeding, but this did not completely stop subsequent corn development especially to reach the VE stage. Ministry of Agriculture (2009) agronomic guidelines show that corn requires between 90 and 120 GDD or 180 CHU from seeding to emergence. These guidelines are based on the assumptions that conditions will be favourable for corn development and does not take into consideration adverse environmental conditions that may be experienced during the period succeeding planting of a crop. Modified GDD observed from seeding to VE in this study are consistent with agronomic guidelines, but CHU is not consistent because during the same period the corn hybrids required 42 to 68 more CHU.

Although the five corn hybrids had different heat unit ratings to reach physiological maturity, this study showed that the difference in heat accumulation among the cultivars was not significant at any phenological stage of development. This could have been due to differences in the criteria used by different companies when assigning heat units to hybrids. The three AAFC hybrids (CM105xCL30, C0450xCL30 and C0450xC0442) had a fairly similar CHU rating of 2550, 2600 and 2700 respectively. Furthermore, factors other than temperature or heat units, such as moisture deficit, can contribute to a delay in phenological development. The measured CHU accumulation to physiological maturity was always greater than the CHU in the maturity ratings for each hybrid. In particular, the two early-maturing commercial hybrids (P7958AM and PrideA4408G2) required substantially more CHU than their ratings. It is also important to note that GDD and CHU stopped accumulating when temperatures were below minimum thresholds of 10°C and 4.4°C, respectively. However, GTI continued to accumulate at temperatures near 0°C. This could be indicative that the GTI can be explored further to ascertain whether it can be used as an alternative to the CHU system in modeling phenological development of grain corn on the Canadian Prairies. The present study was conducted over a two-year period (15 site-years) with similar weather conditions; which might be too short a time to detect significant differences among the hybrids. Moreover, the corn hybrids used in this study had similar CHU ratings which, could also help explain non-significant differences in thermal unit requirements to reach maturity.

2.5.2 Precision of Thermal Indices and Calendar Days

In this study, coefficient of variation (CV) of heat unit accumulation was used as a measure of reliability and consistency among sites for each thermal index as a tool to model phenological development of corn on the Canadian Prairies. The study showed that all indices had CVs less than 10.5% at R6 and they were not significantly different from GTI having the lowest CV less than 5% (Table 2.6 and 2.7). However, at the VE and V2 stages, CVs were high for all indices, probably due to differences in seeding dates and time to emergence as a result of low temperatures during the first week of seeding at most locations and wet soil conditions, especially at the Portage la Prairie location. These results are consistent with those reported by Ma et al. (2004) who found that corn emergence under wet and cool soil conditions takes more than seven days even if nutrients are not limiting.

The GTI assumes that corn development continues to take place even at temperatures near 0°C whereas the other indices assume no development below their base temperatures. When all thermal indices were compared, it was clear that GTI indicated faster development rates of corn than did GDD and CHU for days with very low temperatures towards R6. Similar results obtained by Stewart et al. (1998) and Tojo Soler et al. (2005) indicate that GTI accounts properly for the influence of low temperatures on corn development. The GTI may therefore, be important indicator for a tool that can be used for accuratley modeling phenological development of corn under cool conditions that prevail on the Canadian Prairies considering its low variability compared to other indices.

The GTI supports the observation by other researchers that plant characteristics such as ear declination, thickness of husks, number of husk leaves, kernel type (dent or flint), and cob length and diameter impact drying late in the season when weather conditions are unfavourable for drying. At low temperatures, a hybrid that has thin and fewer husks, and shorter cob length and diameter tends to dry faster without relying as much on warm temperatures.

It is also important to note that in some instances, thermal indices may continue to accumulate heat units under cloudy conditions but those heat units may not help with drying of corn kernels because there will not be much water loss from the kernels. This could have been the case in this study with the observation of more thermal units while corn was getting to physiological maturity. Under warm temperatures, the drying process of kernels is twofold: evaporation from the surface of the kernels and through dry matter accumulation. In cases where weather (through evaporation) does not contribute much to the drying process, the corn plant uses its plumbing mechanism whereby water loss will take place as dry matter accumulation occurs in the kernels. During such periods, the corn plant efficiently uses its internal plumbing mechanism to expel water from the kernels because water movement out of the corn kernels is correlated with the amount of dry matter accumulation. Therefore, GTI may be an alternative index that can simulate some of the physiological processes that take place within the plant during dry kernel dry down even at low temperatures close to 0°C.

2.5.3 Grain Yield

This study showed significant differences in grain yield among hybrids despite the lack of significant differences in heat unit accumulation among the hybrids. Grain yield assessment was not the core objective of this study; however, it remains an important evaluation since corn producers are mainly interested in final yield. Across the 12 site-years, AAFC hybrid C0450xC0442, which had the highest CHU rating, produced significantly more grain yield than the C105xCL30 hybrid while it had similar grain yield to the C0450xCL30 hybrid. Although traits of these hybrids show that they have between 12 and 14 kernel rows each, the difference was probably because hybrid C0450xC0442 accumulated more dry matter than the other two AAFC hybrids.

A comparison of the five corn hybrids grown in 2016 showed that hybrid P7958AM significantly outyielded the C105xCL30 hybrid, probably because it flowered earlier and its traits reveal that it has more kernel rows (between 14 and 16) than the other hybrids, which had between 12 and 14 rows. Kernel row number is believed to play a significant role in final grain yield attained by a particular corn hybrid (Cai et al., 2014; Crozier et al., 2014). Early flowering and silking early also allow corn hybrids to accumulate sufficient dry matter in the kernels, resulting in higher yields. Similar findings by Severini et al. (2011) revealed that kernel weight at maturity depends on the capable kernel size established during the initial stage of grain filling and the potential of corn to supply assimilates.

Other traits (not measured) that could have contributed to higher yield by hybrid P7958AM than the other hybrids were probably more leaves that would create a good source-sink relationship between the leaves and the kernels. Corn producers are generally concerned with growing corn hybrids that reach physiological maturity and are able to produce higher grain yield so as to get higher returns. Therefore, a hybrid that can fully utilize the short growing season and achieve higher grain yield will be ideal for the Prairies.

2.6 Conclusion

In this study, we have shown that the corn hybrids consistently required more CHU to reach physiological maturity than is indicated by their CHU rating. There is also considerable variation in accumulated thermal units to reach different phenological development stages among locations. The variation is sufficient that hybrids with maturity ratings from 2200 to 2700 CHU showed no significant differences in the mean accumulated values of calendar days, two types of GDD, CHU or GTI to any phenological stage including physiological maturity. Results of this experiment revealed CV of less than 10.5% at R6 for all indices, which may be acceptable for field experiments. Although the differences in CV among thermal units were not significant, they do indicate that it is possible the GTI may be a better alternative to CHU and GDD because of its lower CV in accumulated amount (less than 5% at R6) compared to the other indices for modeling phenological development of corn on the Prairies. The study also showed differences in yield of the five hybrids as a result of differences in their genetic traits. The present study was conducted for 15 site-years only. Further evaluation, especially of early maturity corn hybrids is warranted to determine their suitability for cooler regions of the Canadian Prairies. Further evaluation is also needed to affirm the suitability of GTI as an alternative to CHU in modeling phenological development of corn.

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3. IMPACT OF COLD NIGHTS ON PHENOLOGICAL DEVELOPMENT OF CORN ON CANADIAN PRAIRIES

3.1 Abstract

Corn (*Zea mays* L.) is a warm season crop and is sensitive to prolonged periods of cold temperatures early and late in the growing season. The Canadian Prairies experience cold night temperatures during the growing season which could delay phenological development of corn. Therefore, low temperatures may also alter total thermal units required by corn to reach physiological maturity. A two year field study was initiated in 2015 to assess the impact of air temperature and thermal heat unit accumulation on corn development across eight representative locations on the Canadian Prairies. Physiological maturity (R6) dates of five corn hybrids with 2275, 2200, 2550, 2600 and 2700 corn heat unit (CHU) ratings were determined. The number of thermal units required to reach R6 was estimated using CHU and general thermal index (GTI) models with data obtained from weather stations set at each site. Regression analysis on the relationships between total growing season hours at temperatures below 4.4°C and CHU or GTI to reach maturity revealed an inverse relationship between CHU and cold night temperature and a weak positive relationship between GTI and cold night temperatures. There was no significant influence of cold night temperatures on either CHU or GTI to reach R6 for the five corn hybrids except for the 2700 CHU hybrid in 2015 (R^2=0.83, P = 0.01) and in 2016 (R^2=0.85, P = 0.003). An increased number of cold night hours appeared to reduce the accumulation of CHU from planting to R6 for all the corn hybrids. A weak positive relationship between GTI and cold nights suggests that the index continues to accumulate even at very low temperatures. Additional site years of assessment of hybrids bred for the Canadian Prairie weather conditions may be required as 15 site-years of field study were inadequate to confirm the influence of cold nights.

3.2 Introduction

Corn (*Zea mays* L.) growth and phenological development are mainly driven by air temperature from emergence to physiological maturity following which genetic characteristics and prevailing weather conditions interact to determine harvest maturity (Streck et al., 2008). The most important aspect of corn phenology under Prairie conditions is the ability of the crop to reach physiological maturity and effectively complete critical development stages prior to a killing frost (Kumudini et al., 2014). The Canadian Prairies, unlike Ontario and Quebec, frequently experience low temperatures overnight during the corn growing season (DePauw at al., 2011). As a warm season crop, this becomes a challenge for grain corn to reach physiological maturity under Prairie weather conditions. Specifically, low temperatures during the first few days after seeding corn may affect subsequent crop establishment and final grain yield (Farooq et al., 2009). Extreme temperatures are among the abiotic stresses that cause a serious threat to corn production and low night temperatures for prolonged periods of time result in delayed phenological development because of reduced cell cycle progression (Wang et al., 2003; Rymen et al., 2007).

A study by Riva-Roveda et al. (2016) showed that corn can suspend its growth when exposed to chilling temperatures, especially early in the growing season. In this state, the plant suspends growth and development during cold stress periods and resumes normal growth when favorable warm conditions prevail. This is a desirable trait that is selected for in corn and may be suitable for the Prairies that experience cold spells in almost every season. Hybrids with these traits may be ideal in that they can tolerate cold weather conditions to some extent and resume growth when warmer temperatures resume, provided other factors such as soil moisture and nutrients are adequate (Riva-Roveda et al. (2016).

On the other hand, moderate temperatures during the silking stage are ideal in that they reduce respiration losses and slow down the growth rate, thereby lengthening the grain filling period. Extreme temperatures during pollination may result in flower abortion, causing significant yield losses (Hatfield and Prueger, 2015). Longer grain filling periods may translate to higher grain yields as a result of accumulation of more dry matter, which is a major concern for Prairie corn producers.

The study on thermal unit evaluation described in Chapter 2 showed that the corn heat units (CHU) required to reach maturity were numerically not consistent among locations and years for the same hybrid. The study also showed that, although there were no large differences, the General Thermal Index (GTI) heat unit indicated the most consistent accumulation from planting to physiological maturity for all hybrids tested. The inconsistency in CHU accumulation complicates the selection procedure for suitable corn hybrids for production in a given area. Current industry practice is to provide a single CHU thermal unit rating for each corn hybrid to reach physiological maturity without regard to weather conditions that may alter the growing season CHU requirement. Producers need this information so that they can make proper decisions when selecting corn hybrids to grow in their areas. This study assessed the influence of cold night temperatures on heat unit accumulation during the phenological development of grain corn and how this information could be used to adjust CHU ratings for the selection of corn hybrids on the Canadian Prairies.

3.3 Materials and Methods

3.3.1 Study Sites

A detailed description of the site layout and locations is provided in Chapter 2. Eight study sites located in Manitoba and Alberta were used for thermal unit evaluation as well as to assess the influence of cold night temperatures on phenological development of corn in 2015 and 2016. The sites provided a representative set of weather conditions experienced on the Canadian Prairies.

3.3.2 Treatments

The experiment was laid out as a randomized complete block design (site-year as the replicate) with three and five treatments (corn hybrids) in 2015 and 2016, respectively. The hybrids evaluated in 2015 were obtained from Agriculture and Agri-food Canada in Ottawa and these were rated at 2550, 2600 and 2700 CHU. In 2016, the five corn hybrids evaluated included AAFC's three corn hybrids from the 2015 study and an additional two commercial hybrids, 2200 and 2275 CHU. The five corn hybrids provided a range of CHU ratings that are typical for the Canadian Prairies (Nadler and Bullock, 2011).

3.3.3 Corn Staging

Physiological maturity was determined by randomly sampling five cobs from each plot and manually threshing kernels to identify the presence of a black layer at the tip of the corn kernels. The physiological maturity stage was defined when the majority of kernels of the sampled cobs showed a black or brown dot at their tips. Dates at which this stage occurred were determined before calculating thermal unit requirements.

3.3.4 Weather Data and Calculation of Thermal Units

Automated weather stations (Watchdog 2000 series, model 2900ET) were used to collect hourly weather data for computing thermal units required by each corn hybrid to reach physiological maturity. The description and assessment of the thermal models is provided in Chapter 2. For this study, accumulated GTI and CHU from planting to physiological maturity were the thermal units utilized in the analysis. For each hybrid at each location, the accumulated values of GTI (aGTI) and CHU (aCHU) were calculated. In addition, a dCHU (accumulated CHU from planting to physiological maturity minus CHU rating) was calculated for each hybrid at each location.

The extent of cold temperature was evaluated by totalling the number of hours, from planting to maturity, with a temperature reading less than 4.4°C. Several minimum temperature thresholds were evaluated including 12, 10, 8 and 4.4°C. The latter is reported because it is the minimum threshold for the CHU. The relationship between accumulated growing season heat units and hours below a given temperature was similar for all temperatures evaluated (data not shown).

3.3.5 Statistical Analysis

Simple linear regression analyses were performed to explore the effects of cold nights on the accumulation of GTI and CHU using PROC REG with SAS 9.3 (SAS Institute Inc., 2011). The regression analysis was done separately for 2015 and 2016 and for all 13 site-years with the number of cold night hours, GTI and CHU as the variables. Scatter plots for the same data are also presented in Appendix IV. Significant effects of cold nights were assessed at $\alpha = 0.05$.

3.4 Results

3.4.1 Relationship between Cold Nights and Heat Unit Accumulation

The regression analysis for the number of cold night hours and CHU accumulation showed an inverse relationship for the three hybrids in 2015 (Appendix IV (Figure IV.1)); however, the relationship was statistically significant only for the 2700 CHU hybrid (Table 3.1-3.3). The accumulated GTI displayed no relationship with number of cold night hours in 2015 (Appendix IV (Figure IV.2), Table 3.1). The dCHU versus number of cold night hour relationship in 2015 (Appendix IV (Figure IV.3) is similar to that in Figure IV.1 but provides a perspective on the number of additional CHU, required to reach maturity. The accumulated CHU versus number of cold night hour relationship for five hybrids in 2016 (Appendix IV (Figure IV.4)) showed a pattern similar to that in 2015 but, again, only the 2700 CHU hybrid relationship was significant (Table 3.1-3.3). The dCHU values in 2016 (Appendix IV (Figure IV.5) showed that almost all of the five hybrids at all locations required more CHU than their rated values to reach maturity. In 2015, there was an approximately even split between the hybrids and locations that accumulated more than their rated amount versus those that accumulated less than their rated values. It is not clear why the hybrids required so many more CHU to reach maturity in 2016 compared to 2015. Accumulated GTI, again in 2016 showed no significant relationship with number of cold night hours for the five hybrids (Figure IV.6, Table 3.3). The relationship between CHU accumulation and cold night hours during the vegetative (seeding to tasseling) and reproductive (tasseling to physiological maturity) phase of corn development was inverse for the 5 corn hybrids in 2016 (Figure IV.7 and IV.8).

Table 3.1 Regression analysis for effects of cold nights (hours below 4.4°C) on CHU and GTI accumulation of 3 corn hybrids in 2015.

	CHU rating	Intercept and slope	R^2	RMSE	P-value[z]
CHU	2550	2560.8-0.91x	0.14	156	0.41
	2600	2739.8-1.35x	0.50	98.7	0.11
	2700	2895.5-1.55x	0.83	57.1	0.01
GTI	2550	1123.1+0.32x	0.13	57.2	0.43
	2600	1189.5-0.07x	0.03	32.5	0.76
	2700	1262.7-0.22x	0.32	26	0.24

[z] Cold nights significant at $\alpha = 0.05$

Table 3.2 Regression analysis for effects of cold nights (hours <4.4°C) on CHU and GTI accumulation of 3 corn hybrids across 13 site-years

	CHU rating	Intercept and slope	R^2	RMSE	P-value[z]
CHU	2550	2810.9-2.76x	0.47	120	0.09
	2600	2863.5-2.41x	0.49	107	0.08
	2700	3025-1.73x	0.94	36.4	0.0003
GTI	2550	1192.4-0.34x	0.13	36.05	0.43
	2600	1209.1-0.23x	0.05	43.20	0.63
	2700	1296.5-0.31x	0.74	13.80	0.01

[z] Cold nights significant at $\alpha = 0.05$.

Table 3.3 Regression analysis for effects of cold nights (hours <4.4°C) on CHU and GTI accumulation of 5 corn hybrids in 2016

	CHU rating	Intercept and slope	R^2	RMSE	P-value[z]
CHU	2275	2856.1-1.8x	0.20	192.5	0.32
	2550	2855.3-1.40x	0.06	204.1	0.61
	2600	2830.2-0.83x	0.03	187.6	0.72
	2700	3116.4-1.70x	0.85	72.4	0.003
	2200	2905.8-1.19x	0.37	145.6	0.14
GTI	2275	1205.3-0.36x	0.06	70.1	0.58
	2550	1205.1-0.10x	0.0	70.2	0.90
	2600	1195.7+0.28x	0.03	61.4	0.70
	2700	1322.6-0.33x	0.57	28.4	0.05
	2200	1222.6-0.04x	0.0	52.7	0.89

[z] Cold nights significant at $\alpha = 0.05$

3.5 Discussion

3.5.1 Cold Nights and Grain Corn Phenological Development

The inverse relationship between the number of cold night hours and CHU shows that fewer hours of cold night temperatures during the growing season result in more CHU accumulation across most sites. The relationship was significant for only the 2700 CHU hybrid and was not a consistent trait for all hybrids. It also appeared that thermal unit accumulation by the crop exceeded the rating assigned to each corn hybrid in 2015 and especially in 2016. Further evaluation of influence of cold night temperatures during separate phases of corn development (vegetative and reproductive phases) did not change the inverse relationship. The relationship followed the same trend as that between accumulated CHU versus total cold night hours at physiological maturity. A previous study by Rymen et al. (2007) indicated that low night temperatures are positively linked to a reduction in plant cells as a result of lengthened cell cycle duration. This, in turn, should result in slower phenological development of plants. Under Prairie weather conditions, it might be expected to result in corn failing to reach maturity.

Generally, when non-lethal cold night temperatures are experienced after silking stage, there tends to be a lengthened grain filling period translating to higher yield. Warm night temperatures result in faster accumulation of thermal units that can lead to earlier maturation of corn (Hatfield and Prueger, 2015). This was not the case over the two growing seasons in this study. With progressively more hours of low night temperatures, the corn hybrids generally tended to accumulate fewer CHU from planting to physiological maturity. However, there were clear differences in the response between hybrids. It is possible that progressively more hours of cold night temperatures invoke a coping response from corn plants whereby they advance more rapidly through their phenological stages as a means to successfully reach reproductive maturity. Although the inverse CHU accumulation versus number of cold night hours relationship was significant for only the longest season hybrid in this study, the number of observations might have been too low to adequately assess the statistical significance of the relationships. Two or more additional years of study with more corn hybrids suited for the Prairies would be beneficial to drawing firm conclusions on the influence of cold nights on phenological development of corn.

The inconsistency of CHU accumulation along with its variable response to cold night temperatures raise more questions about its suitability as a tool for identifying appropriate corn hybrids for production in specific areas of the Canadian Prairies. On the other hand, accumulated GTI showed no relationship with cold night hours, which indicates that this thermal index is not affected by cold night temperature. This may occur because GTI continues to accumulate even at very low temperatures. Stewart et al. (1998) observed that the GTI accumulates faster at low temperatures than does the CHU, which stops accumulating at temperatures below 4.4°C. This adds further impetus to the need for exploration of GTI as a potential index to more effectively select suitable corn hybrids for grain production in specific locations on the Canadian Prairies.

3.6 Conclusion

This study suggests an inverse relationship exists between cold night hours and CHU accumulation and that more frequent cold night temperatures reduce total CHU accumulation from planting to physiological maturity resulting in more rapid phenological development of corn. As a result, the general climate change trend for warmer overnight temperatures may result in corn hybrids requiring progressively more heat units to reach maturity. It is important to note that data available for this study is insufficient to generalize too broadly about the impact of cold nights on phenological development of corn; therefore, additional site-years of data are needed to draw more reliable conclusions. This study also indicated that the GTI thermal unit is relatively unaffected by hours of cold night temperature and, thus, may be a more reliable index on the Canadian Prairies, which experience frequent cold nights.

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4. Alternative Approaches to Selecting Appropriate Corn Hybrids for Canadian Prairie Crop Production Areas

4.1 Abstract

There is growing interest among producers in increasing corn production on the Canadian Prairies. However, the current system for selecting suitable corn hybrids for the Canadian Prairies has limited effectiveness. Therefore, a reliable tool is needed to help corn producers select corn hybrids that are suitable for their environments. Three years (2014 to 2016) of corn hybrid trial data were obtained from the Manitoba Corn Committee to assess the relationship between relative maturity (RM) rating and kernel moisture content (KMC) at harvest for different corn hybrids of varying RM ratings. Seeding and harvesting dates were identical for all hybrids within each site. The relationship between KMC and RM was significant for DuPont Pioneer, Pride and Maizex hybrids. Early maturing hybrids were associated with low KMC (21 to 28%) while late maturity hybrids were associated with high KMC (28 to 32%) at harvest. There was a close relationship between RM and corn heat unit (CHU) rating for all hybrids ($p < 0.05$) from different seed companies except Syngenta ($R^2 = 0.75$, $p = 0.087$). The close relationship between RM and CHU rating suggests that these two indices will have similar limitations as tools for selecting corn hybrids on the Canadian Prairies. Since accumulated CHU from planting to physiological maturity has displayed numerically higher CVs than the general thermal index (GTI) across site-years for multiple hybrids, it is likely that RM ratings will display similar inconsistencies. Therefore, the GTI that was identified in Chapter 2 and 3 of this thesis as a promising for modeling phenological development of corn should be explored with additional years of field data to determine if it is truly a more reliable thermal index than CHU for selecting suitable corn hybrids for different environmental conditions on the Prairies.

4.2 Introduction

The Canadian Prairies experience a short growing season and requires corn hybrids that can reach maturity within this period (Nadler and Bullock 2011). Corn hybrid selection on the Canadian Prairies is a challenge because of the inconsistency of corn heat unit (CHU) accumulation for the same hybrid across locations and years. Since CHU is the main thermal index used in this region, an alternative approach is needed to assist corn producers with assessment of risk associated with production of certain hybrids in their locations. The heat unit evaluation study (Chapter 2) showed that the CHU index had a numerically higher coefficient of variation than the GTI, which could be a better alternative as it consistently displayed the lowest coefficient of variation at physiological maturity, even though there was insufficient replication (statistical power the desired 0.8) to establish a statistically significant difference. An alternative approach could be the use of relative maturity (RM) days for selection of hybrids depending on the location in which they are to be grown. Seed companies establish a RM rating for new hybrids prior to determining the CHU rating, so it is possible that RM may offer a more consistent characterization of corn hybrid heat unit requirements. Various seed companies describe early maturity hybrids as those with a range between 70 and 79 day RM, which is equivalent to between 2100 and 2400 CHU. According to Nadler (2007), a maximum of 2700 CHU are accumulated in the warmest areas of the Canadian Prairies once in every 4 years. However, this is based on establishing corn during the last part of April or first half of May of each season, regardless of the soil temperature in the spring.

The RM rating is determined by comparing kernel moisture content at harvest for a new hybrid to the moisture content at harvest for a series of check varieties. The check varieties utilized vary between seed companies with some old checks discontinued and new checks added each year.

Thus, there is no common standard for assigning RM ratings of hybrids for different seed companies. Corn hybrids assigned a high RM rating are usually long season hybrids and will have higher kernel moisture content at harvest than early maturing corn hybrids. Ma and Dwyer (2001) reported variations in grain moisture content among different corn hybrids and this was attributed to differences in the rate of dry matter accumulation. Corn hybrids with a slow rate of dry matter accumulation tend to have higher moisture content at harvest than those with a faster rate. Moisture content of corn kernels is essential for maintaining life processes during the grain filling period (Zhang et al. 2013). However, after harvesting, grain corn needs to be stored at low moisture content to prevent deterioration during storage and to avoid losses due to diseases that favor these conditions.

Most research has focused on yield potential without paying much attention to tools that could be used to select suitable corn hybrids for production in specific environments and whether the hybrids can reach maturity in these environments. The objective of this study was to assess RM as a potential risk assessment tool for selection of suitable appropriate corn hybrids for production in different locations on the Canadian Prairies. It was hypothesised that an alternative approach to CHU could improve producers’ ability to effectively select appropriate hybrids on the Canadian Prairies.

4.3 Materials and Methods

4.3.1 Study Area

The Manitoba corn variety trials (MCVT) occur every year. For this study, 3 years of MCVT data were compiled from 3 separate locations in each year. The locations included Morden, Carman, MacGregor and St Pierre. The trials were conducted for all the 3 years at Morden while the other sites had trials conducted for 2 years. All hybrids had been grown at a plant population of 75000 plants ha^{-1}. Seeding and harvesting dates were similar for each treatment (hybrid) within site but varied among sites (Table 4.1).

Table 4.1 Seeding and harvest dates for Carman, Morden, MacGregor and St Pierre from 2014 to 2016.

Site-year[z]	Seeding date	Harvest date
Carman-14	23-May	21-Oct
Morden-14	17-May	13-Oct
MacGregor-14	28-May	27-Oct
Carman-15	30-May	14-Oct
Morden-15	9-May	22-Sept
St Pierre-15	21-May	16-Oct
MacGregor-16	5-May	15-Oct
Morden-16	9-May	5-Oct
St Pierre-16	17-May	14-Oct

[z] 14, 15 and 16 represent the years 2014, 2015 and 2016 respectively.

4.3.2 Data Source

Grain corn hybrid trial data from the site-years in Table 4-1 included corn hybrids of different maturity ratings from 15 corn seed companies. Kernel moisture content had been determined for each hybrid at each site-year before harvest using a Dickey John moisture meter. Data also included grain yield and bushel weight for each corn hybrid at all sites. The seed company RM rating for each corn hybrid at each site was utilized in this study.

4.3.3 Statistical Analysis

The relationship between kernel moisture content and RM was investigated for MacGregor, St Pierre and Morden in 2016. The relationship between CHU and RM rating was determined for all the hybrids across the 9 site-years. Scatter plots and a simple linear regression were done in SAS using the Regression procedure (SAS Institute Incorporation, 2011).

4.4 Results

4.4.1 Relationship between Relative Maturity and Moisture Content within Site-years

Kernel moisture content and relative maturity data were selected only for 2016 for the purposes of this study. Kernel moisture content was related to relative maturity and there appeared to be greater variation within each company than there was between companies (Appendix V, Figure V.1). Late maturity corn hybrids had high KMC (28 -32%) while early maturity hybrids had low moisture content (22- 28%) at harvest. The relationship between KMC at harvest and RM was not significant for most company hybrids except DuPont Pioneer and Pride in 2016 ($p<0.05$) (Table 4.2). Although significant, DuPont Pioneer hybrids had low R^2 values (0.56, 0.58 and 0.41) for corn hybrids grown at MacGregor, St Pierre and Morden respectively.

Table 4.2 Regression analysis for kernel moisture content at harvest and company relative maturity for different corn hybrids at Macgregor, Morden and St Pierre in 2016.

Site year	Company	Slope and intercept	R^2	RMSE	P Value^z
Macgregor	DuPont Pioneer	42.79+1.24x	0.56	2.80	0.01
	Elite	74.67+0.09x	0.0	2.75	0.90
	North star	66.16+0.39x	0.10	2.5	0.61
	Pride	14.07+2.51x	0.83	1.74	0.03
Morden	DuPont Pioneer	39.86+1.50x	0.58	2.80	0.01
	Elite	46.39+1.21x	0.40	2.83	0.09
	Pride	34.64+1.55x	0.91	1.24	0.01
St Pierre	DuPont Pioneer	40.32+1.54x	0.41	3.23	0.04
	Elite	67.23+0.41x	0.09	2.63	0.63
	North star	32.31+1.91x	0.47	1.91	0.20
	Pride	25.97+2.05x	0.57	2.77	0.14

^{z}Kernel moisture content significant when $p < 0.05$.

4.4.2 Company Relative Maturity and Corn Heat Unit Ratings Across 9 Site-years

There was a strong relationship between RM and CHU rating across the 9-site years (Appendix V: Figure V.2). Most corn hybrids fell between 2150 and 2350 CHU (72 to 80 d RM). The relationships between RM and CHU rating were all significant ($p<0.05$) except for Syngenta hybrids with an R^2 value of 0.83 ($p = 0.09$) and Maizex hybrids with $R^2=0.37$ ($p=0.05$) (Table 4.3, Appendix V: Figure V.2). The highest R^2 values of 0.99 and 0.98 were observed for North Star and Pick seeds hybrids respectively.

Table 4.3 Regression analysis and P values for relative maturity and corn heat unit rating for different corn hybrids from various seed companies across 9 site-years in Manitoba.

Corn hybrid source	**Slope and intercept**	**R^2**	**RMSE**	**P value^z**
Brett Young	-27.53+0.05chu	0.80	1.68	0.04
Delmar	26.64+0.02chu	0.93	0.34	<0.0001
Dow seeds	18.93+0.03chu	0.87	0.84	0.001
DuPont-Pioneer	22.06+0.02chu	0.96	1.06	<0.0001
Elite	26.89+0.02chu	0.96	0.63	<0.0001
Fraser	59.14+0.01chu	0.57	0.49	0.02
Horizon	-6.79+0.04chu	0.94	0.95	<0.0001
Maizex	43.57+0.01chu	0.37	1.26	0.05
Monsanto-DeKalb	24.68+0.02chu	0.97	0.64	<0.0001
North star	18.06+0.03chu	0.99	0.31	0.001
Pick seeds	49.42+0.01chu	0.98	0.14	<0.0001
Pride	-17.95+0.04chu	0.96	0.72	<0.0001
Quarry	12.68+0.03chu	0.97	0.45	0.0004
Syngenta	32.50+0.02chu	0.83	0.71	0.09

4.5 Discussion

Corn hybrids for Du-Pont Pioneer and Pride seeds showed highly significant relationships between KMC and RM rating, probably because there were many hybrids available for analysis from these companies compared to the other corn seed suppliers. The two seed companies had more than 10 hybrids under study, with a wide CHU and RM range while the rest of the companies had between three and six corn hybrids with either a narrow range or similar RM ratings for different CHU ratings. In the present study, the hybrids were seeded and harvested on the same dates so as to compare their differences in relation to the length of the growing season required to reach harvest maturity. At most sites, late maturity hybrids were harvested with KMC of more than 28% while early maturity corn hybrids were harvested with between 22 and 28% kernel moisture content. High KMC at harvest could be influenced by various factors that may include genetic traits of the hybrid, air temperature, humidity, solar radiation, wind speed and planting date (Tsimba et al., 2013). Temperature is considered the major weather factor that influences the rate of moisture loss from corn kernels (Hatfield and Prueger, 2015). Considering low temperatures and early fall frosts that normally occur at the end of September on the Canadian Prairies, it means that dry down of corn will take longer than for locations with warmer temperatures in the period following physiological maturity. The higher expected levels of kernel moisture on the Canadian Prairies means that corn producers will incur extra drying costs in order to safely store their grain.

Relative maturity was positively correlated with CHU for most of the hybrids. The close relationship suggests that the use of RM as a tool for selection of suitable corn hybrids on the Canadian Prairies would give similar results to CHU, which has already been shown coefficient of variation higher than the GTI. It is also important to note that there is no standard followed in assigning RM rating for corn hybrids (Lauer, 1998). Each seed company uses its own check varieties and method to assign RM ratings. However, there is high consistency in RM rating and harvest moisture content between seed companies. Likewise, the RM versus CHU rating is markedly similar between companies. The present study showed more scatter between 70 and 79 d (2150 and 2300 CHU) hybrids, which is a concern for corn producers on the Canadian Prairies because these are regarded as the early hybrids that should mature within the short growing season. Therefore, producers need a risk assessment tool that is more reliable and more consistent than CHU and it is unlikely that RM will provide better consistency. A study by Nielsen et al. (2002) suggested that hybrid maturity ratings based on thermal indices are better than RM especially for late planted corn. This could be true, especially on the Canadian Prairies where corn emergence is prolonged as a result of cold soil temperatures early in the growing season.

4.6 Conclusion

Despite differences in check varieties between seed companies, there is a strong, consistent correlation between RM and kernel moisture content at harvest as well as RM and CHU ratings between hybrids from different companies. Since CHU has shown higher CV than GTI in accumulation between site-years (Chapter 2) as well as inconsistent response to cold overnight temperatures frequently experienced on the Canadian Prairies (Chapter 3), the RM rating system with high correlation to CHU is unlikely to be any more satisfactory. Relative maturity as a risk assessment tool for selecting corn hybrids for a specific area would be similar to using the CHU rating.

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5 OVERALL SYNTHESIS

5.1 Summary of Results

With the observed long term positive trends in seasonal thermal units on the Canadian Prairies, producers have an opportunity to increase production of warm season crops such as corn. However, a reliable measure of thermal requirements of their hybrids would enable effective selection. The Ontario corn heat unit system has been the major tool used for characterizing corn hybrid heat unit requirements, which are designed to be used with CHU accumulation risk maps to select suitable locations for corn production in Canada (Brinkman et al. 2016; Brown and Bootsma 2016). Thermal indices are widely accepted as an effective tool for selecting suitable corn hybrids as well as characterization of a region in terms of crops that can be grown to maturity within a growing season. Apart from thermal indices, various approaches can also be used to aid selection of suitable corn hybrids for a given area. Currently, corn producers rely on government weather stations as well as their experience to characterize their areas of production when selecting grain corn hybrids that they can successfully grow.

This study evaluated thermal indices and alternative approaches that could be used for modeling phenological development of grain corn on the Canadian Prairies. Phenological development of corn is mainly driven by temperature, which is the major weather factor responsible for biochemical and physiological processes that take place within plants. Inadequate heat accumulation during the growing season may result in slow development and failure of grain corn to reach maturity, especially in cold regions such as the Canadian Prairies, which experience short growing seasons. In Chapter 2, four thermal indices were evaluated to distinguish heat unit requirements from planting to physiological maturity for corn hybrids with a range of CHU ratings. The variability among sites and the limited number of replications likely explains the lack of significant differences among hybrids in thermal unit accumulation at any stage of grain corn development. In addition, the coefficient of variation of thermal unit accumulation was calculated at each phenological stage for each hybrid, but again, the differences in CV between thermal units accumulated to each phenological stage were not significant. However, the CV for accumulated GTI gave an indication that it can be accurately used for accurately modeling grain corn phenological development if explored further with more field data. This suggests that it is worthy of further assessment as an alternative index to CHU and that it could improve the accuracy of determining heat requirements of grain corn. The low CV observed for GTI may be attributed to its ability to accurately simulate corn development when temperatures were low, hence recognizing useful heat near 0°C. This is in agreement with the observation that corn plants continue to mature when temperatures are low as a result of other traits that a hybrid may possess.

Other approaches could possibly improve the accuracy of modeled phenological development for different grain corn hybrids. In Chapter 3, the impact of cold night temperatures on grain corn development was assessed to determine if a correction factor could be used to adjust CHU requirements between growing seasons. More frequent numbers of cold night hours during the growing season resulted in generally reduced accumulation of CHU only for one hybrid while there was little impact of cold night hours on accumulation of GTI. In this study, some locations experienced more hours of cold night temperature than others but still reached physiological maturity. It is possible that during exposure to cold night temperatures, the corn plants shifted to standby mode and resumed growth after exposure to warmer temperatures (Riva-Roveda et al. 2016). Duration of exposure to cold temperatures is also important in corn development. If the period of exposure is prolonged, this might have a stronger influence on the ability of corn to reach maturity and produce sensible grain yield. On the other hand, a short exposure to cold night hours may be compensated by warm day temperatures, which enable corn plants to develop rapidly even after short periods of minor chilling stress. The inverse relationship between cold night hours and CHU accumulation to R6 in this study did not facilitate the determination of a “cold temperature correction” and thus was an unsuccessful strategy to improve the accuracy of estimating grain corn CHU requirement. However, the fact that accumulated GTI was unaffected by number of cold night hours is another factor indicating the desirability of GTI for consideration as a heat unit for use on the Canadian Prairies.

Kernel moisture content at harvest was closely related to relative maturity rating for hybrids from several companies. Late maturity hybrids displayed higher moisture content at harvest than earlier maturing hybrids with a lower RM rating. This suggests that a progressively longer grain filling period is required by grain corn hybrids with progressively later maturity. A longer grain filling period translates to higher grain yield, which is what producers want to achieve. However, it is imperative to select corn hybrids that can mature within the short growing season, which will normally require a sacrifice in yield potential. Relative maturity and CHU ratings for hybrids from various companies were very closely related regardless of the different check varieties utilized by each company for assigning the RM rating to their hybrids. Therefore, RM would behave similarly to CHU as a measure of heat unit requirements and there was no expected advantage to utilizing RM as a risk assessment tool for selecting appropriate hybrids. It should be noted that there was more scatter in the RM-CHU relationship at values between 70 and 79 day RM (between 2150 and 2300 CHU). This is the range regarded as early season hybrids suitable for production in areas with moderate CHU accumulation on the Canadian Prairies. The variability in the RM-CHU relationship within this range is consistent with the concerns expressed by producers about lower confidence in the ratings assigned to early season hybrids.

5.2 Implications of the Current Research

Accurate assessment of corn thermal unit requirements remains the most important aspect for selection of appropriate grain corn hybrids in areas with a short growing season and limited heat accumulation (Kumudini et al. 2014). With the observed long term positive trends in seasonal heat unit accumulation in some agricultural regions of the Canadian Prairies (Nadler and Bullock 2011), it would be ideal for producers, especially those that have minimal experience with the crop, to have confidence in agrometeorological tools that they can use for selecting corn hybrids for their areas. However, the inverse relationship between cold night hours and CHU accumulation by the 2700 CHU grain corn hybrid suggests another potential impact of climate change. In future, with a reduced number of cold night hours, the CHU requirement by corn hybrids would be expected to increase. This may result in difficulty breeding of grain corn with limited heat unit requirements as well as growing them successfully in non-traditional production areas.

Consistent tools or indices would aid in expanding the area under grain corn production and hence increase availability of resources for the food, feed and fuel industries. Furthermore, it would be helpful for corn breeders as well as physiologists to be able to characterize their hybrids based on temperature requirements as well as the extent to which corn plants are stressed by temperature extremes. Proper quantification of thermal requirements to reach each phenological development could be crucial in making corn management decisions and timing of operations such as the ideal stage of application of nutrients, spraying chemicals for pest control and expected dates of harvesting.

The GTI assessment indicated that, with a sufficient number of replications, it may display lower variability than the other indices from V4 to R6, indicating the index's potential to be a more accurate simulation of corn development early and late in the growing season. The CHU and both GDD indices had CV between 6 and 10.5%, which was numerically greater than that of the GTI (less than 5%) at R6. It is recommended that the GTI undergoes further assessment for consideration as an alternative for assigning heat unit ratings to grain corn hybrids intended for the Canadian Prairies.

The strong relationship between RM and CHU suggests no advantage in using either index for selecting corn hybrids suitable for production on the Canadian Prairies. Both indices may yield similar results if used as tools for selecting suitable grain corn hybrids for production in specific environments. While working on finding a lasting solution for hybrid selection on the Canadian Prairies, corn producers need to be aware of performance of the current corn hybrids so as to make effective selection of the ones that will mature within the short growing season that they experience.

5.3 Limitations of the Research and Recommendations

In Chapter 2, similar thermal unit accumulation was observed at each phenological development stage, regardless of the index and hybrid in the analysis. Moreover, the GTI was established as a potential alternative to CHU for modeling phenological development of corn. Additional site-years of field data are needed to delineate thermal unit requirements for corn hybrids adapted to the Canadian Prairies. Furthermore, the GTI needs to be explored with more field data of the same hybrids so as to affirm its suitability as an alternative consistent and reliable thermal index.

In this study, there were few replications and the calculated statistical power was 0.7, which is less than the desired power of 0.8. The current field study had less than 15 site-years when greater than 17 site-years were required with the same number of hybrids to achieve the desired statistical power. This impacted on the inability to obtain statistically significant differences among the corn hybrids with very different maturity ratings. In addition to Manitoba and Alberta sites, the initial plan was to set up sites in Saskatchewan, which could have provided more site-years of field data. However, there were limitations in terms of equipment and travel costs as well as finding collaborators able to assist with conducting the trials in that province. In future studies, it would be ideal to determine statistical power and sample sizes that result in detection of meaningful effects. If these options are not possible, the researcher can also consider restructuring the experimental designs to achieve suitable sample sizes (Ledolter, 2013). In future, field trials should also be conducted in Saskatchewan so as to have total representation for all the Canadian Prairies.

Corn seeding dates varied from site to site with some sites seeding as early as the first week of May while others were seeded during the second half of May. Early seeding did not help because soil temperatures on the Canadian Prairies are normally cold and under these conditions, seedlings took several more days to emerge than when warm soil temperatures prevailed. Selection of corn hybrids that can tolerate and emerge early under these conditions would also help with extending the potential growing area of grain corn on the Canadian Prairies. Corn producers on the Canadian Prairies can also select early corn hybrids that can reach maturity before killing frost that is experienced towards the end of the growing season in this region. Timeous nutrient application, particularly phosphorus could also allow fast growth of roots, which will in turn enable corn roots to scavenge for more nutrients and water from the soil. The

Canadian Prairies are well known for experiencing cold soil temperature in the spring, which delays corn emergence. However, tillage practices such as strip till may also help with warming of the soil allowing for a favorable environment for corn to emerge from the ground. This would help with faster phenological development and ability to mature within the short growing season.

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Appendices

Appendix I: Characterization of the study locations

1.1 Corn phenology study sites' soil texture and classification across Prairie Ecological regions.

Study site	Ecoregion	Soil texture	Classification
Fort Whyte, MB	Lake Manitoba Plain[z]	Clay loam	Black Chernozem
Carman, MB	Lake Manitoba Plain[z]	Sandy loam	Orthic black
Portage la Prairie, MB	Lake Manitoba Plain[z]	Clay loam	Orthic black
Carberry, MB	Lake Manitoba Plain[z]	Clay loam	Solonetzic black
Roblin, MB	Aspen Parkland[y]	Clay loam	Dark grey Chernozem
Melita, MB	Aspen Parkland[y]	Clay loam	Cumulic Regosol
Lethbridge, AB	Moist Mixed Grassland[x]	Clay loam	Dark brown Chernozem
Vauxhall, AB	Moist Mixed Grassland[x]	Sandy loam	Brown Chernozem

[z] North western Manitoba starting from the International Boundary of the United States to Dauphin Lake

[y] South western Manitoba towards the north western side through Saskatchewan to the northern apex in Alberta

[x] Northern extension of open grasslands in the interior Plains of Canada, characteristic semiarid moisture condition.

Appendix II: Accumulated heat units by three AAFC corn hybrids in 2015.

II.1 Fortwhyte

Thermal index	Hybrid	Phenology stages						
		VE	V2	V4	V6	VT	R1	R6
CHU	CM105xCL30	269	432	617	823	1388	1526	2573
	C0450xCL30	269	452	602	798	1471	1552	2701
	C0450xC0442	253	452	589	847	1552	1665	2792
GTI	CM105xCL30	121	189	268	355	595	655	1115
	C0450xCL30	121	198	263	345	630	666	1177
	C0450xC0442	114	198	257	365	667	715	1226
$mGDD_{10.30}$	CM105xCL30	103	163	238	321	560	626	1056
	C0450xCL30	103	171	234	310	599	637	1105
	C0450xC0442	97	171	229	330	637	682	1139
GDD_{10}	CM105xCL30	83	144	211	296	533	598	1008
	C0450xCL30	83	151	208	285	570	611	1044
	C0450xC0442	77	151	204	305	611	656	1075
DAP	CM105xCL30	25	33	43	52	76	81	131
	C0450xCL30	25	34	42	51	79	82	139
	C0450xC0442	24	34	41	53	82	87	143

II.2 Carman

Thermal index	Hybrid	Phenology stages						
		VE	V2	V4	V6	VT	R1	R6
CHU	CM105xCL30	177	293	512	729	1193	1328	2392
	C0450xCL30	177	364	493	756	1236	1355	2628
	C0450xC0442	177	388	527	756	1410	1516	2795
GTI	CM105xCL30	79	127	220	310	508	566	1036
	C0450xCL30	79	157	213	321	526	578	1154
	C0450xC0442	79	167	227	321	602	646	1245
mGDD$_{10.30}$	CM105xCL30	74	116	206	291	494	548	1014
	C0450xCL30	74	145	198	304	509	562	1114
	C0450xC0442	74	155	211	304	587	636	1174
GDD$_{10}$	CM105xCL30	67	109	198	306	482	539	1001
	C0450xCL30	67	138	158	293	498	552	1069
	C0450xC0442	67	149	202	293	577	628	1108
DAP	CM105xCL30	10	16	26	38	55	61	109
	C0450xCL30	10	19	26	37	57	62	124
	C0450xC0442	10	20	27	37	64	68	136

II.3 Carberry

Thermal index	Hybrid	Phenology stages						
		VE	V2	V4	V6	VT	R1	R6
CHU	CM105xCL30	180	341	526	783	1361	1477	2625
	C0450xCL30	180	364	590	783	1361	1455	2647
	C0450xC0442	180	341	590	832	1536	1637	2713
GTI	CM105xCL30	77	149	224	336	584	632	1170
	C0450xCL30	77	159	252	336	584	622	1200
	C0450xC0442	77	149	252	356	658	701	1245
$mGDD_{10.30}$	CM105xCL30	67	134	202	313	572	619	1088
	C0450xCL30	67	143	229	313	572	609	1094
	C0450xC0442	67	134	229	334	643	678	1117
GDD_{10}	CM105xCL30	61	132	194	306	556	603	1006
	C0450xCL30	61	142	220	306	556	594	1069
	C0450xC0442	61	132	220	325	626	662	1015
DAP	CM105xCL30	11	18	28	39	63	68	130
	C0450xCL30	11	19	31	39	63	67	137
	C0450xC0442	11	18	31	41	71	76	143

II.4 Portage la Prairie

Thermal index	**Hybrid**	**Phenology stages**						
		VE	**V2**	**V4**	**V6**	**VT**	**R1**	**R6**
CHU	CM105xCL30	238	378	564	813	1313	1469	2741
	C0450xCL30	238	427	587	786	1336	1442	2844
	C0450xC0442	238	401	564	786	1498	1577	2913
GTI	CM105xCL30	104	162	239	343	555	618	1175
	C0450xCL30	104	185	248	332	565	607	1225
	C0450xC0442	104	173	239	332	634	667	1287
$mGDD_{10.30}$	CM105xCL30	93	148	221	303	546	616	1139
	C0450xCL30	93	170	229	316	555	603	1179
	C0450xC0442	93	157	221	316	630	665	1199
GDD_{10}	CM105xCL30	89	146	216	321	539	608	1106
	C0450xCL30	89	170	224	310	548	594	1141
	C0450xC0442	89	157	216	310	623	659	1148
DAP	CM105xCL30	13	19	28	38	58	64	124
	C0450xCL30	13	21	29	37	59	63	128
	C0450xC0442	13	20	28	37	65	68	139

II.5 Roblin

Thermal index	**Hybrid**	**Phenology stages**						
		VE	**V2**	**V4**	**V6**	**VT**	**R1**	**R6**
CHU	CM105xCL30	229	349	580	694	1463	1533	2420
	C0450xCL30	229	323	604	752	1484	1560	.
	C0450xC0442	229	411	604	737	1612	1685	.
GTI	CM105xCL30	97	149	250	297	618	648	1166
	C0450xCL30	97	138	259	320	627	659	.
	C0450xC0442	97	174	259	313	685	718	.
$mGDD_{10.30}$	CM105xCL30	82	127	218	262	563	594	845
	C0450xCL30	82	117	227	283	571	607	.
	C0450xC0442	82	149	227	277	632	660	.
GDD_{10}	CM105xCL30	76	119	208	253	551	582	816
	C0450xCL30	76	112	217	272	559	595	.
	C0450xC0442	76	136	217	267	621	659	.
DAP	CM105xCL30	14	21	33	38	74	77	138
	C0450xCL30	14	19	34	41	75	78	.
	C0450xC0442	14	25	34	40	80	86	.

II.6 Lethbridge

Thermal index	Hybrid	Phenology stages						
		VE	V2	V4	V6	VT	R1	R6
CHU	CM105xCL30	143	260	415	603	1267	1377	2480
	C0450xCL30	143	279	415	562	1267	1352	2548
	C0450xC0442	158	279	434	562	1449	1552	2655
GTI	CM105xCL30	60	109	179	259	553	600	1142
	C0450xCL30	60	118	179	242	553	590	1192
	C0450xC0442	67	118	188	242	632	682	1239
$mGDD_{10.30}$	CM105xCL30	53	100	163	238	525	575	1043
	C0450xCL30	53	108	163	221	525	564	1072
	C0450xC0442	63	108	170	221	603	654	1112
GDD_{10}	CM105xCL30	20	53	117	181	465	511	895
	C0450xCL30	20	61	117	167	465	501	905
	C0450xC0442	25	61	125	167	538	589	905
DAP	CM105xCL30	17	25	33	44	75	80	144
	C0450xCL30	17	26	33	42	75	79	150
	C0450xC0442	18	26	34	42	84	89	153

II.7 Vauxhall

Thermal index	**Hybrid**	**Phenology stages**						
		VE	**V2**	**V4**	**V6**	**VT**	**R1**	**R6**
CHU	CM105xCL30	155	233	390	500	1161	1247	2289
	C0450xCL30	155	243	390	500	1161	1273	2483
	C0450xC0442	155	243	412	500	1273	1359	2552
GTI	CM105xCL30	61	96	162	215	511	554	1070
	C0450xCL30	61	100	162	215	511	564	1156
	C0450xC0442	61	100	184	215	560	598	1201
mGDD$_{10.30}$	CM105xCL30	59	89	147	197	484	516	971
	C0450xCL30	59	93	147	197	484	527	1044
	C0450xC0442	59	93	157	197	527	566	1074
GDD$_{10}$	CM105xCL30	19	46	98	152	431	463	877
	C0450xCL30	19	47	98	152	431	473	908
	C0450xC0442	19	47	109	152	473	509	914
DAP	CM105xCL30	17	22	31	36	69	74	132
	C0450xCL30	17	23	31	36	69	75	142
	C0450xC0442	17	23	32	36	75	79	153

Appendix III Accumulated heat units by five corn hybrids at various locations in 2016

III.1 Fortwhyte

Thermal index	**Hybrid**	**Phenology stage**						
		VE	**V2**	**V4**	**V6**	**VT**	**R1**	**R6**
CHU	P7958AM	274	455	729	945	1555	1655	2871
	CM105xCL30	274	455	701	885	1555	1633	2913
	C0450xCL30	274	455	701	885	1529	1581	2913
	C0450xC0442	274	455	701	861	1655	1775	3023
	PrideA4408G2	292	492	729	911	1555	1655	2913
GTI	P7958AM	118	187	300	389	640	680	1204
	CM105xCL30	118	187	289	364	640	671	1231
	C0450xCL30	118	187	289	364	630	650	1238
	C0450xC0442	118	187	289	354	681	732	1324
	PrideA4408G2	125	202	300	375	640	680	1243
mGDD$_{10.30}$	P7958AM	110	169	273	354	599	640	1113
	CM105xCL30	110	169	262	333	599	632	1126
	C0450xCL30	110	169	262	333	588	609	1126
	C0450xC0442	110	169	262	323	640	692	1168
	PrideA4408G2	115	180	273	343	599	640	1126
GDD$_{10}$	P7958AM	95	147	251	333	577	618	1055
	CM105xCL30	95	147	239	311	577	610	1059
	C0450xCL30	95	147	239	311	567	587	1059
	C0450xC0442	95	147	239	300	618	670	1090
	PrideA4408G2	100	160	251	322	577	618	1059
DAP	P7958AM	18	28	41	51	77	81	140
	CM105xCL30	18	28	39	48	77	80	144
	C0450xCL30	18	28	39	48	76	78	144
	C0450xC0442	18	28	39	47	81	86	153
	PrideA4408G2	19	30	41	49	77	81	144

III.2 Carman

Thermal index	**Hybrid**	**Phenology stages**						
		VE	**V2**	**V4**	**V6**	**VT**	**R1**	**R6**
CHU	P7958AM	269	406	659	879	1557	1620	2945
	CM105xCL30	249	392	609	822	1478	1579	2948
	C0450xCL30	269	392	560	773	1423	1579	2948
	C0450xC0442	269	376	585	751	1671	1791	2950
	PrideA4408G2	287	392	585	773	1579	1768	2945
GTI	P7958AM	110	165	271	362	640	668	1255
	CM105xCL30	101	159	250	339	607	648	1276
	C0450xCL30	110	159	231	317	585	647	1275
	C0450xC0442	110	152	241	308	690	739	1295
	PrideA4408G2	117	159	241	317	649	729	1261
mGDD$_{10.30}$	P7958AM	103	148	249	331	608	632	1144
	CM105xCL30	95	143	228	312	573	615	1145
	C0450xCL30	103	143	209	292	549	615	1145
	C0450xC0442	103	139	219	284	656	704	1146
	PrideA4408G2	108	143	219	292	616	696	1144
GDD$_{10}$	P7958AM	94	135	239	324	599	623	1085
	CM105xCL30	85	131	218	304	564	606	1085
	C0450xCL30	94	131	198	282	541	606	1085
	C0450xC0442	94	127	209	273	647	697	1085
	PrideA4408G2	98	131	209	282	606	689	1085
DAP	P7958AM	13	21	32	42	70	73	141
	CM105xCL30	12	20	30	39	67	71	145
	C0450xCL30	13	20	28	37	65	71	145
	C0450xC0442	13	19	29	36	75	80	151
	PrideA4408G2	14	20	29	37	71	79	141

III.3 Carberry

Thermal index	Hybrid	Phenology stages						
		VE	V2	V4	V6	VT	R1	R6
CHU	P7958AM	244	383	636	856	1517	1594	2738
	CM105xCL30	244	362	591	842	1542	1640	2738
	C0450xCL30	231	334	541	695	1569	1682	2742
	C0450xC0442	254	362	564	797	1495	1569	2742
	PrideA4408G2	288	410	541	817	1618	1721	2742
GTI	P7958AM	103	160	266	356	630	673	1197
	CM105xCL30	103	151	246	350	641	683	1214
	C0450xCL30	98	139	226	289	653	701	1236
	C0450xC0442	106	151	235	331	621	652	1235
	PrideA4408G2	120	172	226	341	675	720	1227
mGDD$_{10.30}$	P7958AM	87	136	238	316	580	615	1045
	CM105xCL30	87	129	221	312	591	635	1045
	C0450xCL30	84	119	200	258	604	649	1046
	C0450xC0442	89	129	209	293	571	604	1046
	PrideA4408G2	102	149	200	302	625	665	1046
GDD$_{10}$	P7958AM	83	127	230	310	573	609	979
	CM105xCL30	83	119	212	306	588	629	979
	C0450xCL30	81	111	191	249	597	643	979
	C0450xC0442	83	119	200	288	563	597	979
	PrideA4408G2	94	140	191	297	619	660	979
DAP	P7958AM	13	21	32	43	72	74	140
	CM105xCL30	13	20	30	42	73	77	143
	C0450xCL30	12	18	28	35	74	79	143
	C0450xC0442	14	20	29	40	71	74	147
	PrideA4408G2	16	22	28	41	76	81	140

III.4 Portage la Prairie

Thermal index	Hybrid	Phenology stage						
		VE	V2	V4	V6	VT	R1	R6
CHU	P7958AM	328	498	667	940	1523	1631	3006
	CM105xCL30	310	498	667	940	1479	1631	3006
	C0450xCL30	328	515	667	893	1479	1656	3006
	C0450xC0442	352	498	667	870	1587	1739	3012
	PrideA4408G2	310	515	613	920	1507	1609	3006
GTI	P7958AM	133	203	272	384	626	666	1267
	CM105xCL30	127	203	272	384	605	666	1266
	C0450xCL30	133	209	272	366	605	677	1266
	C0450xC0442	142	203	272	355	650	712	1307
	PrideA4408G2	127	209	250	377	615	657	1267
$mGDD_{10.30}$	P7958AM	117	182	251	355	597	638	1158
	CM105xCL30	112	182	251	355	574	638	1158
	C0450xCL30	117	187	251	337	574	649	1158
	C0450xC0442	127	182	251	327	621	686	1160
	PrideA4408G2	112	187	227	349	586	630	1158
GDD_{10}	P7958AM	109	173	241	347	588	631	1109
	CM105xCL30	103	173	241	347	566	631	1109
	C0450xCL30	109	177	241	330	566	642	1109
	C0450xC0442	117	173	241	319	613	679	1109
	PrideA4408G2	103	177	218	341	577	622	1109
DAP	P7958AM	17	25	32	44	68	72	141
	CM105xCL30	16	25	32	44	66	72	141
	C0450xCL30	17	26	32	42	66	73	141
	C0450xC0442	18	25	32	43	70	75	148
	PrideA4408G2	16	20	30	41	67	71	141

III.5 Roblin

Thermal index	Hybrid	Phenology stages						
		VE	V2	V4	V6	VT	R1	R6
CHU	P7958AM	183	323	494	726	1426	1503	.
	CM105xCL30	183	345	494	750	1408	1484	.
	C0450xCL30	214	365	510	726	1312	1408	.
	C0450xC0442	214	345	494	965	1584	1662	.
	PrideA4408G2	214	323	475	903	1408	1503	.
GTI	P7958AM	73	128	197	292	577	610	.
	CM105xCL30	73	137	197	300	569	602	.
	C0450xCL30	85	145	204	292	529	568	.
	C0450xC0442	85	137	197	384	644	672	.
	PrideA4408G2	85	128	189	360	569	611	.
mGDD$_{10.30}$	P7958AM	57	109	170	253	517	545	.
	CM105xCL30	57	118	170	261	511	537	.
	C0450xCL30	68	124	177	253	472	511	.
	C0450xC0442	68	118	170	337	572	601	.
	PrideA4408G2	68	109	165	316	511	544	.
GDD$_{10}$	P7958AM	48	95	158	239	501	528	.
	CM105xCL30	48	105	158	246	495	520	.
	C0450xCL30	57	111	164	239	456	495	.
	C0450xC0442	57	105	158	322	554	580	.
	PrideA4408G2	57	95	152	300	495	528	.
DAP	P7958AM	11	18	26	38	70	74	.
	CM105xCL30	11	19	26	39	69	73	.
	C0450xCL30	13	20	27	38	65	69	.
	C0450xC0442	13	19	26	36	78	82	.
	PrideA4408G2	13	18	25	36	69	74	.

III.6 Lethbridge

Thermal index	Hybrid	Phenology stages						
		VE	V2	V4	V6	VT	R1	R6
CHU	P7958AM	188	271	535	856	1485	1609	2590
	CM105xCL30	188	271	535	835	1387	1485	2606
	C0450xCL30	188	258	516	738	1436	1533	2606
	C0450xC0442	202	308	535	757	1595	1720	2650
	PrideA4408G2	188	285	535	757	1575	1698	2640
GTI	P7958AM	80	117	236	372	628	682	1144
	CM105xCL30	80	117	236	362	587	627	1150
	C0450xCL30	80	112	229	322	608	648	1150
	C0450xC0442	85	132	236	330	675	727	1231
	PrideA4408G2	80	123	236	330	665	718	1192
$mGDD_{10.30}$	P7958AM	75	101	207	326	573	624	1006
	CM105xCL30	75	101	207	317	530	573	1014
	C0450xCL30	75	96	201	282	551	595	1014
	C0450xC0442	79	114	207	288	620	668	1027
	PrideA4408G2	75	107	207	288	610	660	1024
GDD_{10}	P7958AM	52	68	175	288	522	571	876
	CM105xCL30	52	68	175	279	483	522	879
	C0450xCL30	52	66	170	243	503	544	879
	C0450xC0442	55	75	175	250	567	612	881
	PrideA4408G2	52	72	175	250	558	604	881
DAP	P7958AM	15	25	39	57	86	92	149
	CM105xCL30	15	25	39	56	82	86	150
	C0450xCL30	15	24	38	51	84	88	150
	C0450xC0442	16	28	39	52	91	97	164
	PrideA4408G2	15	26	39	52	90	96	157

III.7 Vauxhall

Thermal index	**Hybrid**	**Phenology stages**						
		VE	**V2**	**V4**	**V6**	**VT**	**R1**	**R6**
CHU	P7958AM	233	429	639	926	1477	1550	2550
	CM105xCL30	207	429	621	904	1383	1477	2515
	C0450xCL30	207	429	639	878	1230	1341	2610
	C0450xC0442	248	327	576	904	1570	1665	2617
	PrideA4408G2	207	429	639	878	1525	1713	2610
GTI	P7958AM	104	192	281	402	628	658	1142
	CM105xCL30	92	192	274	392	588	627	1125
	C0450xCL30	92	192	281	383	522	571	1197
	C0450xC0442	111	144	256	392	667	711	1236
	PrideA4408G2	92	192	281	383	649	730	1214
mGDD$_{10.30}$	P7958AM	96	174	256	369	584	616	1008
	CM105xCL30	86	174	250	360	544	584	995
	C0450xCL30	86	174	256	349	482	528	1030
	C0450xC0442	101	131	236	360	623	661	1032
	PrideA4408G2	86	174	256	349	606	680	1030
GDD$_{10}$	P7958AM	61	133	210	320	526	557	872
	CM105xCL30	58	133	205	311	487	526	863
	C0450xCL30	58	133	210	302	424	471	876
	C0450xC0442	66	87	193	311	563	601	876
	PrideA4408G2	58	133	210	302	548	618	876
DAP	P7958AM	22	34	45	59	85	88	148
	CM105xCL30	18	34	44	58	81	85	146
	C0450xCL30	18	34	45	57	74	79	157
	C0450xC0442	23	29	41	58	89	94	167
	PrideA4408G2	18	34	45	57	87	96	160

III.8 Melita

Thermal index	**Hybrid**	**Phenology stages**						
		VE	**V2**	**V4**	**V6**	**VT**	**R1**	**R6**
CHU	P7958AM	334	453	616	865	1510	1627	2533
	CM105xCL30	272	433	568	824	1360	1486	2627
	C0450xCL30	272	453	616	803	1360	1486	2627
	C0450xC0442	272	433	593	716	1575	1694	2823
	PrideA4408G2	272	497	639	824	1486	1550	2627
GTI	P7958AM	134	184	253	357	625	676	1082
	CM105xCL30	108	177	232	340	560	613	1127
	C0450xCL30	108	184	253	331	560	613	1127
	C0450xC0442	108	177	243	296	655	708	1246
	PrideA4408G2	108	202	264	340	615	643	1127
mGDD$_{10.30}$	P7958AM	115	166	231	322	586	638	1009
	CM105xCL30	93	159	211	307	521	576	1046
	C0450xCL30	93	166	231	298	521	576	1046
	C0450xC0442	93	159	221	267	614	668	1112
	PrideA4408G2	93	182	240	307	576	602	1046
GDD$_{10}$	P7958AM	109	160	227	321	586	640	985
	CM105xCL30	86	153	206	306	520	576	1010
	C0450xCL30	86	160	227	298	520	576	1010
	C0450xC0442	86	153	217	266	615	672	1054
	PrideA4408G2	86	176	237	306	576	603	1010
DAP	P7958AM	16	22	29	41	68	73	118
	CM105xCL30	14	21	27	39	62	67	124
	C0450xCL30	14	22	29	38	62	67	124
	C0450xC0442	14	21	28	34	71	76	141
	PrideA4408G2	14	24	30	39	67	70	124

Appendix IV Scatter plots for relationships between thermal units accumulated to R6 and the number of cold night hours across various locations in 2015 and 2016.

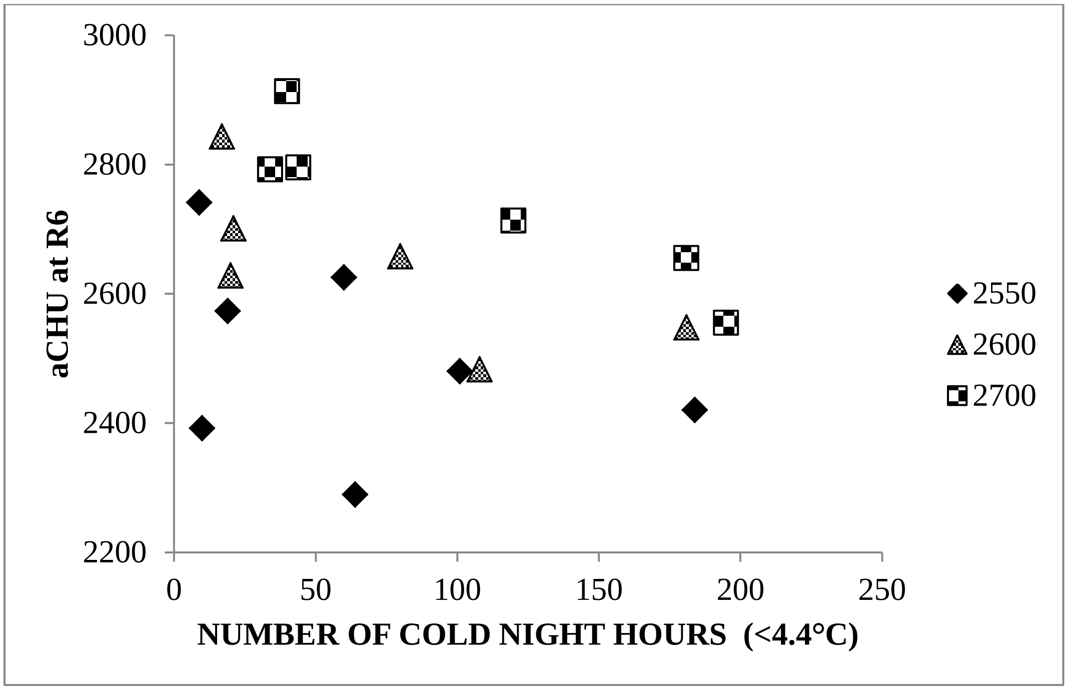

Figure IV.1 Relationship between CHU accumulated to R6 and number of cold night (<4.4°C) for 3 corn hybrids across 7 locations on the Prairies in 2015.

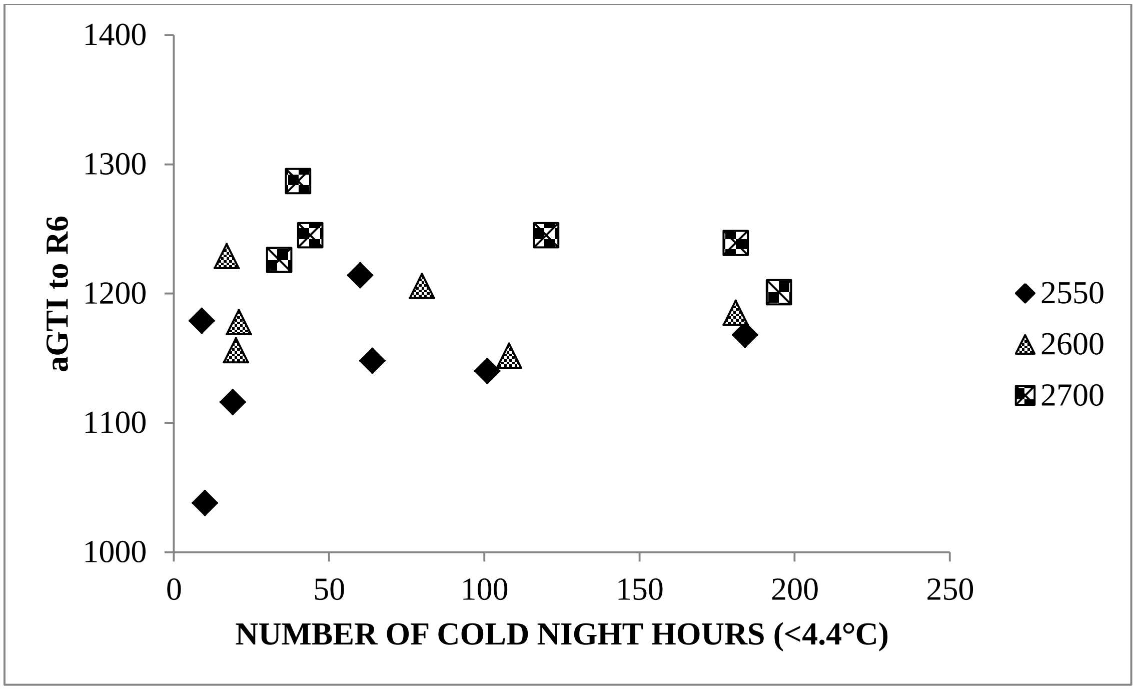

Figure IV.2 Relationship between GTI accumulated to R6 and number of cold night hours (<4.4°C) for 3 corn hybrids across 7 locations on the Prairies in 2015.

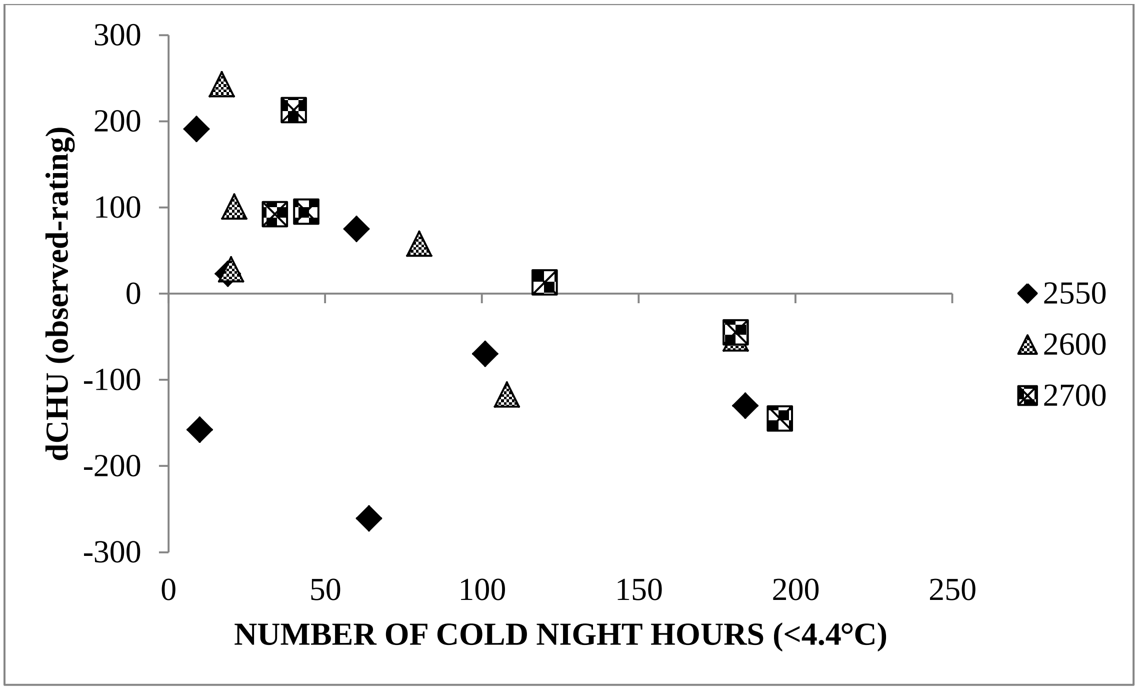

Figure IV.3 Relationship between dCHU and number of cold night (<4.4°C) for 3 corn hybrids across 7 locations on the Prairies in 2015.

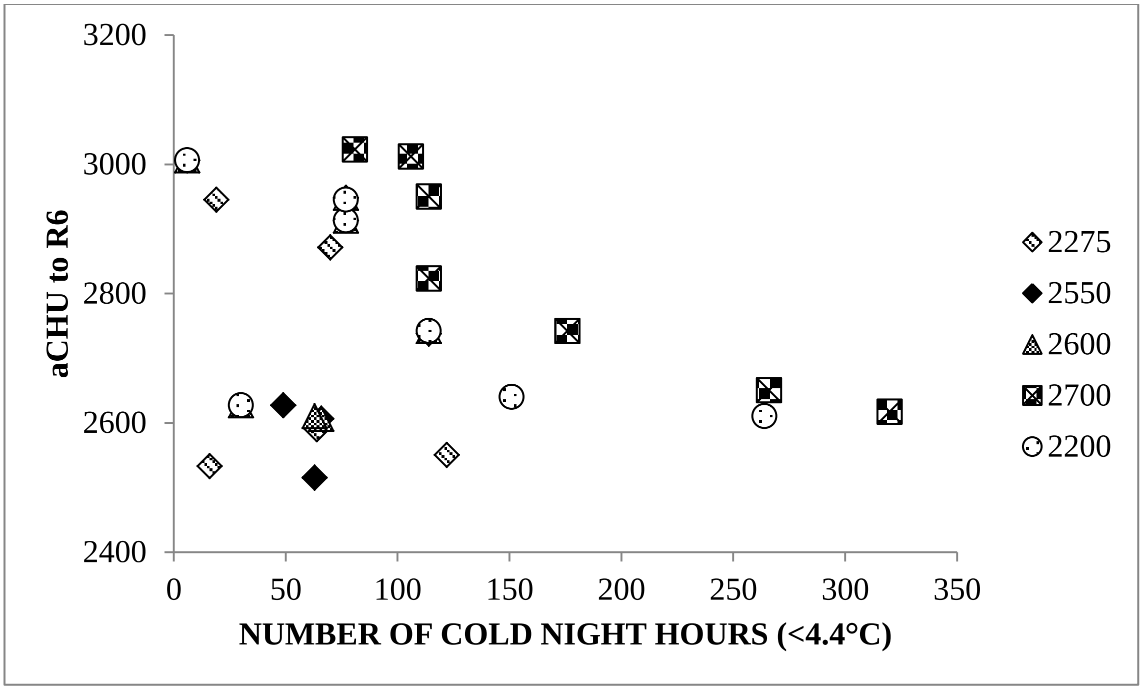

Figure IV.4 Relationship between CHU accumulated to R6 and number of cold night hours (<4.4°C) for 5 corn hybrids across 7 locations on the Prairies in 2016.

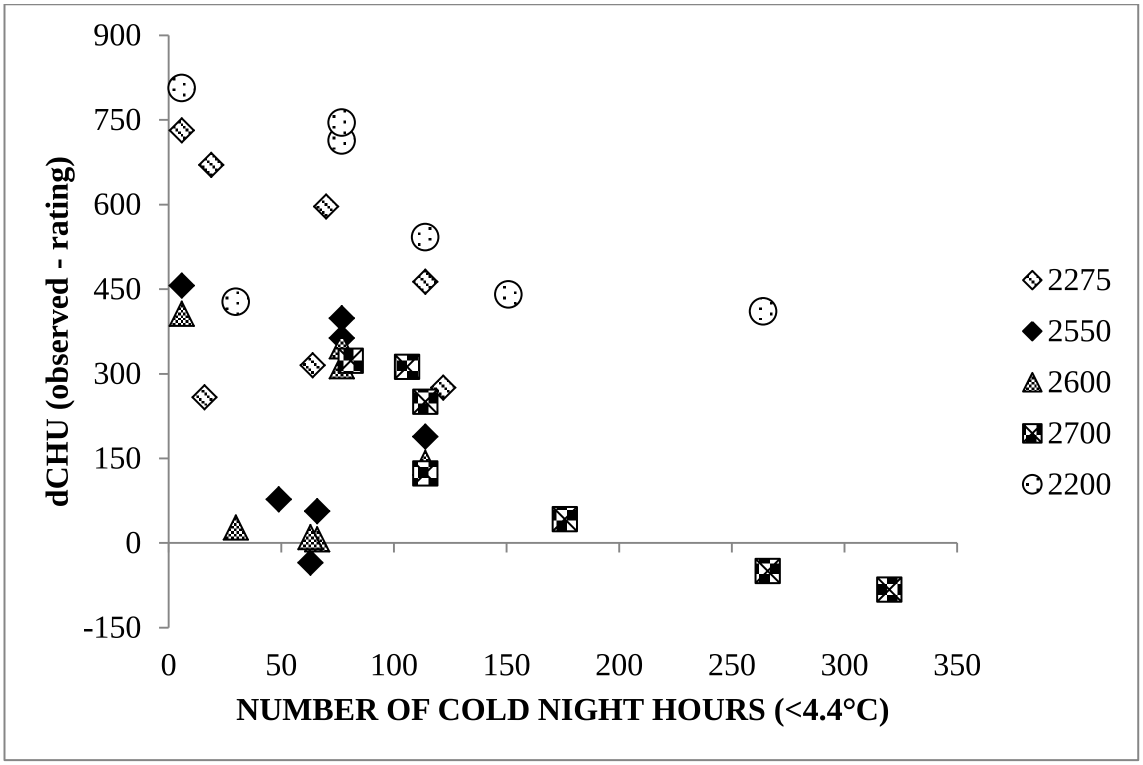

Figure IV.5 Relationship between dCHU and number of cold night hours (<4.4°C) for 5 corn hybrids across 7 locations on the Prairies in 2016.

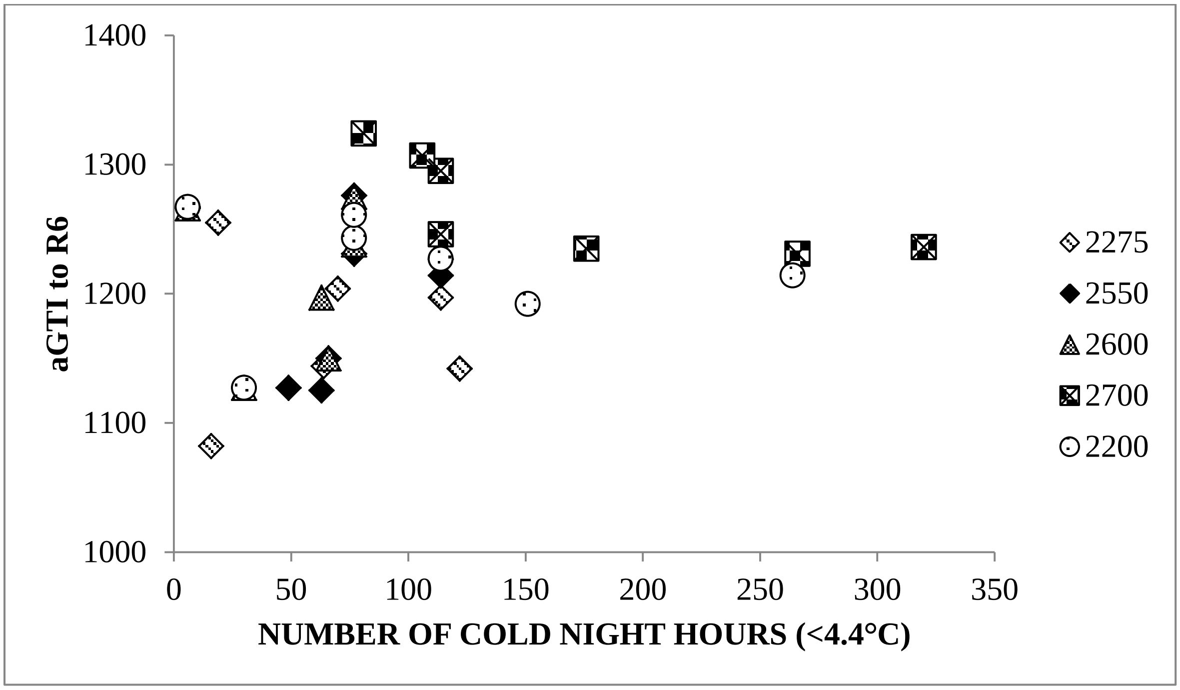

Figure IV.6 Relationship between GTI accumulated to R6 and number of cold night (<4.4°C) for 5 corn hybrids across 7 locations on the Prairies in 2016.

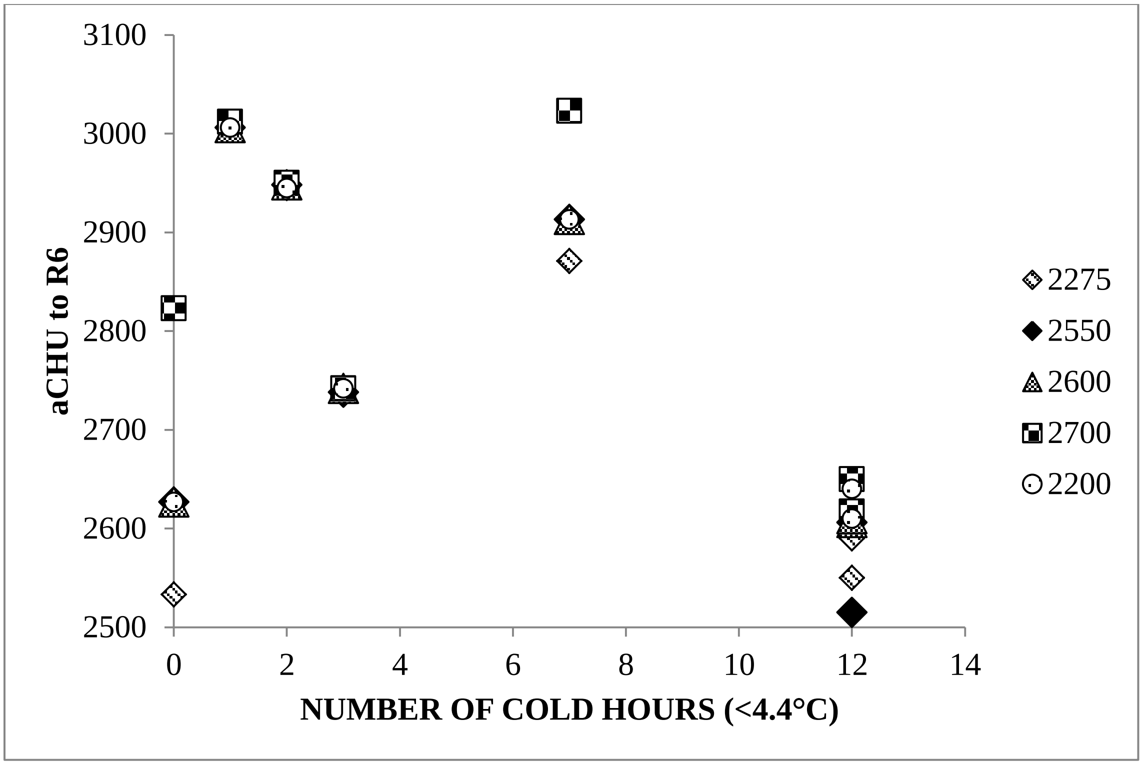

Figure IV.7 Relationship between CHU accumulated to R6 and number of cold night hours (<4.4°C) from seeding to tasseling for 5 corn hybrids across 7 locations in 2016.

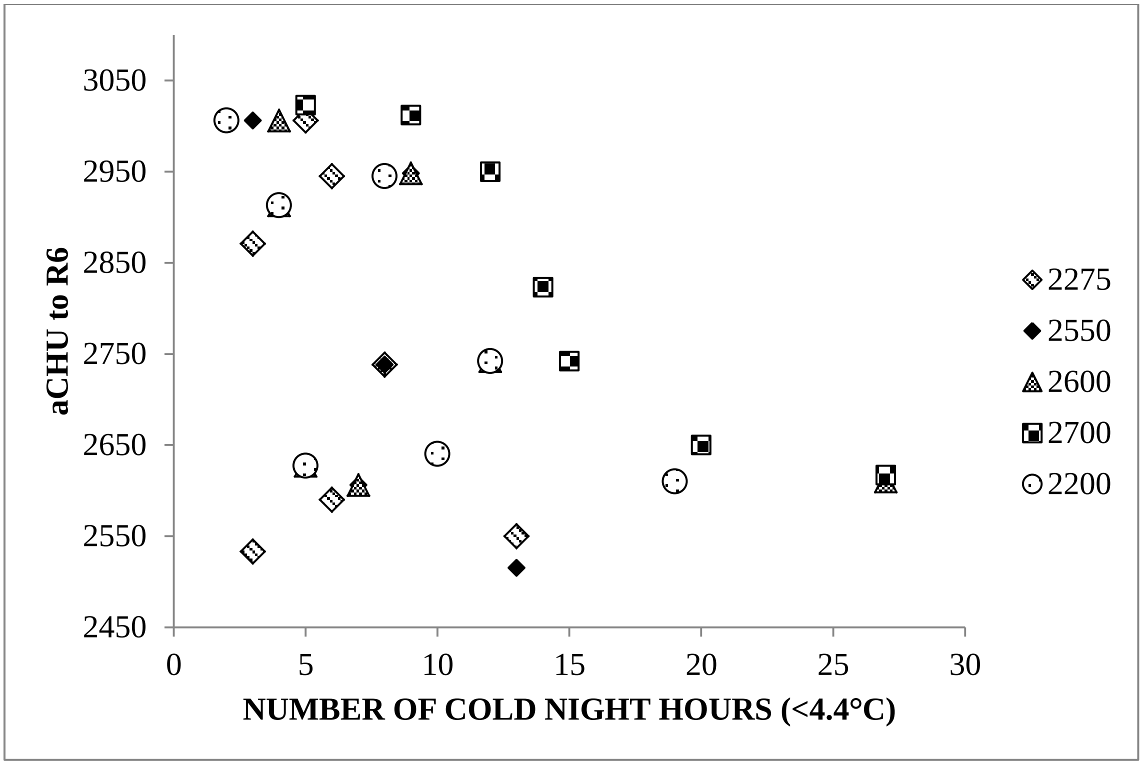

Figure IV.8 Relationship between CHU accumulated to R6 and number of cold night hours (<4.4°C) from tasseling to R6 for 5 corn hybrids across 7 locations in 2016.

Appendix V Regression analysis for RM versus KMC and CHU versus RM

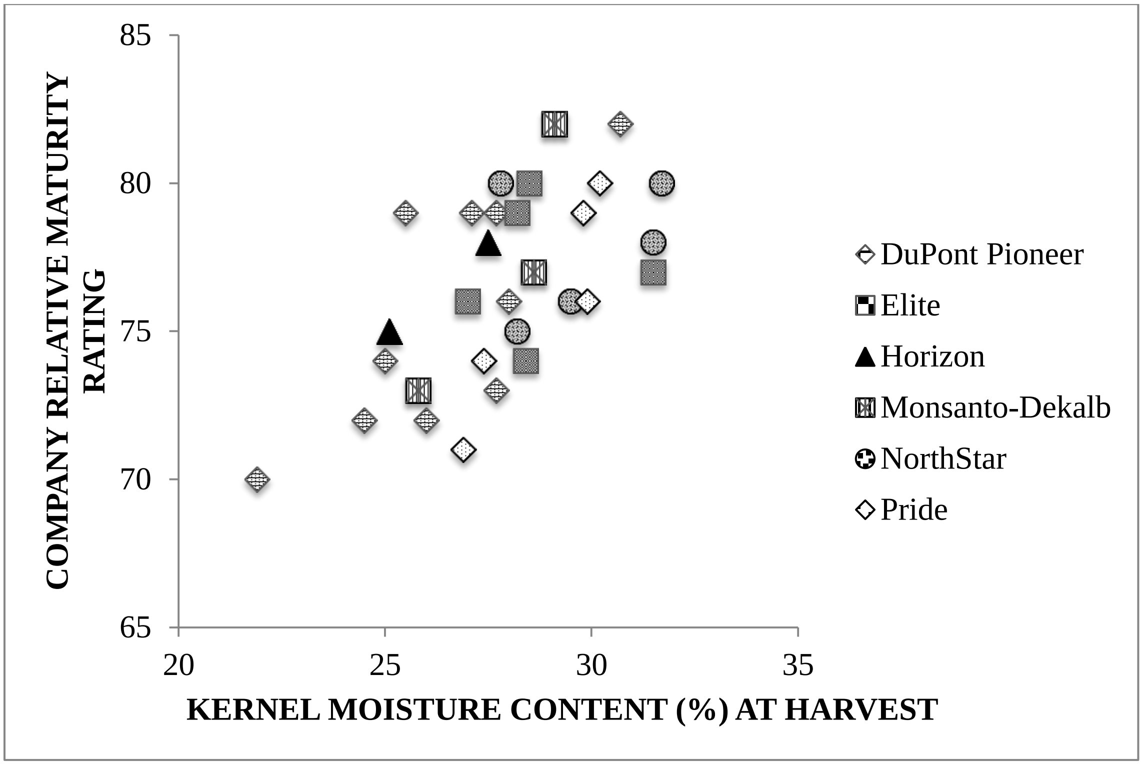

Figure V.1 Relationship between kernel moisture content at harvest and company relative maturity ratings for 31 corn hybrids at MacGregor in 2016.

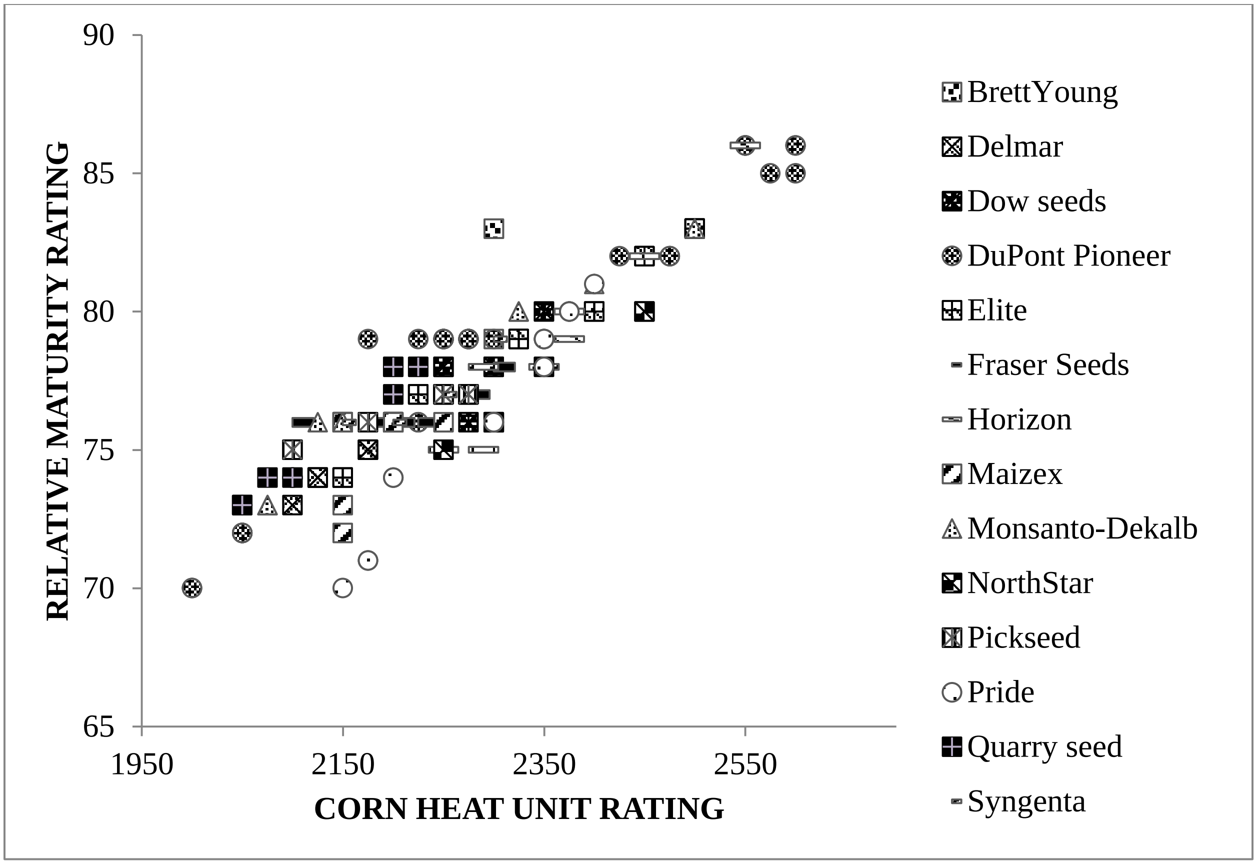

Figure V.2 Relationship between CHU and RM rating of different corn hybrid from various companies across 9 site-years in Manitoba.